

PIOTR STRZAŁKOWSKI¹, MAREK JENDRYŚ^{1*}**ENVIRONMENTAL HAZARDS ASSOCIATED WITH MINE SHAFT CLOSURE:
A PRACTICAL AND COMPUTATIONAL CASE STUDY**

This paper presents a comprehensive analysis of the challenges associated with mine shaft closure, emphasising hazards arising from long-term environmental impacts and ground-surface stability. The study focuses on Shaft I in Upper Silesia, decommissioned in the 1990s. Based on archival documentation and field investigations, we assessed the current technical condition of the shaft backfill, its impact on the surrounding ground environment, and the potential risk of discontinuous deformations in the form of sinkholes. We then performed numerical modelling using the finite difference method in FLAC3D to analyse zones of plasticity in the rock mass and to identify potential hazard areas around the shaft. The simulations indicate the possibility of vertical displacements and structural disturbance in rock layers persisting decades after formal closure. We underscore the need for continuous gas emission monitoring and observation of ground surface deformation. The findings support updating guidelines for long term supervision of post-mining structures and can inform the development of more effective shaft safeguarding and environmental risk management methods in former mining regions.

Keywords: Environmental hazards; mine shaft closure; numerical simulations

1. Introduction

The environmental impact of mining includes a wide range of factors affecting the atmosphere, hydrosphere, and lithosphere. This problem concerns both surface and underground mining [1,2]. Particularly significant nuisances to local communities are associated with surface mining operations, especially in rock quarries where excavation is carried out by blasting [3-5]. Interference with the natural environment also occurs after the closure of mining operations, particularly underground mines.

¹ SILESIAN UNIVERSITY OF TECHNOLOGY, 2A AKADEMICKA STR., 44-100 GLIWICE, POLAND

* Corresponding author: marek.jendryś@polsl.pl



© 2026. The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0). The Journal license is: <https://creativecommons.org/licenses/by/4.0/deed.en>. This license allows others to distribute, remix, modify, and build upon the author's work, even commercially, as long as the original work is attributed to the author.

The shift from coal as a primary energy resource and progressive depletion of deposits have reduced the number of mines in Upper Silesia. Mine closures entail specific problems and environmental hazards. This is corroborated by experience in Germany's Ruhr District, where 170 mines have been closed. The following impacts were observed [6]:

- Release of mine gases (CO , CO_2 , CH_4) from abandoned shafts into the atmosphere due to improper closure, which is also confirmed by observations from other coal basins [7].
- Occurrence of continuous and discontinuous deformations for a period after cessation of extraction [8,9].
- Necessity of reclaiming waste tips that degrade land and cause air pollution through dusting, fires, and associated gas emissions.
- Changes in hydrogeological conditions in the rock mass.

For residents of post-mining areas, shaft closure is the most visible and tangible process. As reported by Czaja [10,11], 392 shafts were decommissioned in Poland between 1970 and 2005, and 24 were converted into water pumping stations. Only one case posed a threat to the surroundings (a methane explosion). Closure works must follow safety principles and should achieve the following outcomes:

- Formation of a stable backfill column and prevention of material loss from the shaft.
- Adequate support to the lining to ensure long-term stability.
- Proper closure of the shaft collar with a slab enabling backfill control and replenishment, as well as monitoring and venting of gas volumes.
- Control over water conditions in the rock mass after restoration of hydrogeological balance.
- Environmental monitoring and the option for land reclamation.

In addition, entries to shaft stations should be secured with dams to prevent migration of backfill.

A suitable solution would be to use fly ash as a component of the backfill material. Due to its binding properties, fly ash could make it possible to obtain a consolidated backfill column without the use of cement [12,13]. Moreover, an appropriate type of fly ash can be selected to protect the concrete shaft lining against sulphate attack [14]. Another benefit of using fly ash is its pozzolanic properties, which allow binding of water present in the backfill material [15].

Old mine shafts – especially those with timber linings – pose significant sinkhole hazards at the surface [16-19]. Where shafts were lined with masonry, the risk is generally lower. Constructing a backfill and sealing the shaft with a reinforced concrete slab is usually sufficient to protect the surface [11, 20-22] – see Fig. 1. Often, however, information is lacking regarding the geological and mining conditions and the specific method of shaft closure. In such cases, geophysical tests should be performed to verify whether the shaft was filled with backfill and whether that material has not migrated deeper into the rock mass. Only based on such tests can a hazard mitigation strategy be developed [23-25].

A research project on securing abandoned shafts [26] produced a handbook of safety rules for decommissioning works. It highlights hazards posed by such workings (e.g., falls into open shafts, methane explosions, injuries due to poor surface structure conditions), the need to secure sites (fencing near the shaft), proper shaft sealing, monitoring of backfill condition, and gas hazards. It also evaluates solutions used in shaft closure.

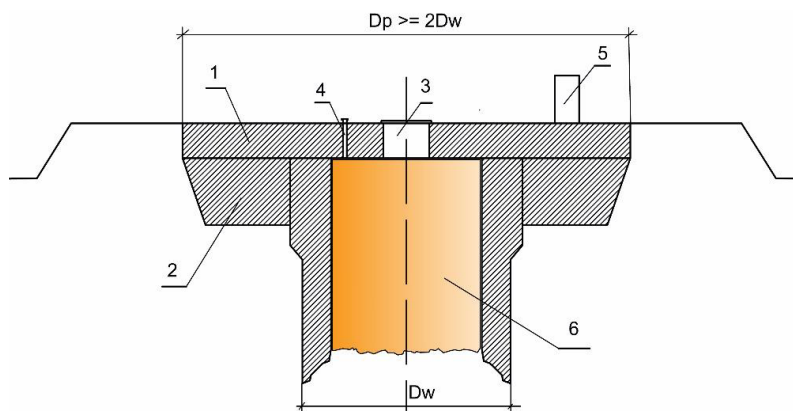


Fig. 1. Typical shaft closure arrangement (after [24], based on [11,20]): 1 – reinforced concrete slab; 2 – strengthening masonry; 3 – inspection opening; 4 – gas-vent nozzle; 5 – information plate; 6 – backfill material

Comprehensive studies on the safety condition of old shafts were conducted under a European project [27], covering more than 100 shafts that had suffered damage. Observations showed that failures resulted from:

- Backfill settlement: 40%,
- Collar protection damage: 29% (e.g., bridgework failures),
- Lining damage: 10%,
- Increased hydraulic loading: 14% (water-bearing layers),
- Gas emissions: 1%,
- Quicksand/gypsum/plug instability: 3%.

For shafts closed at the end of the last century, modernisation and repair of surface shaft protections are often required. Collar closures were frequently executed contrary to current principles, and reinforced concrete slabs have corroded. The present work provides general guidelines for such remedial actions developed from the presented example. These activities are crucial to ensure safety in the vicinity of decommissioned shafts.

The topics of mine shaft closure and associated long-term environmental and structural hazards have been present in international literature for many years. The literature is dominated by approaches based on protection engineering, monitoring, and case-based documentation of good practices for selecting closure techniques [26,28,29].

The MISSTER project provides a concise set of best practices for shaft closure and protection (e.g., deep plugs/dams, staged filling with grouts, sealing injections, structural headworks closures, monitoring and degassing), as well as a risk assessment procedure and solution selection depending on hazard scenarios and local context [30].

A normative framework for such practices can be found in the NRCS guidance [31], which defines objectives and design criteria for closing mine shafts and adits, including method selection (filling, plugging, capping, barriers), O&M requirements, signage, and control of water and gas migration. From an environmental perspective, methane emissions from abandoned or decommissioned coal mines when migration pathways run through shafts justify incorporating degassing (passive/active) and gas monitoring into the design [32].

European case studies confirm real hazards to the surface and infrastructure due to improper closure or degradation of closures: collapse of backfill columns, lining failures, and gas migration [29]. For example, at Shaft V (Knurów-Szczygłowice coal mine), a lining failure and dynamic material inflow produced a depression crater with an estimated volume of $\sim 30,000 \text{ m}^3$; remedial actions included constructing isolating/pressure dams at intermediate levels, injections with materials of $\geq 15 \text{ MPa}$ strength, staged backfilling, and reclamation.

Sandve et al. [33] presented a case study of closing the shaft in Canada using a polyurethane foam plug, effectively securing the shaft and enabling subsequent inspection and monitoring. This illustrates an alternative to classic mass backfilling and reinforced concrete slabs.

The conclusions indicate that effective safeguarding of decommissioned shafts requires integrating structural techniques with environmental and geophysical monitoring, thereby minimising hazards to buildings and enabling safe transformation of post-mining land.

2. Materials and methods

2.1. Rock mass structure

The rock mass at the location of Shaft I comprises Quaternary overburden and the coal-bearing Carboniferous strata (see Fig. 2). The overburden thickness is 48.5 m. It consists of

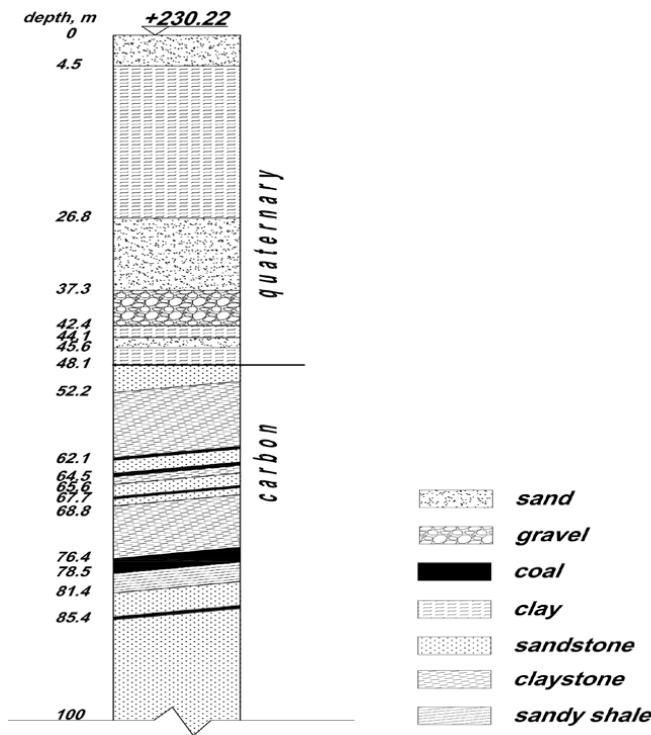


Fig. 2. Geological structure at the location of Shaft I

44 m of Quaternary layers developed as sands, loams, and gravels. Below 44 m lies the Tertiary, developed as sandy mudstones. From a depth of 48.5 m, the Carboniferous occurs, developed as the Poreba, Jaklowiec, and Gruszow series. The Carboniferous is composed of interbedded mudstones and sandstones with hard coal seams.

2.2. Shaft characteristics

Information on Shaft I is provided by the “Technical Design with Closure Technology for Shaft I” (1996) [34]. Based on this, the shaft was constructed between 1916 and 1919 to a depth of 795.24 m with a diameter of 6 m. The lining was built as follows: masonry lining to a depth of 1.5 m; tubbing lining down to 108.26 m; masonry brick lining below that depth. Below 591.94 m, the shaft was flooded.

The shaft had lateral inlets at the 130, 235, 385, and 550 m levels. It served as an extraction and access shaft, equipped with two skips for coal haulage from the 550 m level. The cage hoist was decommissioned. In the shaft cross-section, the ladderway and pipe/cable compartments were distinguished. The shaft was equipped with C-section steel members and timber guides for the hoisting conveyances. Two Ø300 pipelines – one for main dewatering and one for compressed air – were installed from the collar to the 550 m level, along with cables.

The scope of closure works, according to the liquidation project, included:

- Equipment removal: Partial dismantling of shaft and station equipment; removal of pipelines and cables; removal of ladderway equipment (ladders, landings, protective netting); removal of fixed platforms in the shaft; dismantling of hoisting equipment and sealing of smaller inlets.
- Isolation dams: Construction of isolation dams at the 130, 235, 385, and 550 m levels.
- Surface preparation: Installation of structures enabling delivery of backfill material.
- Backfilling and collar closure: Shaft closure by placement of backfill material and collar closure.

Closure works began with the construction of isolation dams at the inlets. These were masonry dams of BSz 2 shaft block concrete, Class B 200 (~20 MPa), on cement mortar, arched with a radius of 25 m and convex towards the shaft. Dam walls were keyed into the sidewalls, roof, and floor to a depth equal to two-thirds of the wall thickness (0.36–0.74 m), such that the keying extended beyond zones of weathered rock. Dam dimensions were determined by calculations of loading. Between the dams at successive levels, resisting plugs of stowing rock were formed as piles at the internal friction angle.

The shaft was filled with backfill consisting of coal processing waste, 40–80 mm fraction. After filling the shaft to the collar, the surface was levelled with a 5–10 cm sand layer. A 0.5 m thick reinforced concrete slab of B20 concrete was then constructed. A cross-section of the slab sealing the shaft is shown in Fig. 3 (after the “Technical Design with Closure Technology for Shaft I” [34]). According to Fig. 3, the slab bears on the shaft lining and was built as a construction of rolled I-beams encased in concrete.

The sequence of closure works was as follows:

- Start of closure: 16 October 1996,
- Closure of the shaft with a concrete slab: 31 May 1997,
- Inspection of the shaft condition: 16 June 1997,
- Backfill replenishment: 17 March 1998 to 10 April 1998,

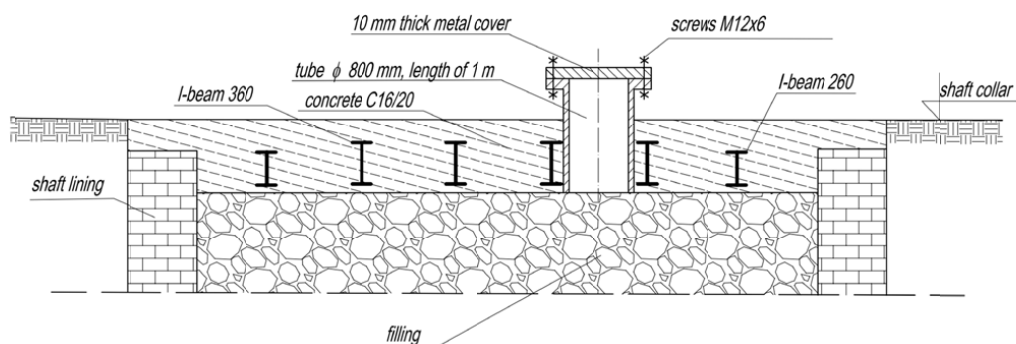


Fig. 3. Cross section through the concrete slab closing the shaft

- Concreting of the closing slab: 15 April 1998,
- Inspections of completed work: 12 May 1998 and 23 September 1998.

After approximately 20 years, the slab was destroyed, and reinforcement made from rails was partially stolen. Fig. 4 shows the slab condition from that period.



Fig. 4. View of the destroyed shaft capping slab P

2.3. Methodology

Numerical modelling was used to simulate the mechanical response of the rock mass in the vicinity of the decommissioned shaft. Simulations were performed for two variants: an intact shaft lining and a degraded lining scenario associated with possible fill migration into adjacent

workings. Due to the specifics of the problem, requiring representation of a geological structure composed of layers with contrasting mechanical parameters intersected by the shaft lining, proper representation of the geological and mining situation necessitated a three-dimensional model. Simulations were performed using FLAC3D (Fast Lagrangian Analysis of Continua) by Itasca Consulting Group, based on the finite difference method.

According to the developer, FLAC3D is an ideal tool for solving 3D problems in rock-mass mechanics, and its selection for modelling the rock mass around the shaft is fully justified [35–37].

The use of FLAC3D in this study enabled the determination of stress–strain changes in the modelled rock mass and, based on that, the identification of failure zones where plastic yielding occurs, which in reality may lead to large displacements, cracking, and ultimately to caving, cavities, and sinkhole formation.

3. Delineation of the hazard zone around the shaft

3.1. Numerical model construction

Owing to the axial symmetry of the problem with respect to the shaft centreline, the numerical model represents a quarter-cylindrical rock mass domain with a 75 m radius. The model depth was limited to 75 m to focus on the near-surface zone controlling the potential development of sinkhole-type deformation. This depth includes the entire overburden sequence and the upper part of the Carboniferous strata, which are the most relevant units for analysing the upward propagation of failure towards the ground surface. Since mine shafts have small transverse dimensions relative to their length, modelling the full shaft depth would also substantially increase computational cost while providing limited additional value for the specific near-surface failure mechanism analysed in this study.

The adopted model does not represent the full shaft depth and therefore should not be interpreted as a complete simulation of the mechanical response of the entire shaft system. Instead, it is intended to assess the near-surface failure mechanism and the possible extent of the hazard zone at the ground surface.

Displacement boundary conditions were applied as follows:

- Nodes on the bottom face were fixed vertically, with in-plane horizontal displacements allowed.
- Nodes on lateral vertical faces were fixed in the horizontal direction normal to each face.

The shaft lining was modelled using three-dimensional continuum elements (finite-difference zones) forming a 0.5 m thick shell along the shaft boundary. A linear elastic constitutive model was adopted for the lining, and the corresponding deformability parameters assigned to the concrete lining are listed in TABLE 2.

The simulation was executed in stages:

1. Establishment of the initial stress state by equilibrating the model under self-weight.
2. Modelling of the shaft by removing finite-difference elements inside the shaft excavation and re-equilibrating the model elastically.
3. Introduction of the lining and computation in the elastic–plastic range.
4. Simulation of lining degradation by removing lining elements from the model.

Stage 3 was required to establish a realistic loading state of the shaft lining under elastoplastic rock-mass conditions. In Stage 2, the excavation was analysed without lining and under elastic response only. The lining was introduced only after switching the rock mass model to elastoplastic behaviour, so that the lining load reflected the influence of plastic-zone development around the shaft. This avoided non-representative loading associated with purely elastic deformation and ensured proper lining–rock mass interaction before simulating lining degradation.

A Mohr-Coulomb elastic-plastic constitutive model was adopted for the rock mass, with a tensile cut-off. Failure is defined by:

$$\sigma_1 = \sigma_3 \cdot N_\phi + 2c\sqrt{N_\phi} \quad (1)$$

where:

σ_1 is the major principal stress,

σ_3 is the minor principal stress,

c is cohesion,

ϕ is the internal friction angle.

$$N_\phi = \frac{1 + \sin(\phi)}{1 - \sin(\phi)}$$

Layering in the model followed the shaft lithological profile (see Fig. 5). The geomechanical parameters should be treated as representative simplified values adopted for numerical analysis based on archival technical documentation, engineering experience, and reference values reported in the literature [1]. The adopted parameter set (see TABLE 1) reflects the geological and geotechnical conditions of the analysed shaft.

TABLE 1

Strength parameters of the lithological layers

Symbol	Layer	Depth		Cohesion	Internal friction angle	Tensile strength
		Top	Bottom	C	ϕ	R_t
		m	m	kPa	°	kPa
I/1	sand	0	5	1	35	0
I/2	clay	5	28	10	20	1
I/3	sand	28	38	1	35	0
I/4	gravel	38	44	0.5	40	0
I/5	claystone	44	48.5	100	30	10
I/6	Carboniferous rock mass	48.5	75	1000	35	100

A limitation of the study is the lack of recent site-specific laboratory testing, which introduces uncertainty in the adopted parameter values. However, the model is intended to represent the general mechanical behaviour of the rock mass rather than provide a fully calibrated site-specific simulation.

Strength parameters (see TABLE 1) were assigned separately to individual lithological layers identified in the shaft profile. In contrast, deformability parameters (see TABLE 2) were simplified and assigned at the level of two major geological units: the overburden and the Carboniferous

rock mass. This assumption was adopted to maintain a tractable numerical model while preserving the key mechanical contrast controlling the analysed failure mechanism.

TABLE 2

Deformability parameters adopted in the numerical model

Material	K	G
	MPa	MPa
Overburden	222	74
Carboniferous strata	2780	2080
Concrete	27800	20800

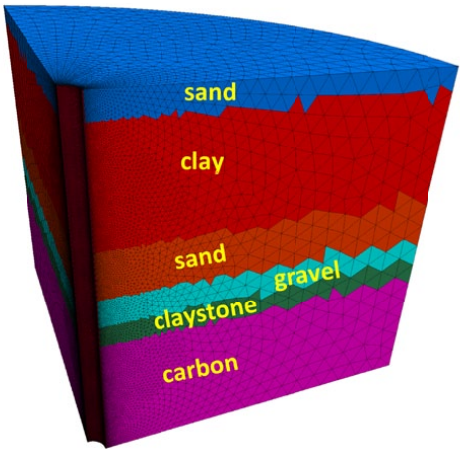


Fig. 5. Layering scheme represented in the model

3.2. Numerical simulation results

In the first computation stage, before shaft excavation was introduced, the initial stress state was established as distributions of major and minor principal stresses (see Fig. 6). In FLAC3D, compressive stress is negative and tensile stress is positive. The minor principal stress magnitude reaches 1.76 MPa, consistent with the vertical overburden stress at 75 m depth. Peak horizontal stresses occur in the lower part of the overburden and are 0.61 MPa.

After the shaft excavation was introduced into the model, the initial stress field was redistributed, as shown in Fig. 7. Adjacent to the lining, horizontal stress decreased in the radial direction (unloading) and increased circumferentially. Stress in the lining depends on the extent of plastic zones formed nearby. In the present model, maximum compressive stress values occur along the lining segment crossing the clay layer and reach approximately 2.18 MPa.

Next, a worst-case scenario for sinkhole hazard was assumed: the backfill migrates into horizontal mine workings, simultaneously causing degradation of the upper lining segment. In this scenario, the rock mass structure can collapse, causing blocks of rock to move into the void and form a sinkhole. A conservative worst-case scenario was adopted to evaluate the maximum pos-

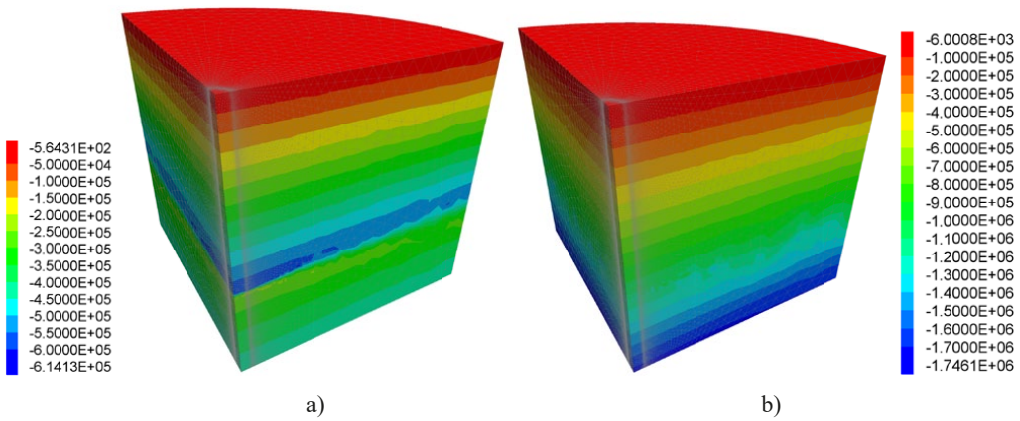


Fig. 6. Initial stress state: (a) major principal stresses; (b) minor principal stresses

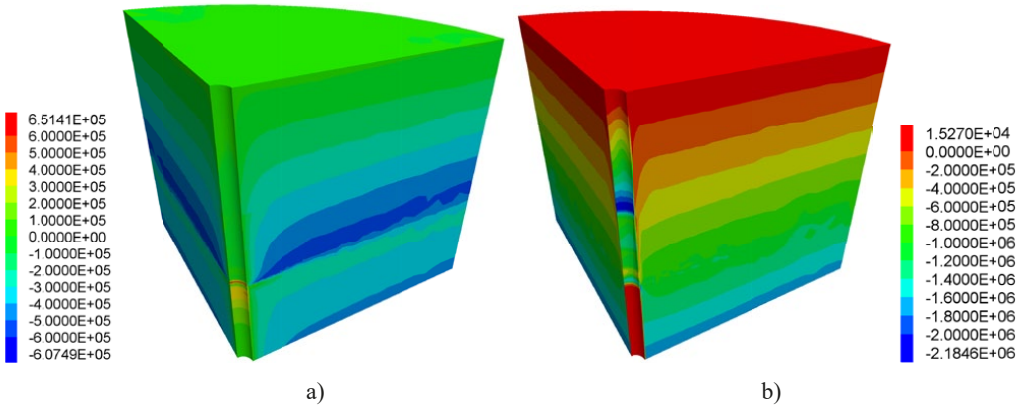


Fig. 7. State of the model after shaft excavation: (a) major principal stresses; (b) minor principal stresses

sible extent of near-surface failure and the associated hazard zone. This scenario assumes severe degradation of the upper shaft lining combined with downward migration of the fill material into the adjacent workings. Such a scenario may be triggered by long-term deterioration of the shaft lining, corrosion or structural damage of closure elements, gradual loss or loosening of fill material, water-related weakening of the surrounding strata, and the existence of voids or migration pathways connected with old workings. This process is illustrated in Fig. 8, which shows plastic zones in the modelled rock mass. Plastic zones indicate elements that have reached the failure criterion; in reality, these correspond to large strains, structural degradation (fracturing), and may ultimately lead to caving and sinkhole formation at the surface. In the presented results, colours distinguish zones failing in tension and in shear. Owing to the iterative solution scheme, results also indicate whether failure is reached in the current iteration (shear n, tension n) or occurred in earlier iterations (shear p, tension p). Elements not at failure are grey (none).

Results in Fig. 8 indicate that near the degraded lining segment, the rock mass yields primarily in shear. In the relatively strong Carboniferous layers, the lack of lining does not lead to failure

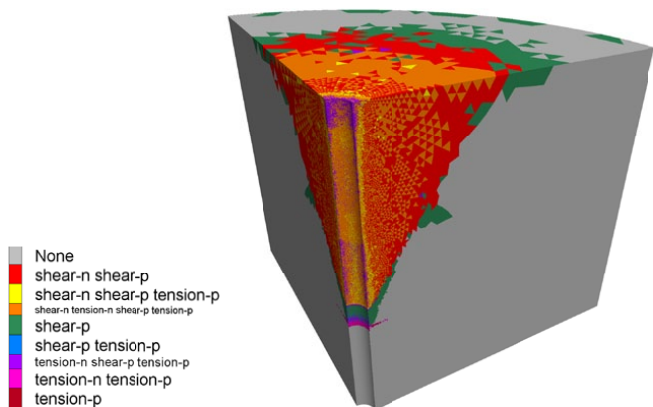


Fig. 8. Plastic zones near the modelled shaft after the backfill level dropped to the top of the Carboniferous

propagation. Once the lining degrades, the strength of the surrounding rock mass becomes the controlling factor. In the analysed case, above 48.1 m depth, the rock mass consists of overburden rocks that fail and undergo large deformations due to movement toward the shaft axis. At the surface, this zone extends to a radius of approximately 30 m, as shown in Fig. 9, which presents shear strain magnitudes.

Hydrogeological conditions were not explicitly included in the numerical model. The available archival documentation did not provide a sufficiently reliable basis for defining groundwater conditions in the analysed zone, and the original hydrogeological system may also have been altered by long-term drainage associated with past mining activity. Therefore, the present analysis was limited to the mechanical response of the rock mass under the assumed failure scenario. The possible influence of water infiltration on weakening of the strata and on the extent of the plastic zones should be treated as a limitation of the study.

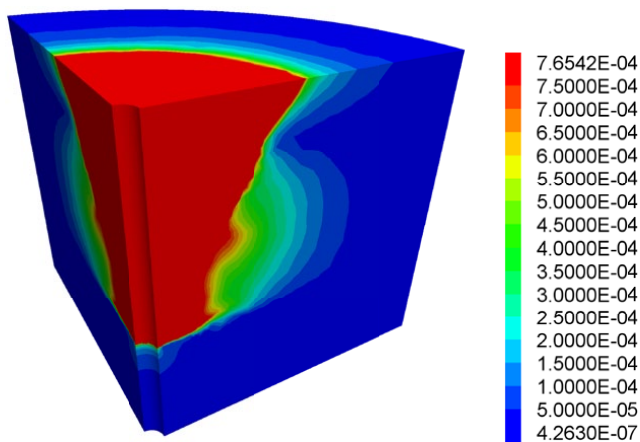


Fig. 9. Distribution of shear strains in the Shaft I model after lining removal.
The surface extent of the deformation zone is ~30 m

It should be noted that the present model was not directly calibrated against field measurements of surface deformation or subsidence. Therefore, the results should be interpreted primarily as a scenario-based assessment of the possible failure mechanism and hazard-zone extent, rather than as a quantitative reproduction of observed ground movements.

4. Remedial works on the shaft closure and environmental monitoring

Remedial work began by replacing the brick masonry lining at the collar. The new lining was constructed from precast concrete shaft blocks, as shown in Fig. 10. The backfill was topped up with rubble. Subsequent work followed the arrangement shown in Fig. 1. A reinforcing masonry collar was constructed with a width of 0.7 m at a depth of 1 m, and the lining near the collar was replaced. A reinforced concrete slab 0.45 m thick in the middle and 0.40 m at the perimeter was constructed on a blinding concrete layer with a damp-proof membrane, according to the design [38].

Reinforcement consisted of a double layer mesh of Ø16 bars at approximately 150 mm spacing – see Fig. 11. The slab incorporates a Ø900 cased opening for backfill level inspection and replenishment, and a gas vent nozzle – as in Fig. 12.



Fig. 10. Reconstructed masonry lining fragment at the shaft collar



Fig. 11. Reinforcement of the slab sealing the shaft



Fig. 12. View of the concrete slab

Environmental control includes routine inspections of the closing slab and measurement of backfill level, as well as determination of gas concentrations at the outlet of the vent pipe embedded in the slab (Fig. 13b) using an S316 pumping multi-gas detector. The backfill level is measured monthly and shows no changes exceeding the instrument accuracy when measured with a laser distance meter. For each reading, the cover on the pipe is removed, and the distance is read with the meter seated at the same reference point (Fig. 13a). Gas concentrations monitored include CH_4 , CO_2 , CO , and H_2S . Periodic measurements yielded average values: CH_4 – 0%, CO_2 – 230 ppm, CO – 0%, H_2S – 0%, indicating no gas migration through the backfill.



Fig. 13. Measurements: (a) backfill level; (b) gas concentration

5. Summary and conclusions

Shaft closures executed in the last century do not always meet modern safety standards. Land containing former closed shafts is increasingly being developed, which necessitates condition assessment and, where needed, remedial works. The present study does not provide a quantitative

probability assessment of this failure scenario. Instead, it focuses on a scenario-based evaluation of its possible mechanical consequences for ground-surface safety. A further limitation of the study is the lack of representative field deformation data that would allow direct quantitative validation of the numerical model. Based on the presented example, the following general conclusions can be formulated:

- Shafts should be protected at the collar by a reinforced concrete slab bearing on strengthening masonry. According to the literature, the slab diameter should be 1.5-2.0 times the shaft excavation diameter. It should include an inspection opening for backfill control and replenishment, and a gas vent nozzle.
- In cases where the analysed failure mechanism involves degradation of the upper shaft lining and instability propagation through the overburden, the hazard zone around the shaft should be assessed using numerical simulations focused on the near-surface rock mass. In the analysed case, the hazard zone radius obtained from the model was conservatively increased by a factor of 1.5 in order to define a precautionary no-build zone. This coefficient should be treated as a case-specific engineering recommendation rather than a generally applicable rule, and its broader applicability requires validation based on a larger number of case studies representing different geological conditions.
- To ensure safety on land with closed shafts, routine visual inspections of the slab, backfill level measurements, and gas concentration monitoring should be conducted at regular intervals.

References

- [1] M. Chudek, *Mechanika górotworu z podstawami zarządzania ochroną środowiska w obszarach górniczych i pogórnich*. Wydawnictwo Politechniki Śląskiej, Gliwice (2010).
- [2] P. Strzałkowski, *Zagrożenia na terenach górniczych i pogórnich z elementami rekultywacji*. Wydawnictwo Politechniki Śląskiej, Gliwice (2025).
- [3] D. Demir Şahin, H. Eker, A Comprehensive Technical-Economic Cost Analysis of Drill and Blast Operations in a Basalt Quarry. *Periodico di Mineralogia* **94** (5), 57-70 (2025). DOI: <https://doi.org/10.5281/zenodo.17183365>
- [4] D. Demir Şahin, H. Eker, Environmental Assessment of Blasting in a Copper Quarry. *Baltica* **38** (6), 62-98 (2025). DOI: <https://doi.org/10.59879/bt7pg>
- [5] D. Demir Şahin, H. Eker, Assessment of hazards and risks in a marble quarry. *Black Sea J. Eng. Sci.* **7** (6), 1294-1301 (2024). DOI: <https://doi.org/10.34248/bsengineering.1532507>
- [6] J. Kretschmann, A.B. Efremkov, A.A. Khoreshok, From mining to post-mining: The sustainable development strategy of the German hard coal mining industry. *IOP Conf. Ser. Earth Environ. Sci.* **50**, 012024 (2017). DOI: <https://doi.org/10.1088/1755-1315/50/1/012024>
- [7] C. Lagny, The emissions of gases from abandoned mines: Role of atmospheric pressure changes and air temperature on the surface. *Environ. Earth Sci.* **71**, 923-929 (2014). DOI: <https://doi.org/10.1007/s12665-013-2495-8>
- [8] P. Strzałkowski, Mathematical model of forecasting the formation of sinkhole using Salustowicz's theory. *Arch. Min. Sci.* **60** (1), 63-71 (2015). DOI: <https://doi.org/10.1515/amsc-2015-0005>
- [9] P. Strzałkowski, Duration of the final phase of mining area deformation process in the conditions of Upper Silesia (Poland). *Bull. Eng. Geol. Environ.* **80** (7), 5769-5780 (2021). DOI: <https://doi.org/10.1007/s10064-021-02255-2>
- [10] P. Czaja, Ocena rozwiązań projektowych likwidacji szybów zastosowanych w procesie restrukturyzacji polskiego górnictwa węglowego. *Górnictwo i Geoinżynieria* **3** (1), 105-119 (2009).
- [11] P. Czaja, *Technologie likwidacji szybów oraz ich infrastruktury podziemnej i powierzchniowej*, Wydawnictwo AGH, Kraków (2011).

- [12] D. Demir Şahin, E. Isik, I. Isik, M. Cullu, Artificial neural network modeling for the effect of fly ash fineness on compressive strength. *Arab. J. Geosci.* **14**, 2705 (2021). DOI: <https://doi.org/10.1007/s12517-021-09120-w>
- [13] H. Eker, D. Demir Şahin, M. Çullu, Effect of Reduced Fineness of Fly Ash Used on the Alkali-Silica Reaction (ASR) of Concrete. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **47**, 2203-2217 (2023). DOI: <https://doi.org/10.1007/s40996-023-01090-1>
- [14] D. Demir Şahin, H. Eker, Effects of Ultrafine Fly Ash against Sulphate Reaction in Concrete Structures. *Materials* **17** (6), 1442 (2024). DOI: <https://doi.org/10.3390/ma17061442>
- [15] D. Demir Şahin, I. Cavusoglu, A.O. Yilmaz, Evaluation of Pozzolanic Activity of Two Different Types of C and F Fly Ashes with Fineness Factor. *J. Min. Environ.* **14** (2), 435-448 (2023). DOI: <https://doi.org/10.22044/jme.2023.12795.2324>
- [16] J. Hunter, Old mines and new sinkholes along the Hucklow Edge vein, Derbyshire. *Mercian Geol.* **18** (4), 213-226 (2015).
- [17] P. Strzałkowski, Sinkhole hazard caused by inactive mining shafts as illustrated by a selected example. *Pure Appl. Geophys.* **178**, 1697-1707 (2021). DOI: <https://doi.org/10.1007/s00024-021-02716-z>
- [18] F.G. Bell, Land development. State of the art in location of old mine shafts. *Bull. Int. Assoc. Eng. Geol.* **37**, 91-98 (1988). DOI: <https://doi.org/10.1007/BF02590374>
- [19] Z. Pilecki, A. Baranowski, Estimation of dimension of regular-type sinkhole activated by abandoned shafts. *Publ. Inst. Geophys. Pol. Acad. Sci., Monogr. M-29*, 395-404 (2006).
- [20] S. Piechota, Podstawowe zasady i technologie wybierania kopalin stałych. Biblioteka Szkoły Eksploatacji Podziemnej, Kraków (2003).
- [21] P. Dobak et al., Zasady dokumentowania warunków geologiczno-inżynierskich dla celów likwidacji kopalń. Ministerstwo Środowiska, Warszawa (2009).
- [22] Główny Instytut Górnictwa (GIG), Zasady likwidacji szybów i wyrobisk przyszybowych w kopalniach węgla kamiennego. Poradnik techniczny, Seria Instrukcje nr 6, Główny Instytut Górnictwa, Katowice (1997).
- [23] A. Kotyrba, Ł. Kortas, Sinkhole hazard assessment in the area of an abandoned mining shaft based on microgravity survey and modelling – Case study from the Upper Silesia Coal Basin in Poland. *J. Appl. Geophys.* **130**, 62-70 (2016). DOI: <https://doi.org/10.1016/j.jappgeo.2016.04.010>
- [24] P. Strzałkowski, R. Ścigała, K. Szafulera, K. Kołodziej, Surface deformations resulting from abandoned mining excavations. *Energies* **14** (9), 2495 (2021). DOI: <https://doi.org/10.3390/en14092495>
- [25] P. Strzałkowski, Identification of small old shafts locations and a proposal for their protection. *Pure Appl. Geophys.* **179**, 2889-2904 (2022). DOI: <https://doi.org/10.1007/s00024-022-03093-x>
- [26] A. Lecomte, A. Muños Niharra, Handbook to best practices for mine shaft protection (Deliverable D4, MISSTER), INERIS / Research Fund for Coal & Steel, Verneuil-en-Halatte (2013).
- [27] R. Salmon, A. Marshall, S. Bock, A. Madrza, S. Rapp, A. Muños Niharra, M. Bedford, Mine shafts: Improving security and new tools for the evaluation of risks (MISSTER), Publications Office of the European Union, Luxembourg (2015).
- [28] R. Salmon, M. Degas, Mine shafts in the Nord and Pas-de-Calais coalfield, France: Risk assessment and treatment techniques. *Min. Technol.* **112** (1), 1-8 (2003). DOI: <https://doi.org/10.1179/037178403225011088>
- [29] A. Lecomte, R. Salmon, W. Yang, A. Marshall, M. Purvis, S. Prusek, L. Gajda, J. Dziura, A. Muños Niharra, Case studies and analysis of mine shaft incidents in Europe, in: *Proc. 3rd Int. Conf. on Shaft Design and Construction (SDC 2012)*, London, UK (2012), HAL-INERIS: hal-ineris.archives-ouvertes.fr/ineris-00973661/document.
- [30] R. Salmon, A. Marshall, S. Bock, A. Madrza, S. Rapp, A. Muños Niharra, M. Bedford, Mine shafts: Improving security and new tools for the evaluation of risks (MISSTER) (EUR 27086 EN), Publications Office of the European Union, Luxembourg (2015). DOI: <https://doi.org/10.2777/269972>
- [31] United States Department of Agriculture, Natural Resources Conservation Service, Conservation Practice Standard: Mine Shaft and Adit Closing (Code 457), USDA–NRCS, Washington, DC (2020).
- [32] Global Methane Initiative, Methane emissions from abandoned coal mines in China, Global Methane Initiative, Washington, DC (2023).
- [33] L. Sandve, E. Forkheim, M. Slater, G. Bonin, Mitigation of an open shaft at a legacy mine site in British Columbia, Canada using polyurethane foam, in: M. Tibbett, A. Fourie, L. Barron (Eds.), *Mine Closure 2023: Proceedings of the*

- 16th International Conference on Mine Closure, Australian Centre for Geomechanics, Perth (2023), pp. 1185–1196.
DOI: https://doi.org/10.36487/ACG_repo/2315_096
- [34] Technical project, Technical Design with Closure Technology for Shaft I. Internal Report, unpublished (1996).
- [35] G. Dyduch, P. Jarczyk, M. Jendryś, Geomechanical analysis of the rock mass stability in the area of the Regis shaft in the Wieliczka salt mine. In: *Minefill 2020-2021*, CRC Press/Taylor & Francis, Boca Raton 349-359 (2021).
DOI: <https://doi.org/10.1201/9781003205906-31>
- [36] M. Jendryś, Analysis of stress state in mine shaft lining, taking into account superficial defects. *IOP Conf. Ser. Earth Environ. Sci.* **261**, 012016 (2019). DOI: <https://doi.org/10.1088/1755-1315/261/1/012016>
- [37] M. Jendryś, H. Kleta, Strefa zapadliskowa spowodowana uszkodzeniem obudowy szybu w świetle symulacji numerycznej metodą elementów odrębnych. *Bud. Górn. Tunel.* **21** (1), 7-14 (2015).
- [38] H. Erle, D. Duda, Projekt wykonawczy zamknięcia szybów. Unpublished design report, Gliwice (2022).