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Keywords

coal mining; shaft liquidation; climate change

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RESEARCH ARTICLE

Shaft Liquidation Method Adjusted for High Precipitation Associated with Climate Change Impact

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Abstract

In connection with the implementation of the international project TEXMIN within the framework of the RFCS fund, a project for the liquidation of the Głowacki Shaft in Rybnik (Poland) was undertaken, which takes into account the effects of climate change, i.e. evaluation of the increase of precipitation in the region. In addition to the standard research undertaken before liquidation activities, precipitation data recorded by the Institute of Meteorology and Water Management from 1995 to 2019 was collected and the precipitation variability was analysed. As a result, a method for liquidation of the shaft was selected consisting of constructing a permeable backfill column in the shaft and using a shaft pipe filled with permeable backfill material. Metallurgical aggregate was identified as a suitable backfill material, for which degradation tests, filtration coefficient tests and an assessment of its impact on water quality were carried out. It has been determined that a backfill column constructed in this manner can fulfil its function as a long-term gravity-driven water flow.

Keywords: coal mining, shaft liquidation, climate change

1. Introduction

In the world concerned with the burden of climate change consequences, mining is not an exception. In fact, the mining sector is one that is affected by this issue in a complex manner in every part of the mining value chain from exploration, through extraction, transport to closure [15]. Climate change will impact mining both directly (raising operational costs) and indirectly (securing supplies and rising energy costs) [22].

In recent years, there has been a growing number of scientific research on the potential consequences and effects of climate change in mining activities [9,12,13]. Climate models on various scales have so far failed to take into account the impact on mining both during and after active exploitation. This is the subject of the Project TEXMIN (The impact of EXtreme weather events on MINing operations) implemented between 2019 and 2022 as part of the Research Fund for Coal and Steel (RFCS) by a consortium composed of: Central Mining Institute - GIG (Poland), University of Exeter (United Kingdom), Silesian University of Technology – Politechnika Śląska (Poland), Centre for Research and Technology Hellas (Greece), Subterra Ingenieria, S.L. (Spain), DMT GmbH & Co. KG (Germany), Výzkumný ústav pro Hnědé Uhlí (Czech Republic), Spółka Restrukturyzacji Kopalń S.A (Poland) and Tauron Wydobycie S.A. (Poland). Project received funding from the Research Fund for Coal and Steel under Grant Agreement no 847250 and from the Polish Ministry of Science and Higher Education under Contract No 5042/FBWiS/2019/2.

As part of Project TEXMIN, GIG, together with SRK SA, developed a project for the liquidation of the Głowacki Shaft in Poland. In addition to the standard research undertaken before liquidation

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activities [1–4,8,11,23], in this case climate change forecasts prepared including increased water inflows associated with the occurrence of extreme precipitation events were taken into account [10,14,24]. The aim of this paper is to indicate the direction of a new approach to design work in the field of mining, including mine closure with reference to climate change. To ensure high quality of this kind of projects, impacts brought about by increase in precipitation, temperature and sudden changes in atmospheric pressure must be identified. Depending on the location, different factors may have a significant value for the design team. Moreover, appropriate planning of the shaft filling, considering climate change impacts related to a general trend of precipitation and its yearly average increase or decrease, as well as prediction of mine water inflows to the shaft in the future, will result in better stability and hazard reduction to the surface in the near vicinity of similar objects. Presented methods of selecting shaft filling materials, accordingly to the overall construction and hydrogeological conditions, will improve risk mitigation in the transition process of similar mining objects.

2. Materials and methods

The selection of an optimum variant for the liquidation of the Głowacki Shaft and the assessment of the possibility of using the shaft as a water flow route was based on the analysis of hydrogeological-mining conditions in the area of the shaft, the existing water inflow system in the excavations towards the shaft, the system of water inflow to the area, the predicted deformations within the area of the decommissioned protective pillar resulting from the impact of the planned mining exploitation until 2042 and the identified and predicted technical condition of the shaft lining [6,7,21,24].

The liquidation project of the Głowacki Shaft takes into account the variability of hydrogeological conditions in its vicinity as well as the impact of climatic changes in the years 1995–2018. These changes were characterized based on Polish Meteorological Institute (IMiGW) data on annual precipitation. Changes in the quantity of water inflowing to the Głowacki Shaft area in the period of its exploitation, after its completion, after the liquidation of the neighbouring Kościuszko Shaft up to the present time were analysed in relation to precipitation recorded at meteorological stations in Rydułtowy and Rybnik.

In order to determine the range of changes in hydrogeological conditions in the area of the Głowacki Shaft to be decommissioned, the results of hydrogeological studies and geological and mining documentation related to the shaft and its vicinity as well as to the neighbouring liquidated Kościuszko Shaft were taken into account. An adequate hydrologic study was based on historic and up-to-date documentation.

The studies analysed the geological structure, and water table in the area under consideration, current inflows of mine waters to the shaft and adjacent mine workings, mining operations carried out and planned and their impact on the shaft pipe and the surface as well as the condition of the shaft lining.

3. Results and discussion

3.1. Technical conditions of the Głowacki Shaft

The Głowacki Shaft is located in the town of Rybnik-Niewiadom, in the area of the former Ignacy Hard Coal Mine (Fig. 1), which was incorporated into the Rydułtowy Hard Coal Mine in 1968. Currently the Głowacki Shaft is separated from the structures of PGG S.A. KWK ROW Rydułtowy Shaft and belongs to SRK S.A. with the seat in Bytom, 'Jas-Mos – Rydułtowy I' – 'Rydułtowy I'. The Głowacki Shaft is situated approximately 50 m to the SWW of the decommissioned Kościuszko Shaft. The area where the shaft is located is covered by dense cubature and linear industrial buildings (see Fig. 2).

Until 2008 the Głowacki Shaft was used as a material and transport shaft, and therefore it was equipped with two two-storey cages. Later it only performed the function of ventilation – the downcast shaft. It was decommissioned, and all reinforcement and equipment were removed. In the shaft, there was only a drip pipe for shaft water Ø150 mm, from the depth of 50 m to the depth of 600 m, which was located on the north-eastern side. The Głowacki Shaft had a shaft-top building and a steel, single-shaft hoisting tower built in 1901, reinforced in 1947 with a rivet-welded structure made of cylindrical profiles.

The sinking of the Głowacki Shaft was commenced in 1892 and then deepened in stages as coal reserves were extracted from the deposits and the rock mass drained. During stage I, the shaft was sunk to a depth of 115.0 m. Stage II was completed in 1897, and the shaft was deepened to a depth of 192.0 m. In stage III, the shaft was deepened to the depth of 300 m, and this was done in 1913. Stage IV was completed in 1944–45, and the shaft reached a depth of 400.0 m. The sinking of the shaft was completed in 1976 when the shaft reached its present depth of 625.33 m.

Fig. 1. The location of the Głowacki Shaft, Silesian Voivodeship (Poland).

The cross-section of the shaft pipe varied according to the stages of its excavation and depth. The type of lining was not uniform along the entire length of the shaft pipe. The section from the edge to the depth of 400 m was built with a brick lining. The remaining section was lined with concrete masonry. The shaft documentation does not contain information on the strength parameters of the lining material and the brand of the mortar used for the lining. The shaft lining types are listed in Table 1.

Fig. 2. Głowacki shaft tower.

Table 1. Types of lining made in the Głowacki Shaft.

Depth [m]	Cross-section of shaft lining	Cross-sectional area of lining [m^2]	Lining type and thickness
0.00–115.00	Barrel-shaped 4.80 × 3.75 m	16.5	brick masonry thickness – 0.4 m
115.00–200.00	Rectangular 4.27 × 3.36 m	14.3	brick masonry thickness – 0.4 m
200.00–400.00	Circular 4.83 m	18.3	brick masonry thickness – 0.4 m
400.00–625.33	Circular 4.83 m	18.3	concrete masonry thickness – 0.4 m

3.2. Hydrogeological conditions and drainage conditions in the area of the Głowacki Shaft

In the vicinity of the Głowacki and Kościuszko Shafts, there are relatively simple hydrogeological conditions with two aquifers: Quaternary and Carboniferous. The mining activity and a high degree of urbanization in the area of the shaft caused significant changes in hydrogeological conditions in the Quaternary. The mining activity, which has been carried out for more than 200 years, has resulted in the formation of a cone of depression with a considerable extent and drainage of aquifers manifesting itself in the disappearance of the water in wells of neighbouring farms.

The Quaternary aquifer is characterized by the changeability of the shape and deposition of aquifers. The sediment thickness of the Quaternary aquifer ranges from about 9 to about 32.5 m. The basic forms of formation of sand and gravel aquifers are lenses and low-spreading aquifers with a thickness of about 0.5–10 m.

The depth of the Quaternary formations at the Głowacki and Kościuszko Shafts is about 10.0 m, where sands mixed with clay lie to a depth of 3.0 m and below a layer of sand with gravel, 7.0 m thick. The first water symptoms on the brickwork appear at a depth of 16 m, i.e. already in the Carboniferous rocks, which rather indicates a lack of Quaternary waterlogging in the vicinity of the shaft, which is associated with many years of mining drainage.

The Carboniferous aquifer in the area of the Głowacki and Kościuszko Shafts is related to a thick complex of Porębskie layers lying in the entire profile of the shafts and deeper, with the layers of sandstone insulated with layers of clay and mudstones in this complex. On the other hand, in the mining area of the former Ignacy mine, the saddle layers, constituting the highest link of the Upper Carboniferous in the Jejkowicka Basin, also occur and were intensively exploited.

3.3. Dewatering conditions in the area of the Głowacki Shaft

In order to determine the scope of changes in hydrogeological conditions in the area of the Głowacki Shaft to be decommissioned, the results included in hydrogeological studies and geological and mining documentation concerning the shaft and its region, as well as the adjacent liquidated Kościuszko Shaft, were taken into account. Moreover, water inflows to the shaft and yearly average precipitation in this area were taken into account. The geological structure and waterlogging of the rock mass in the area in question, the current mine water inflows to the shaft and the adjacent mine workings, the performed and planned mining operation along with the effects of the impact on the shaft pipe and the surface as well as the condition of the shaft casing, were analysed.

Mining activities and a high degree of urbanization in the area of the shaft resulted in significant changes in the hydrogeological conditions in the Quaternary. Mining operations for over 200 years have resulted in the creation of a considerable extent of the depression cone and drainage of aquifers, which resulted in the disappearance of the water in the wells.

In the aspect of the planned liquidation of the Głowacki Shaft, the water level of Quaternary sandy sediments is important in terms of the safety of the shaft and the protection of the area around it. The water horizons of the Quaternary layer are mainly waters suspended locally on the lenses of impermeable or poorly permeable formations and are dynamic waters originating from precipitation, seeping deeper into the Carboniferous layers. The Quaternary horizons in this region are generally characterized by the phreatic water table. Hydrogeological observations and measurements carried out in these wells confirm the free nature of the first water table. A slightly tense mirror of this level is found less frequently and has a local range. The depth of the water table level is from 0.2 to 18.0 m. Quaternary aquifers are supplied on most of the area's surface directly by precipitation, less frequently by surface watercourses.

In the area of the Głowacki and Kościuszko shafts, the overburden consisting mainly of Quaternary sediments plays a significant role in waterlogging and qualitative nature in the Carboniferous layers. In the area of these shafts, the Quaternary formations lie directly on the Carboniferous roof. The presence of permeable Quaternary sediments in this part of the mining area increases the possibility of infiltration of subsurface waters into the rock mass. The waters infiltrate in places where Carboniferous sandstones come into contact with permeable Quaternary overburden sediments and feed the tributaries to mine workings and old goafs, especially those located in the depth zone up to 400 m. In the range up to the final depth of the Głowacki shaft, there are two aquifers of sandstone complexes. The sandstones here are made up of numerous layers, in places of considerable thickness, separated by insulating clay layers, hence the supply is provided on sandstone outcrops under water-permeable Quaternary formations and along fault fissures. The inflow of waters is mainly associated with thicker layers of sandstone lying above the seams 602 and 604 and between the seams 608 and 613/1.

The Carboniferous aquifer originally (before the commencement of mining operations) consisted of a number of separate water-bearing horizons subordinated to individual layers or sandstone complexes, in which water mineralisation increased with depth, which is characteristic of the hydrogeochemical conditions of the USCB. The mining excavations cutting through the Carboniferous rock mass at individual levels constitute an extensive drainage network of the Carboniferous aquifer, which means that the Carboniferous aquifer is now a single water horizon, connected by a system of mining excavations and post-mining fractures. On this horizon, along a thickness of about 600 m (from the Carboniferous roof to the depth of the shaft bottom), static water resources were drained and replaced by water from dynamic resources originating from infiltration of precipitation water coming mainly from open cracks and fissures and through old shafts.

In the area of the Głowacki Shaft, in the Carboniferous section cut through the shaft, the Carboniferous aquifer was significantly drained as a result of long-term drainage by the shaft and other mine workings. At present, dampness, seepage and leakage of water from the casing can be observed in several depth zones, mainly in the section from 16 to 292 m, where the intensity of individual leakages is within the range of 0.005–0.015 m^3/min, in total about 0.10 m^3/min. In the area of the Głowacki and Kościuszko Shaft, where the Carboniferous roof is located very close to the land surface, there are favourable conditions for infiltration of surface and Quaternary waters into Carboniferous formations and for its supply. The infiltration in these areas is facilitated due to the lack of isolating layer and the fact that the overburden and sandy sediments are mostly located directly on the permeable Carboniferous roof. The water infiltrates in places where contact between Carboniferous sandstones and permeable Quaternary sediments occurs and feeds tributaries to mine workings and old goafs, especially those located in the depth zone up to about 400 m. Small inflows come from distant circulation and residual static resources from greater depths at the edge of the cone of depression.

Waters flowing from behind the lining wall into the Głowacki and Kościuszko Shafts are moderately mineralised waters with mineralisation of 3.56–4.56 g/dm^3 and weakly alkaline reaction (pH = 7.5–7.7), with chloride ion content of 0.71–1.23 g/dm^3, sulphate ion content of 0.75–0.98 g/dm^3 and bicarbonate ion content of 0.65–0.87 g/dm^3. The analysis of the chemical composition of waters flowing into the Głowacki and Kościuszko Shafts (small seepages and leakages in the greater part of the depths of both shafts) indicates that they are, to various extent, waters of infiltration origin, fed indirectly from the surface and, to a small extent, waters from static Carboniferous resources, where water exchange is slow. The Głowacki and Kościuszko Shafts were the drainage zone of waters mainly from dynamic resources.

3.4. Water inflow to the Głowacki Shaft with respect to precipitation

The inflow to the Głowacki Shaft in the period after the backfilling of the Kościuszko Shaft, i.e. in the last period 2009–2019, is monitored at the level of 600 m. In order to determine the hydrogeological conditions for the liquidation project of the Głowacki Shaft, inflow variability was analysed concerning precipitation data for the area in question.

The amount of precipitation in the area of the Głowacki Shaft is recorded by the Polish meteorlogical Institute. Until 2014, the Rydułtowy precipitation station located in the direct vicinity of the Rydułtowy-Anna mine was in operation. Since 2015, the nearest functioning precipitation station is located in Rybnik (at a distance of about 8.5 km). Based on the data on daily precipitation sums, the variation in precipitation from 1995 to 2019 was analysed (Fig. 3).

In the analysed period, the average annual precipitation amounted to 788 mm, with the maximum annual amount in 2010 (1109.8 mm) and the minimum in 2018 (531.4 mm). A downward trend in precipitation amounts is evident – between 2011 and 2018, the annual total only once slightly exceeded 800 mm, while this occurred ten times between 1995 and 2010. Twenty-five years period of observations is taken into account to predict the overall characteristic of the yearly average trend of mine water inflow to the shaft in the adjacent area with open hydrogeological conditions. In relation to annual precipitation totals, the heights of inflows to the Głowacki Shaft were analysed. These were both direct inflows to the shaft pipe and inflows through the backfill of the Kościuszko Shaft.

As seen from the comparison of inflows and annual precipitation, there is no direct, clear relationship between these values. These quantities are characterised by a very weak positive linear

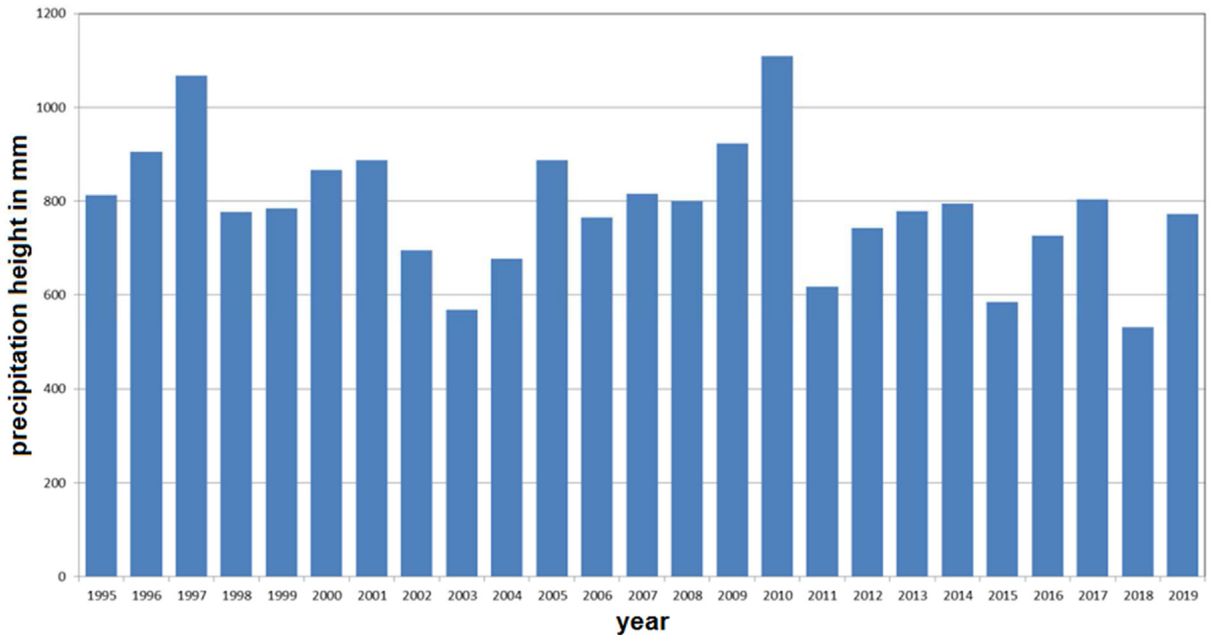

Fig. 3. Annual precipitation totals at Rydułtowy (until 2014) and Rybnik (from 2015 to 2019) stations.

correlation coefficient. There is an evident lack of influence of precipitation values in the years 2016–2019, where precipitation values range from 531.4 to 804.1 mm (nearly 30%), and the inflow to the Głowacki Shaft increases from 1.034 m^3/min (average from 2016) to the value of 1.100 m^3/m (years 2018 and 2019), i.e. about 6%. This indicates a relatively low sensitivity of inflows to the shaft regarding variations in precipitation. It should be expected that in the case of a wet year with precipitation totals above 1.000 mm (as in 2010), inflow to the Głowacki Shaft will not increase by more than 15%. Therefore the inflow volume to the shaft may increase to about 1.3 m^3/min. This is primarily caused by the favourable hydrogeological conditions for the recharge of Quaternary and Carboniferous aquifers where, as previously mentioned, there is no continuous isolating layer. The dynamic character of water inflow infiltrating through Carboniferous outcrops and permeable Quaternary overburden with increasing precipitation and simultaneous reduction of the mining drainage range as a result of discontinued drainage will tend to stabilise the inflow and outflow conditions in the region under discussion.

3.5. Drainage methods in the area of the Głowacki Shaft

Water flowing into the Głowacki Shaft from the upper levels and the level 400 is collected at the cut-off dams located in the excavations near the shaft. It is captured there in pipelines installed in the dams and directed at the level of 400 to a discharge pipeline installed in the Głowacki Shaft.

Water is conveyed by means of this pipeline from the level of 400 m to the level of 600 m, where four dams were built in order to dam up water for its gravitational flow to the transport cross-cut E1 and further to the inclined cross-cut E1 to the seam 624, where water flows further through its workings to the reservoir Wp.166/2001.

Water leaking through the backfill of the Kościuszko Shaft flows through the workings at the level of 600 m, where it is dammed up together with the water flowing down the Głowacki Shaft. Water from the former Ignacy mine, together with water from the decommissioned Rymer mine, is pumped from this reservoir through pipelines in the TW1 water dam by the main drainage system at the Leon IV shaft from the level of 800 m to the surface.

An overview of the amount of water flowing into the shaft is given below in Table 2.

3.6. Choice of the liquidation method for the Głowacki Shaft

The selection of the optimal variant of the liquidation of the Głowacki Shaft and the assessment of the possibility of using the shaft as a water flow route was based on the analysis of hydrogeological-mining conditions in the area of the shaft. Moreover, the following were taken into consideration during the analysis: the existing system of water inflow in

Table 2. Water inflow to the Głowacki Shaft.

Depth [m]		Volume of water entering the shaft [l/min]			Observations
from	to	leaks from the lining	inflow from inlets	Total	
0	115	400	0	**400**	100 l/min – inflow from the Kościuszko Shaft at the level of 600
115	200		250	**650**	
200	240		100	**750**	
240	300		100	**850**	
300	400		50	**900**	
400	625.3		400	**1300**	
				Total	**1400**

the excavations towards the shaft, the system of water inflow to this area, forecast deformations within the decommissioned protective pillar resulting from the impact of the planned mining exploitation until 2042 together with the identified and forecast technical condition of the shaft lining.

Taking into account the existing hydrogeological and mining conditions in the area of the shaft and the further safe operation of the KWK ROW Ruch Rydułtowy, the optimum option for the liquidation of the Głowacki Shaft has been identified as the one involving the construction of a permeable backfilling column in the shaft and the use of a shaft pipe filled with permeable backfilling material as a route for water run-off from higher levels to the level of 600 m. The proposed solution will prevent water accumulation in the excavations in the vicinity of the shaft. The analysis of hydrogeological and mining conditions indicates that the decommissioned Głowacki Shaft may long continue to function as a route for gravitational water flow through the permeable backfill.

3.7. Selection of material for filling the shaft pipe

In order to ensure the stability of the backfill column in the shaft during liquidation [17,19], the material used to fill the shaft pipe must meet the condition of water permeability. Required filtration coefficient:

$$k = \frac{Q}{F} \tag{1}$$

where:

Q – water supply to the shaft.

F – shaft cross-section in the lining inner diameter.

The required minimum values of the filtration coefficient for the backfill material, calculated for each depth interval, taking into account the cross-section and water inflow in a given shaft section, are shown below in Table 3.

The maximum required value of the filtration coefficient is reached in the shaft section in the depth range from 400 to 625.33 m, and it amounts to $k = 1.18 \cdot 10^{-3}$ m/s.

Available backfill materials used for shaft liquidation were analysed, and metallurgical aggregate was selected for further study to determine its filtration coefficient and its effect on potential contamination of water flowing into the shaft.

3.7.1. Studies on the degradation and filtration coefficient of metallurgical aggregates

In the Central Mining Institute, metallurgical aggregate intended to be used for the liquidation of a mine shaft was subjected to laboratory tests in two-grain size fractions: 11.2–34.5 mm and 31.5–63.0 mm. Figs. 3 and 4 show the grain size degradation of the metallurgical aggregate before and after dumping into the shaft (see Fig. 5 and 6).

Table 3. Values of filtration coefficient in the Głowacki Shaft.

Depth from [m]	Depth to [m]	Leaks from the lining [l/min]	Inflow from inlets [l/min]	Total inflows [l/min]	Total inflows [m^3/s]	Cross-section [m^2]	Filtration coefficient [m/s] · 10^{-3}
0	115	400	0	400	0.006667	16.5	**0.40**
150	200		250	650	0.010833	14.3	**0.76**
200	240		100	750	0.012500	18.3	**0.68**
240	300		100	850	0.014167	18.3	**0.77**
300	400		50	900	0.015000	18.3	**0.82**
400	625.33		400	1300	0.021667	18.3	**1.18**

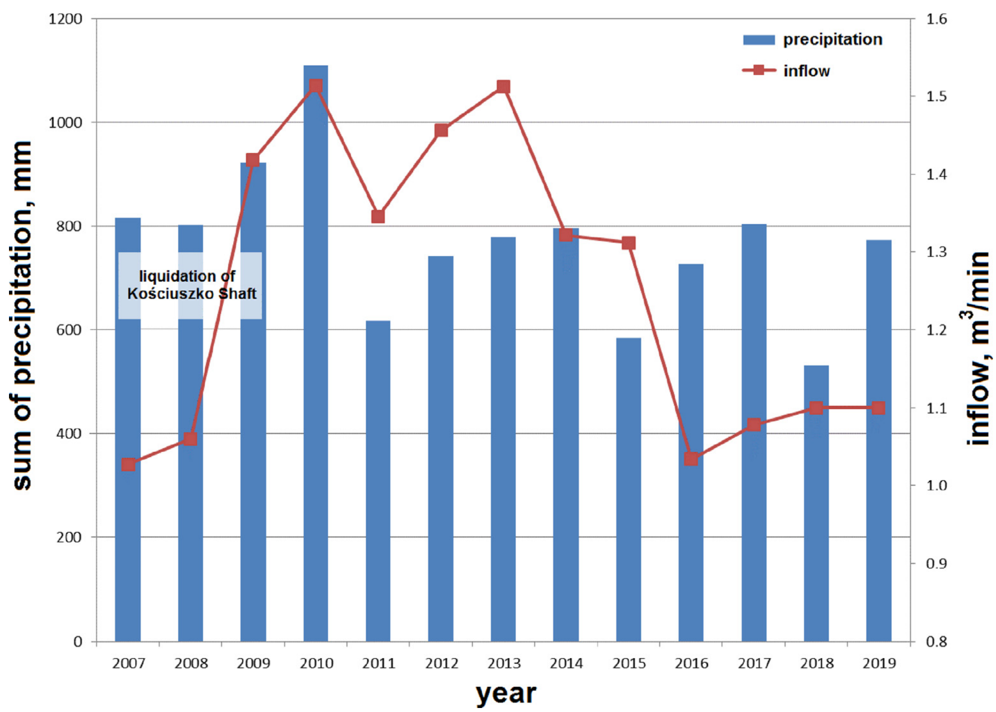

Fig. 4. Variability of natural inflow of mine waters to the Głowacki Shaft in relation to the variability of precipitation in the period 2007–2019.

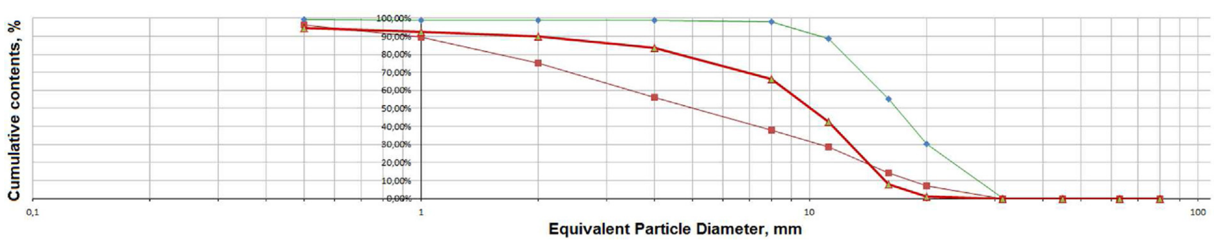

Fig. 5. Grain degradation of metallurgical aggregate 11.2–31.5 mm before and after dumping into the shaft (green line material before, red line material after dumping).

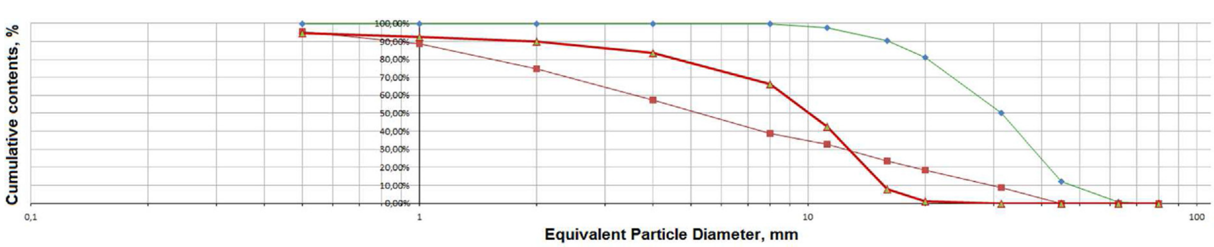

Fig. 6. Grain degradation of metallurgical aggregate 31.5–63.0 mm before and after dumping into the shaft (green line material before, red line material after dumping).

Table 4 presents the study's results including the determined values of median D_M, d_M and degradation coefficient i_M for metallurgical aggregate.

The results of investigations to determine changes in compressibility and filtration coefficient with the progress of shaft filling with dumped material and taking into account pressure increase in the backfill column, performed in accordance with the research methodology of Bromek and Bukowski. are presented in Tables 5 and 6.

On the basis of the conducted examinations, it was concluded that the material after being discharged into the shaft is still characterized by very good water permeability, corresponding to very well-

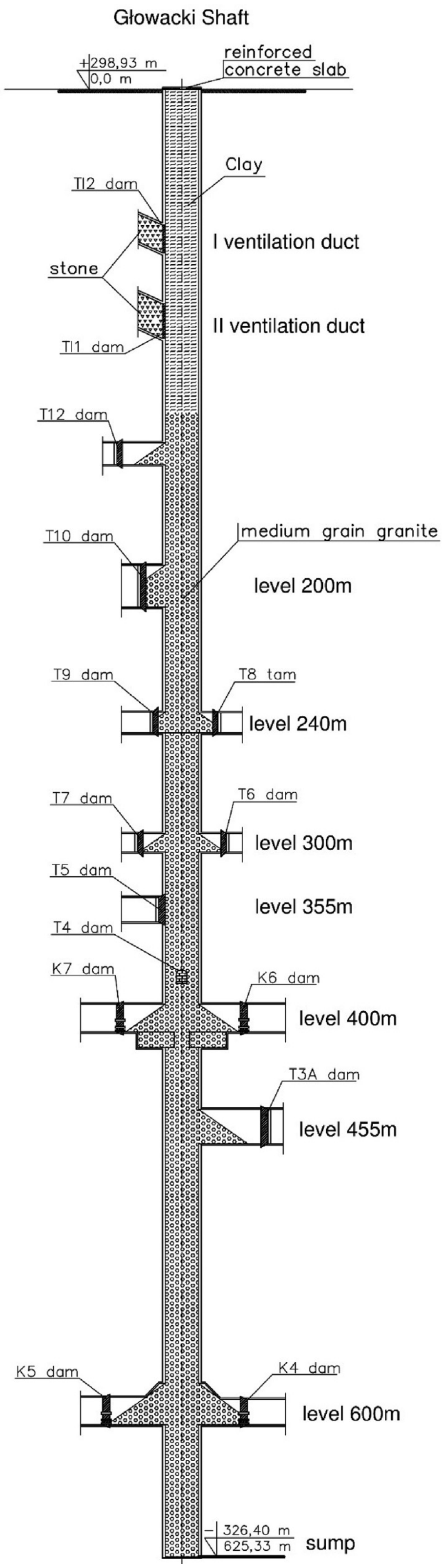

Fig. 7. Construction of the shaft backfill.

permeable rocks according to the classification of Pazdro and Kozerski [16]. In the pressure range of 0–12 MPa, the value of the coefficient of filtration was of the order of 10^{-2}–10^{-3} m/s which corresponds to well-permeable materials and is sufficient to drain water from the designed backfill of the Głowacki Shaft for material grain sizes of 31.5–63.0 mm.

3.7.2. Assessment of the impact of metallurgical aggregate on water quality

The leachability of soluble substances of metallurgical aggregate was studied using mine water taken from the Głowacki Shaft at level 600 [5,20]. The chemical composition of the water is presented in Table 7.

Leaching of impurities from samples of metallurgical aggregate was carried out in accordance with the PN-Z-15009 standard [18]. The study was carried out using pit water from the Głowacki Shaft, level 600. The results of the chemical analysis of water leachates are presented in Table 8.

The results of the investigations do not indicate any negative impact of water leachates from metallurgical aggregate on groundwater pollution at level 600 near the Głowacki Shaft.

3.8. Construction of the shaft backfill

The inlets at the levels in the Głowacki Shaft have been closed with isolation dams. Due to their close proximity to the shaft, they will be subjected to the pressure of backfilling and water thus, they are likely to be damaged. This will result in the inlet being rapidly filled with backfill material in sufficient quantity to create a stopper, preventing the material from moving from the shaft column to the horizontal workings. The above-mentioned stoppers and filters will allow water flowing into the shaft to seep through the shaft backfill.

After taking into account hydrogeological, ventilation and technological conditions, it was assumed that the shaft from the bottom to the top would be

Table 4. Median values of D_M, d_M and degradation coefficient i_M for the tested materials dumped into the shaft.

Material	D_M	d_M	i_M
	mm	mm	–
Materials filled the shaft at a depth of 800 m			
Metallurgical aggregate 11.2–31.5 mm	18.0	10.0	1.8
Metallurgical aggregate 31.5–63.0 mm	30.0	10.0	3.0

Table 5. Results of laboratory tests of filtration coefficient and compressibility of metallurgical aggregate 31.5–63.0 mm after dumping into a shaft.

Sample loading in endometer	Vertical pressure in the backfill column	Compressibility	Water permeability coefficient
MN	MPa	%	m/s
0	0	0	$6.75 \cdot 10^{-3}$
0.025	0.44	9.3	$5.40 \cdot 10^{-3}$
0.05	0.87	13.9	$5.01 \cdot 10^{-3}$
0.1	1.75	19.9	$4.50 \cdot 10^{-3}$
0.2	3.49	28.7	$4.09 \cdot 10^{-3}$

Table 6. Results of laboratory tests of the coefficient of filtration and compressibility of 11.2–31.5 mm metallurgical aggregate after dumping into a shaft.

Sample loading in endometer	Vertical pressure in the backfill column	Compressibility	Water permeability coefficient
MN	MPa	%	m/s
0	0	0	$2.23 \cdot 10^{-2}$
0.025	0.44	14.7	$1.46 \cdot 10^{-2}$
0.05	0.87	17.6	$7.13 \cdot 10^{-3}$
0.1	1.75	18.5	$1.6 \cdot 10^{-3}$
0.2	3.49	20.7	$1.13 \cdot 10^{-3}$

Table 7. Chemical composition of underground waters from the Głowacki Shaft, level 600.

pH	8.0 ±0.2	Permanganate index [mg/l O_2]	0.7 ±0.14
Intrinsic conductivity [μS/cm]	1520 ±76		
Sodium [mg/l]	162 ±16	Chlorides [mg/l]	251 ±25
Potassium [mg/l]	7.82 ±1.56	Sulphates [mg/l]	286 ±29
Chromium [mg/l]	< 0.005		
Zinc [mg/l]	< 0.03	Total cyanides [mg/l]	< 0.002
Cadmium [mg/l]	< 0.001	Sulphides [mg/l]	< 0.01
Copper [mg/l]	< 0.005		
Nickel [mg/l]	< 0.005		
Lead [mg/l]	< 0.01		

Table 8. Leachability of chemical impurities of aggregate with pit water from the Głowacki Shaft, level 600.

		Permanganate index [mg/l O2]	5.5 ±1.2
Sodium [mg/l]	184	Chlorides [mg/l]	266
Potassium [mg/l]	9.42	Sulphates [mg/l]	172
Chromium [mg/l]	< 0.005		
Zinc [mg/l]	< 0.03	Total cyanides [mg/l]	< 0.005
Cadmium [mg/l]	< 0.001	Sulphides [mg/l]	< 0.05
Copper [mg/l]	< 0.005		
Nickel [mg/l]	< 0.005		
Lead [mg/l]	< 0.01		.

backfilled with one type of material with suitable strength and filtration parameters. Metallurgical aggregate with the following parameters was designed for the liquidation of the Głowacki Shaft:

- grain size between 31.5 and 63 mm,
- volume density greater than 2.0 T/m^3,
- filtration coefficient after discharge into a shaft greater than $1.18 \cdot 10^{-3}$ m/s,
- compressive strength exceeding 100 MPa,
- material resistant to water influence ('A' in Skutta's method),
- does not adversely affect the chemical composition of underground water.

In order to improve the filtration coefficient of the backfill material, it was assumed that sub-grains would be removed from the material immediately before being thrown into the shaft.

4. Conclusions

In order to design the liquidation method for the Głowacki Shaft, the following analyses were conducted: hydrogeological-mining conditions in the area of the shaft, the existing water flow system in the excavations in the direction of the shaft, the system for transporting inflowing water to the area, forecast deformations within the area of the liquidated protective pillar resulting from the impact of mining operations planned to be conducted until 2042 and the identified and forecast technical condition of the shaft lining. In addition to the standard procedures undertaken prior to liquidation activities, climate change projections were taken into account in this case, including increased water inflows associated with extreme precipitation events. On this basis, it was determined that the inflow could increase by up to 15% due to rainfall variability.

The optimum solution for liquidation of the shaft was to construct a permeable backfill column in the shaft and use a shaft pipe filled with permeable backfill material. A metallurgical aggregate with certain parameters was selected for the backfilling column. The analysis of hydrogeological and mining conditions has shown that the decommissioned Głowacki Shaft can function for an extended period of time as a route for gravitational water flow through permeable backfill.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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Conflict of interest

None declared.

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