Chapter

Polish Experiences in Handling Water Hazards during Mine Shaft Sinking

Piotr Czaja, Paweł Kamiński and Artur Dyczko

Abstract

The geological structure of most Polish mining regions is rich in groundwater, making shaft sinking difficult. In recent years, more than a dozen shafts, some almost 700 m deep, have been sunk in Poland using various methods of water hazard elimination. The vast majority of shafts that pass through aquifer formations have been sunk using artificial rock freezing, waterproof tubing, and concrete lining. Generally, this system has proven to be very effective. However, there have been cases of complications during sinking, including occasional flooding. This paper presents two cases of highly problematic flooding in shaft sunk using the freezing method, both leading to considerable construction delays and a significant increase in shaft sinking costs. The first case involved water inflow into the bottom section of the R-XI shaft at KGHM with rocks near the melting point of ice. In the other case, problems occurred passing through an Albian layer in the S. 1.3 shaft sunk for the Lubelski Węgiel Bogdanka S.A. mining corporation, where the freezing process was carried out while it was necessary to heat the rocks in the upper part of the shaft to protect the final lining from damage.

Keywords: mining shaft, water hazard, grouting, dewatering

1. Introduction

Exposing deep-seated mineral deposits requires the construction of new shafts. In Poland, where usable minerals are usually covered by thick layers of heavily waterlogged overburden, the construction of new shafts poses extraordinary difficulties. New shafts continue to be designed and constructed in quite challenging hydrogeological conditions in Poland, as well as in other countries worldwide. Hence, it would be fruitful to look at some Polish experiences in coping with this extremely difficult hydrogeology while mining deposits of both hard-coal and nonferrous metal ores. A range of detailed examples of how to eliminate such water hazards has been provided elsewhere [1–3]. Over the last three decades, Poland has seen at least several cases involving shaft flooding. These occurred mainly during the sinking phase. There are many methods for eliminating water hazards and dewatering flooded shafts to put them back into operation. This paper presents two cases of highly problematic flooding in shaft sunk through highly waterlogged layers using the freezing method, both leading to considerable construction delays. The first case involved the removal of increased water inflow into the R-XI shaft at KGHM. In the other case, problems occurred due to a shaft passing through an Albian layer in the S. 1.3 shaft sunk for the Lubelski Węgiel Bogdanka S.A. mining corporation. Although completely different from each other, these cases provide useful guidance and a serious warning against hasty shaft design or a careless approach to constructing shafts [4–6]. Considered completely safe for shaft construction, the technological solutions presented here should be of interest to experts in water-related mining issues.

2. Diversion of increased water inflow into the R-XI shaft during sinking

Waterlogged overburden formations as deep as 700 m below the ground have made it necessary for Polish mining corporations to use the freezing method to construct all copper mine shafts and most hard-coal mine shafts. Hundreds of shafts have been successfully sunk in Poland using this technology. However, when it seemed that the engineers had virtually eliminated freezing pipe leaks in the boreholes, a major problem that had caused brine leaks into frozen rock, water hazards emerged in completely unexpected and highly unlikely situations.

2.1 Project specification and the effects of the water hazard

The R-XI shaft was not the first structure of this type constructed by PeBeKa S.A. in the Polish Copper Basin area [7]. Hydrogeological surveys preceding the shaft work at depths of 431.0–630.0 m indicated no significant water hazards along this section. The projected water inflows into the shaft face below the 431.0 m level are shown in **Table 1**. The R-XI shaft was designed to serve as a ventilation shaft and has the following parameters [5]:

- Lining diameter—7.5 m
- Total depth—1250 m
- Aquifer thill depth—630 m
- Freezing depth—635 m

At the time, this shaft had the greatest rock freezing depth at 635 m. PeBeKa Lubin applied many innovative rock freezing solutions. One of them was selective freezing using two types of freezing holes: short holes with a depth of 395 m and

Depth interval [m]	Water inflow [m^3/min]	
	Minimum to maximum	Average
431.0–460.0	0.042–0.070	0.056
460.0–470.0	0.042–0.070	0.056
470.0–500.0	0.061–0.330	0.160
500.0–565.0	0.205–0.490	0.334
565.0–630.0	0.334–0.550	0.425

Table 1.
Predicted water inflows into the shaft [7].

long holes with a depth of 635 m. This method made it possible to achieve a frozen mantle that was thickest in its lower portion, where the water pressure was found to be the highest.

Because a gallery had already been excavated near the shaft at a depth of 1212.7 m, the design included a simplified drainage system for the shaft face below the freezing zone. This was achieved through a dewatering borehole drilled in the shaft axis vertically upwards from a level of 1212.7 m. This made it possible to dispense with the construction of an expensive cascade drainage system and significantly facilitated shaft sinking at depths of 635–1212.7 m. At the 503.6–632.4 m shaft section, the design included a combined panel and concrete lining, i.e., a top-down panel lining and a concrete, monolithic, bottom-up lining using panel forms. The concrete lining was laid on a 2.6-m-thick base ring beam set between depths of 632.4 and 635.0 m (**Figure 1**).

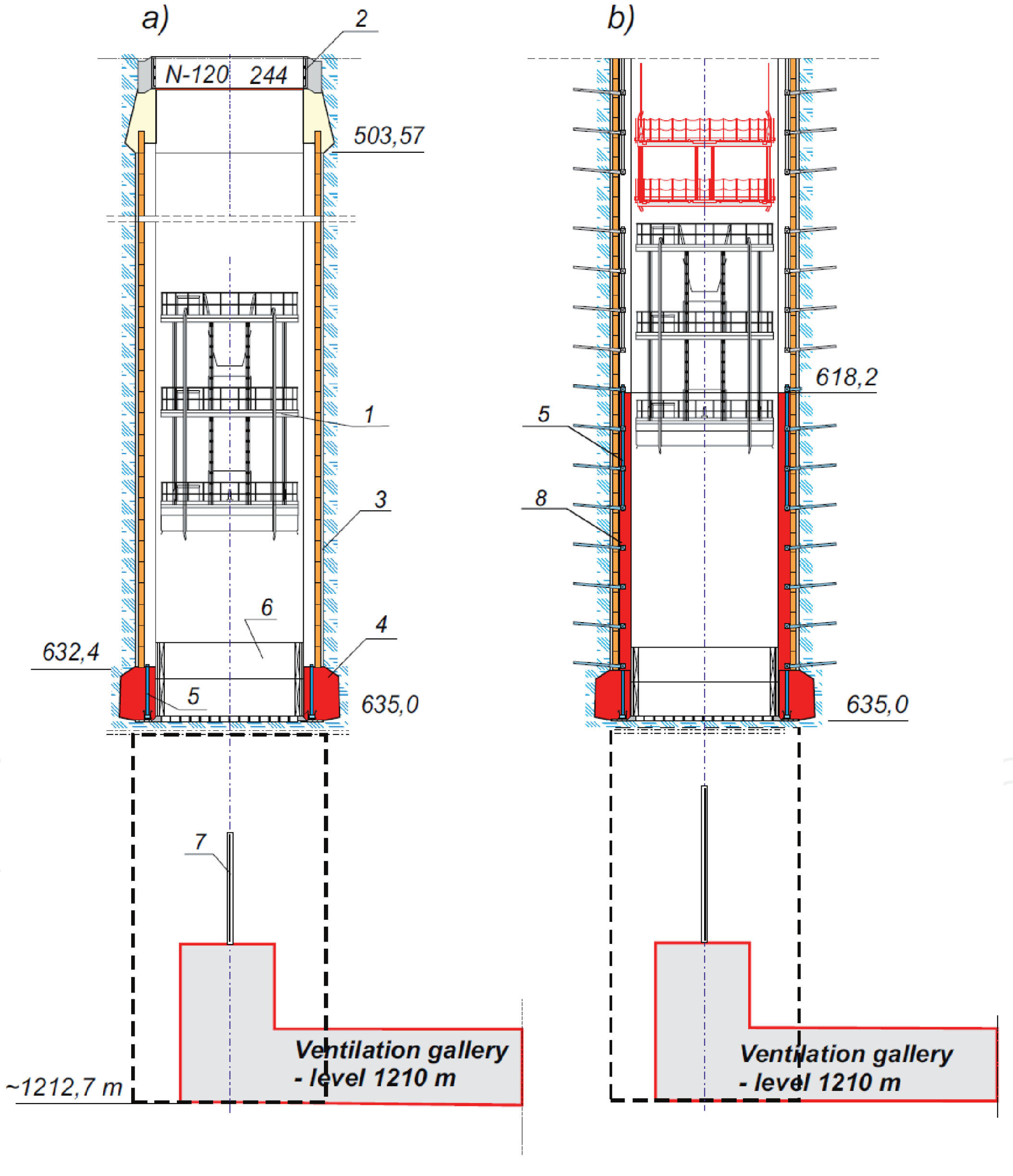

Figure 1.
The last phases of shaft sinking in the frozen rock area. (a) Installation of foundation for the final shaft concrete lining. (b) Section of final shaft concrete lining with drainage. Explanations: 1, three-deck shaft working platform; 2, cast-iron shaft lining; 3, preliminary pre-cast segmental shaft lining; 4, shaft lining foundation; 5, boreholes in the drainage system; 6, sliding formwork H = 3.75 m; 7, dewatering borehole TS-1 (d = 3.5," L = 576 m); 8, final concrete lining.

According to the records [6, 7], the in situ rock temperature at a depth of 632 m was about 32°C. So, it was reasonable to expect that the end portion of the frozen mantle would also be exposed to increased heat from below. When the shaft face reached a depth of 632 m without any difficulties, it seemed that the most challenging section had been sunk as designed and on schedule. Yet, nature retained its unpredictability.

After the two last reinforced concrete panel rings had been completed, with excess material excavated to make a curb gap 4 (**Figure 1**) at a depth of 632 m, a small water leak, estimated at about 3–5 L/min, was noticed at the shaft bottom at the thill sidewall interface. The water was clean, very cold, and slightly salty. For a shaft sunk using the freezing method, in which the freezing core usually has a temperature below −15°C, this was unusual and perplexing. Since the freezing pipes had reached a depth of 635 m, no liquid water should have occurred at a depth of 632 m. However, this phenomenon could be partly explained by the water's salinity. Unfortunately, the electrical conductivity of this water has not been documented. In these circumstances, the TS-1 dewatering borehole work was intensified. Also, work commenced on the final concrete lining 8 (**Figure 1**)—constructed from the bottom up—equipped with a drainage system [7].

It was found that even though all the freezing safety requirements had been observed, the ice mantle along this section was not completely watertight and did not fully prevent water inflow into the shaft face. The movement of slightly saline water at a temperature above zero (tw > 0°C) caused the frozen mantle to be soaked from below and consistently thawed, with water inflows effectively increasing day by day. The situation was becoming dangerous, as no shaft pipe drainage had been planned down to this depth. This meant that the shaft had no pipelines through which the water could be pumped up to the surface. The further section of the shaft was designed to allow drainage via the TS-1 dewatering borehole drilled from a level of 1212.7 m (**Figure 2**).

The increasing inflow of water was diverted to the surface using only buckets. After about 2 weeks of shaft work involving the construction of a concrete curb at a depth of 635 m and the construction of an 18 m final concrete lining, water inflow into the shaft had increased to about 700 L/min. In this situation, it was impossible to continue any work in the shaft other than intensive dewatering using of buckets. Ultimately, this measure did not save the shaft from partial flooding. The water table in the shaft stabilized at a depth of 533.0 m, which means that the water column was 102 m (see **Figure 2**).

Due to the prolonged length of the 564 m TS-1 dewatering borehole and the water level reaching 533 m (**Figure 2a**), the decision was made to use a high-performance RITZ submersible pump (HDM 6723/11DPF). Installed 4 weeks later, with a capacity of 15 m^3/min, the submersible pump succeeded in quickly dewatering the flooded shaft section (**Figure 2b**). Also, after 2 months of further work, the water inflow into the shaft was found to have reached 2.5 m^3/min. The dewatering borehole TS-1 (**Figure 2**) was successfully completed almost at the same time the shaft was dewatered using the submersible pump. After 6 weeks of intensive and highly precise drilling work, the borehole reached the shaft bottom, located only 0.5 m from the shaft axis. By this point, the water inflow had increased to 3.0 m^3/min. Since the water inflow was expected to increase further, the decision was made to drill a second dewatering borehole—TS-2 (**Figure 2c**). Due to the considerable water hazard associated with a water inflow of 3.0 m^3/min, it was also decided that the section with a waterproof tubing lining be extended to the 650 m level. In addition, the decision was made to comprehensively grout the entire area affected by the substantial water inflow.

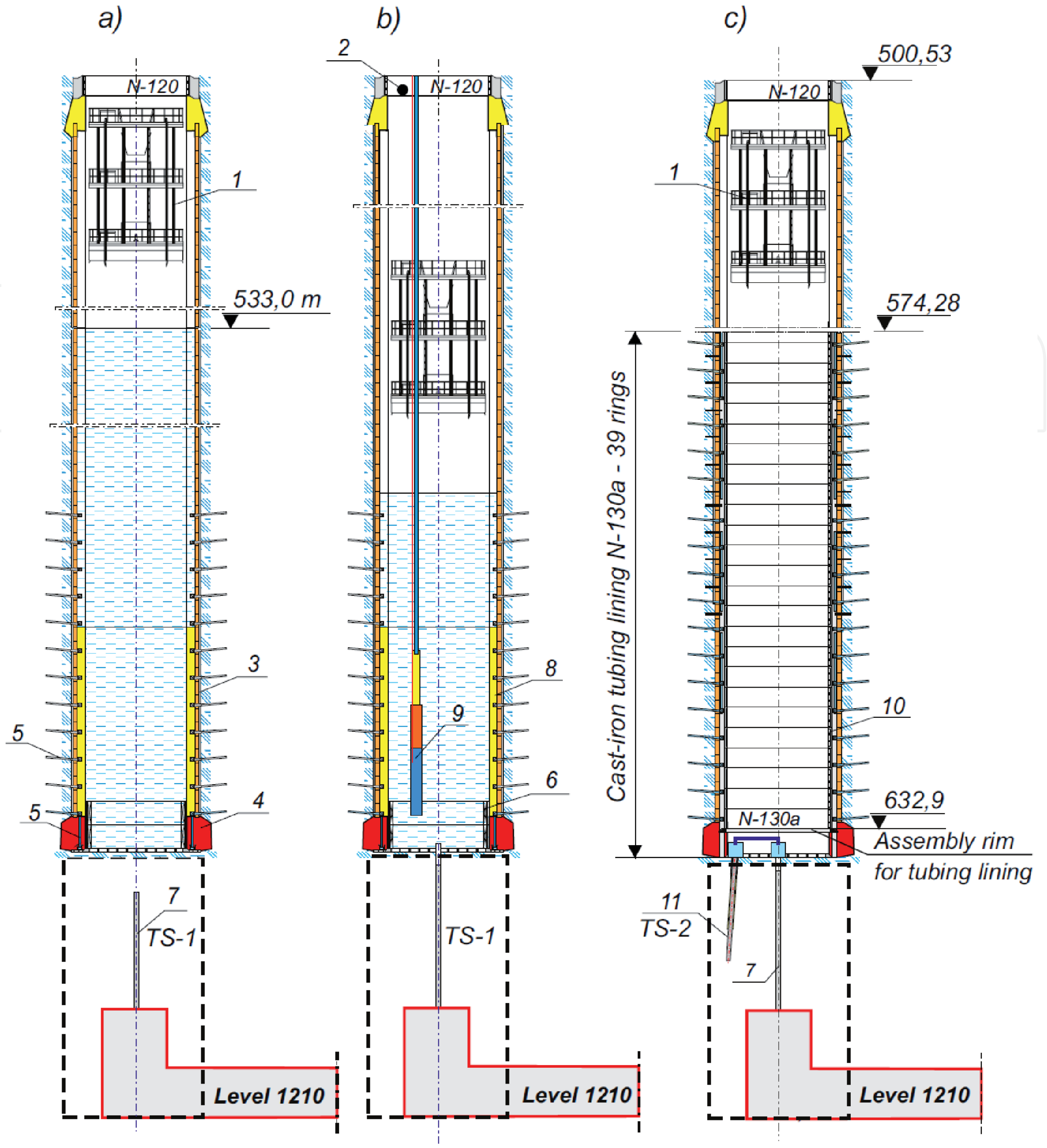

Figure 2.
*The phases of dewatering the sunken shaft section. (a) Shaft flooding. (b) Dewatering of the shaft using a "RITZ" submersible pump, (c) replacing the concrete lining along the 574.3–632.9 m section with a cast-iron tubing lining. Explanations: 1–8, see **Figure 1**; 9, RITZ submersible pump; 10, cast-iron tubing lining; 11, TS-2 dewatering borehole.*

2.2 Removing the causes of the water inflow

The substantial water inflow forced the shaft construction company to both further redesign the shaft lining and adjust the sinking technology along the 635–650-m-deep section. Apart from the costly dewatering, one of the direct effects of the partial shaft flooding was the need to redesign the lining in the flooding area (**Figure 2**). The concrete panel lining was replaced by a tubing panel lining, with a concrete tube set between them (**Figure 2c**) [7]. Due to this replacement, it was additionally necessary to:

a. Demolish the completed 18 m section of the concrete lining above the curb, at a depth of 635 m, without damaging the preliminary panel lining.

b. Partially demolish the curb at a depth of 635 m and mount a steel ring beam on the curb's foundations to lay the first tubing ring.

c. Construct the lining of 39 N-130a tubing rings from the bottom up, to a depth of 574.3 m, without damaging the preliminary panel lining, the initial step being to lay the first ring on the steel ring beam in the curb at a depth of 635 m.

d. Complete the grouting work above the curb, at a depth of 635 m, so that the shaft could be safely sunk along the 635–650 m interval.

e. Sink the shaft along the 635–650 m tubing-lined section, including constructing a curb at a depth of 650 m.

f. Construct the lining of N-120 cast-iron tubing rings from the 574.3 m level upwards to the point of connection between the picotage gap and the upper tubing column at a depth of 500.47 m.

In the first phase, the rock behind the lining was grouted using multiple techniques. In the first phase, 3-m-long holes were drilled in rings 309 and 310 through cement plugs in the tubing lining. A total of 26 t of cement grout were injected behind the lining through these holes to separate the upper water horizons from the problem area of the shaft.

In the second phase, the cement grout was injected behind the lining along the 617.9–635.0 m section, using 2-m-long horizontal holes drilled through the concrete plugs, 10-m-long horizontal holes drilled through the cement plugs, and 15-m-long inclined holes drilled at an angle of 40° through the concrete plugs. Due to the very substantial water inflow from this area, “Ekopur HW” quickset two-component

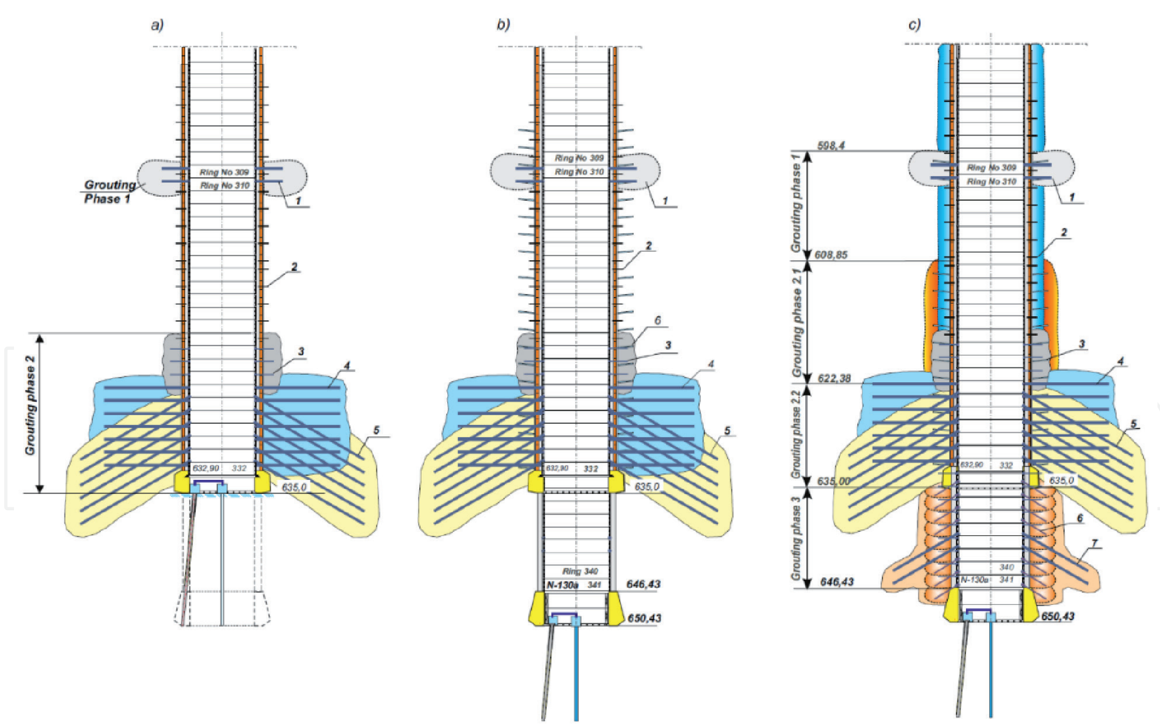

Figure 3.
Grouting process and shaft sinking along the 635–650 m section. (a) Grouting along the 598.4–635.0 m section, phase 1 and 2; (b) shaft sinking along the 635–650 m section, (c) grouting along the 635–650 m section, phase 3. Explanations: 1, cementation of the rock behind the lining (insulating layer) in N-130a tubing rings 309 and 310; 2, grouting of the rock behind the tubing lining through concrete plug holes in the tubing; 3, grouting of the rock and tubing lining through “cementation” holes in tubings (2-m-long horizontal holes); 4, grouting of the rock and tubing lining through “cementation” holes in tubings (10-m-long horizontal holes); 5, grouting of the rock and tubing lining through concrete plug holes (15-m-long inclined holes); 6, grouting of the rock and tubing lining through “cementation” holes in tubings (2.0-m-long inclined holes), 7, grouting of the rock and tubing lining through “cementation” holes in tubings (10.0-m-long inclined holes).

Phase	Grouting materials used [Mg]		
	Cement	**EKOPUR HW polyurethane**	**Total**
Phase 1	45.5	24.5	70.0
Phase 2	33.3	14.8	48.1
Phase 3	16.4	0.32	16.7
Phase 4	342.7	32.4	375.1
Total	**438.0**	**72.1**	**510.1**

Table 2.
Grouting materials used to prevent water inflow [7].

polyurethane adhesive was used in addition to the cement grout. The grouting work is illustrated in **Figure 3** [7]. Once the 635–650 m section of the shaft had been sunk, a curb was made in the tubing lining, comprising 130a tubings (9 rings) installed from the top down at a depth of 650 m, and a shaft face dewatering system was installed using boreholes TS-1 and TS-2 (**Figure 2**).

In the third phase, cement grout was injected behind the lining along the 635–635.0 m section (**Table 2**). Then, as part of the fourth grouting phase, the entire 574–500 m section of the tubing lining was sealed. It took a total of more than 500 t of materials (**Table 2**) to complete the grouting process.

3. Eliminating water hazards associated with the S-1.3 shaft sinking project in the Lublin Coal Basin

The hydrogeology of the Lublin Coal Basin is highly complex, and mining in this area is challenging. At 710 m from the surface, the coal measures are covered by heavily waterlogged Jurassic, Cretaceous, and Quaternary formations. This has considerable implications for mine shaft sinking. A simplified geological profile is presented in **Figure 4**.

All the shafts in this basin had to be sunk using the freezing method, at least along the 0–180 m section [4, 6, 8]. The first shafts for the Bogdanka Mine were given the numbers S-1.1, S-1.2, and S-1.3. After the S-1.1 shaft had been sunk to a depth of 960 m, a disastrous water leakage occurred from the connector pipes left in the lining, which caused extensive flooding. Consequently, it was necessary to fill in and abandon that shaft. Drawing on the S-1.1 experience, the S-1.2 shaft was sunk to the target depth of 995 m without any major difficulties. Although the flooding of the S-1.1 shaft had also caused partial flooding of the S-1.2 shaft through the galleries already sunk to a depth of 960 m, the dewatering proved to be fairly easy. The sinking of the S-1.3 shaft might be the most interesting and perhaps the only such case in the global history of shaft construction, as it ultimately required simultaneous rock freezing in the lower section and rock heating in the upper section. Below is a detailed discussion of how this was done.

3.1 The S-1.3 shaft sinking

The experience gained sinking the S-1.1 and S-1.2 shafts indicated that it was possible to use a different technology, more based on the traditional sinking method, which is much less costly. A decision was made to freeze the rocks along the 0–180 m section before constructing the first section, as it passed through the Quaternary strata and the highly waterlogged layers of Cretaceous formations, with a maximum

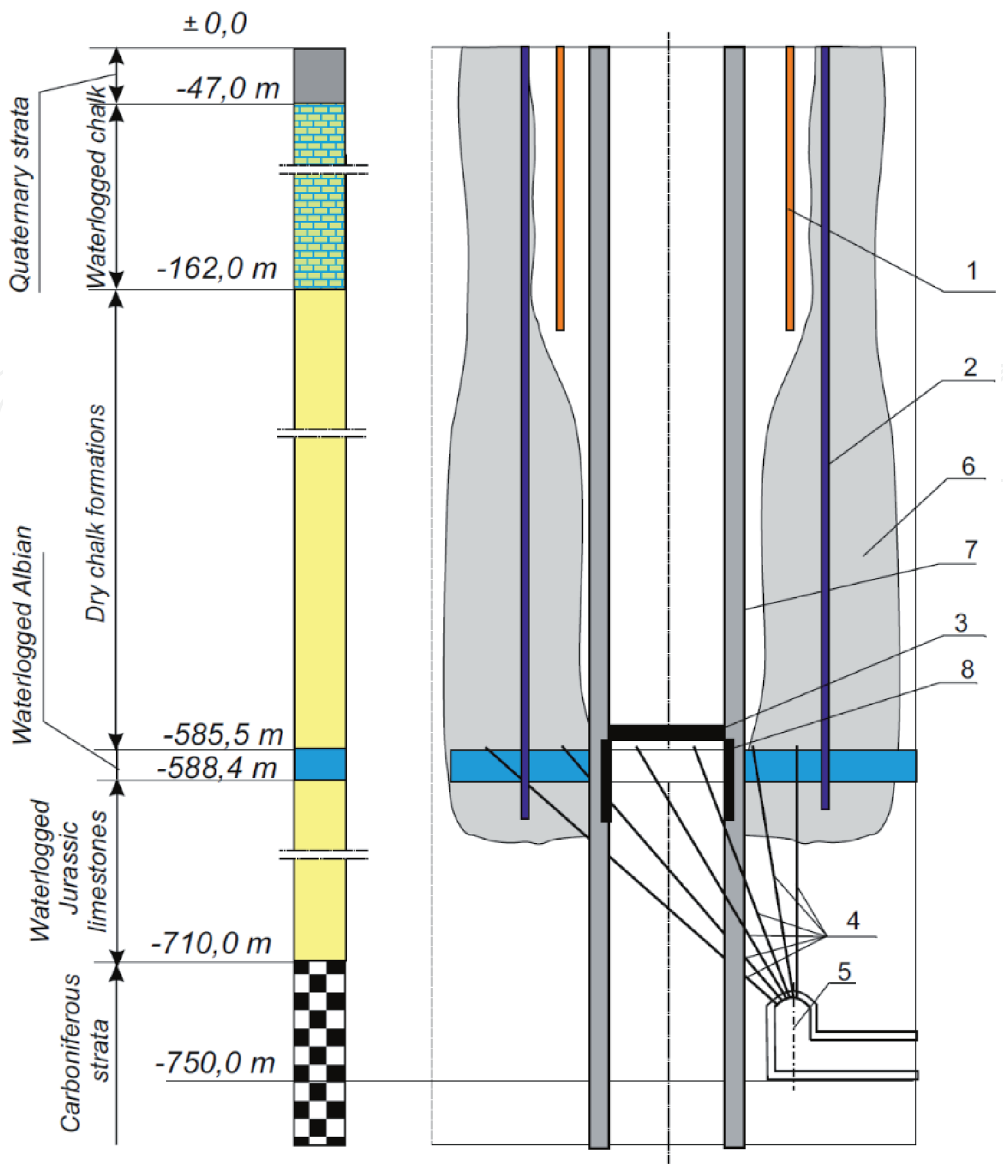

Figure 4.
Diagram of the S-1.3 shaft sinking using both rock freezing and rock heating. 1, boreholes for rock heating along the 0–180 m section; 2, boreholes for deep freezing along the 0–570 m section; 3, concrete plug above the Albian layer; 4, drainage boreholes in the Albian layer; 5, working with a drilling chamber at a depth of 754 m; 6, frozen rock mantle; 7, final concrete panel lining; 8, cast-iron tubing lining along the Albian formation section.

depth of 162 m (see **Figure 4**). Below the 180 m level, the plan was to sink the shaft to a depth of 570 m using conventional method, i.e., without rock freezing. This would substantially reduce costs. The biggest puzzle, and, as the construction company would see, the greatest challenge involved in this shaft sinking project was the thin (≈2.9 m) Albian layer (**Figure 4**), which was composed of sandy-lime quicksand with a water pressure of about 5.5 MPa. An assumption was made that a shaft working could pass through such a thin layer of waterlogged formation once the layer had been provided with borehole drainage system (**Figure 4**) drilled in the working at a depth of 754 m. With the drainage system in place, the pressure could be reduced, making it possible to petrify both the Albian formations and the Jurassic formations deposited underneath, all the way to the Carboniferous roof. This way, the shaft could be sunk conventionally down to the target depth of 1035.45 m.

Here, we should warn those who are enthusiastic about using grouting, regardless of the conditions. In this specific case, the company constructing the shaft failed to provide the mentioned formations with a drainage system. In effect, it became impossible to chemically petrify the Jurassic formations any further, and the only viable sinking option left was the freezing method. At this

Parameter	Design	Actual
Freezing time, months	9.2	About 7
Amount of energy consumed to create the frozen mantle, MJ	71,310,951	45,638,000
Heat supplied through the boreholes along the 14 m diameter circle (0–180 m), MJ	15,323,000	12,509,800
Heat supplied through the air supply duct to the warm-air shaft, MJ	23,197,000	16,130,000
Total energy consumed, MJ	109,830,951	74,277,800

Table 3.
Projected and actual energy consumption in the process of rock freezing when sinking the S-1.3 shaft [3].

point, the expected substantial savings stemming from the use of a different shaft sinking method were no longer viable. In addition, the construction company faced the problem of refreezing within the 0–570 m zone, where the final lining had already been laid. The Polish engineers involved in the project knew that the refreezing of rocks would produce a great pressure surge on the lining, effectively destroying it [6].

The engineers considered it necessary to drill 43 additional boreholes at a depth of 610 m. These had an unusual diameter of 308 mm and were drilled in an 18 m diameter circle [3, 8]. Also, an unprecedented decision was made to use sectional freezing—an approach which, although theoretically known and viable, had not been applied in shaft construction before. Thus, the boreholes were fitted with two freezing pipe columns and a column of downcomer tubes inside a 139.7 mm diameter column. They were properly sealed so that the brine could circulate only in the lower parts of the boreholes, below 570 m.

Regrettably, this plan failed, too. The shrinkage stress in the steel due to the low temperature of the brine caused the outer column to leak, allowing water to enter the borehole. This complicated the whole process of section freezing, making it necessary to reconsider freezing along the entire depth of the shaft. As feared, the freezing caused damage to the lining along the 0–570 m section soon after commenced. At this point, the decision was made to apply a globally unprecedented solution, in which the lower section of the shaft was frozen, while the upper part of the shaft, along the 0–180 m section, was heated with warm water. To provide the inflow of warm water, the engineers used the boreholes drilled to freeze the first section of the shaft along a circle with a diameter of 14 m. The work diagram is presented in **Figure 4**.

Ultimately, this unprecedented project proved a technological success. However, although the shaft was eventually sunk, the project can hardly be described as successful, given the completion period of almost 10 years and the substantial energy costs involved. The substantial costs of sinking the S-1.3 shaft are reflected in the amount of energy consumed in the process of rock freezing and heating. These parameters are shown in **Table 3**. It should be noted that the actual values were much lower (by about 38%) than the design values.

4. Conclusions

This paper shows how changeable and unpredictable hydrogeology can lead to challenging and very costly problems in shaft sinking projects. In the case of the polish shafts, a water hazard that had not been accurately identified by hydrogeological surveys led to a number of adverse effects. These included the substantial amount of grouting materials used, the extended project completion period (it took almost an additional year to finish the project), and the need to replace the concrete panel lining with tubing lining along a 150-m-long section of the shaft.

This paper presents case histories that should serve as the ultimate warning against underestimating the projected inflow of water into a shaft during its sinking. A number of shaft construction projects recently implemented in Poland further illustrate this point. Since water inflow projections proved inaccurate, it is necessary to improve the accuracy of hydrogeological surveys in the areas where mining is planned. Poland has extensive and highly informative experience in successfully dealing with water hazards related to shaft construction.

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