Measures to reduce the environmental impact of the Żelazny Most Tailings Storage Facility

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Abstract. The Żelazny Most Tailings Storage Facility, located in south-western Poland, is one of the largest facilities of its kind in the world. Mining wastes from the processing of copper ores have been disposed continuously for over 40 years. A safe operation of TSF of this size requires the involvement of engineers, specialists and scientists from many fields of science. The article presents the latest experience in activities reducing the environmental impact of the Żelazny Most TSF, including the monitoring of groundwater, air protection and the reliability of pipe infrastructure. KGHM Polish Copper, the TSF operator, has been running the system for monitoring the quality of surface and groundwater in the foreground of dams for more than forty years. Very good diagnosis of the hydrogeological conditions in the TSF foundation allowed the research unit to develop a three-dimensional numerical model of groundwater flow. The article also describes the issues related to dust prevention. Active and passive protection methods for the beaches and slopes were presented. Slurries are pumped over a distance of up to 20 km via multiple pipelines. Due to the high abrasion properties of the rock material, KGHM runs a pipeline testing and replacement program to ensure the highest level of reliability. The issues presented in the article clearly indicate the attitude of the TSF operator to the reduction of the negative impact of waste storage in the natural environment. This is also confirmed by the presence of many rare species of wild animals in the immediate vicinity, such as deer, beavers and birds of prey.

1. Introduction

KGHM Polska Miedź S.A. is one of the largest producers of copper and silver in the world, operating mostly in south-west Poland. It also has assets in South and North America. Polish assets in the form of 3 underground mines, ore enrichment plants (OEP), 2 smelters, rolling mills and tailings storage facility (TSF) constitute the main technological line spread over an area of 900 km². The construction of the mines which started in 1960 resulted in a significant influx of new workers and the development of nearby towns. Currently, the area around KGHM is characterized by a high degree of urbanization, exceeding the national and provincial average [1]. The company carries out many activities in the field of corporate social responsibility. One of its main elements are activities aimed at reducing the environmental impact of the Żelazny Most tailings pond, KGHM's largest facility located on the surface.
2. Tailings Storage Facility Żelazny Most

Żelazny Most is one of the largest tailings storage facilities in the world. All KGHM flotation waste is deposited there. Annually, it absorbs up to 30 million Mg of ground waste rock, as a result of which the tailings pond grows by 1.5 to 2 m per year. TSF is undergoing a continuous development by the upstream method, where each additional 2.5 m embankment is shifted towards the center of the facility. The tailings deposited on the beaches are used for the construction of external dams. The material is pumped from OEP Rudna and Lubin, and discharged through the spigots. The slurries are discharged from the pipeline running along the crest of the dam, and later through spigots, every 10-20 m. On the beach, the coarsest fractions of waste settle the fastest. As the distance from the pipeline increases, less and less material is deposited, resulting in a natural beach slope towards the pond. The finest particles flow into the basin, where a slow sedimentation process takes place. At the same time, 4 out of 26 sections into which Żelazny Most were divided, are operating. The material from OEP Polkowice, characterized by finer particles that do not meet the requirements for the construction of the dams, is discharged by pipelines perpendicular to the dams through 200 m long piers. They are designed to transport fine particles outside the beach zone and the construction site.

Until now, the Żelazny Most has stored about 650 million m$^3$ of post-flotation waste and is undergoing expansion by construction of the Southern Extension. Table 1 presents the basic parameters of the Main Facility (MF) and the South Extension (SE) of TSF Żelazny Most. Deposition of tailings in the SE will be based on a different technology. During the conceptual and design works, the technology of selective storage of thickened tailings was selected. Part of the tailings flux from OEP Rudna will be segregated using hydrocyclones. Coarse grains will remain deposited along the starter dam so as to form the foundation for the target facility elevation. This increases the safety factor of the SE dams. The overflow of the hydrocyclones, containing mainly silty and clay fractions, will be compacted in thickeners or discharged into the Main Facility. After consolidation, it will be dredged and transported to the central part of the SE. The discharge of thickened tailings at the SE is expected to slow down the MF growth rate and both parts of the Żelazny Most TSF are to reach their levels at the elevation of 195 m MSL.

**Table 1.** Basic parameters of Tailings Storage Facility Żelazny Most.

| Parameters                        | Unit | Main Facility | Southern Extension |
|----------------------------------|------|---------------|--------------------|
| Area                             | km$^2$| 15.30         | 6.09               |
| Volume of water                  | m$^3$| 8 000 000     | 2 000 000          |
| Design volume                    | m$^3$| 767 500 000   | 168 450 000        |
| Design elevation of the dam crown| m MSL| 195.00        | 195.00             |
| Current elevation of the dam crown| m MSL| 190.00        | 175.00             |

3. Protection of surface and ground waters

The TSF is situated on the northern slopes of the Dalków Hills, sloping gently northwards towards the Odra River. The Rudna and Ždżerowita rivers flow to the east and west of Żelazny Most. Before its construction, the water from the area, now occupied by TSF, flowed to these rivers and along them towards the Odra River. The area of the facility was also supplied by the Lipówka stream, flowing from the south. During the construction of the TSF a dam was built on the the Lipówka stream valley. The water from the created reservoir, with area of 7.5 ha, flows by gravity to the Rudna river through a pipeline, with length of approx. 5 km. The reservoir is a refuge for freshwater birds and fish, and in its vicinity you can meet beavers and fallow deer. The remaining part of the Lipówka stream catchment is pumped from the foot of the TSF dam also to the Rudna river [2].
In the central part of the TSF, for technological reasons, a water reservoir of 6 to 14 million m$^3$ is maintained [3]. The systematic growth of the facility causes the increase in hydraulic gradient between the reservoir and groundwater. KGHM carries out a number of activities aiming at retaining technological water in the TSF area. These activities take place on two levels: construction and operation of TSF and the barrier of drainage wells. A cross-section with the basic elements of the TSF structure used to retain technological water in the TSF area is presented in Figure 1.

![Cross-section of the TSF's dam.](image)

**Figure 1.** Cross-section of the TSF's dam.

### 3.1. Construction and operation

Operation of the TSF is based on the principles specified by the general designer in the multi-volume operating manual. One of the most important conditions of the manual is to limit the duration of uninterrupted spigoting per section to a maximum of 3 weeks. The next step is switching the tailings flow to a different part of the TSF, and the so far saturated beach must be left for consolidation and drying for a period of 3 to 6 weeks [3]. Filling the sections takes a total of 8 to 12 weeks and takes place in 3 to 5 spigoting-break cycles, after which the formation of a new 2.5 m embankment is performed. The embankment is built by shoveling with bulldozers the coarse-grained material, deposited on the beaches during discharging of tailings. The material is compacted in layers and subjected to compaction control by KGHM services and independent institutions. For the correctness of the later spigoting, it is extremely important to shape a beach slope towards the water. Section depressions, flow-blocking thresholds may lead to the formation of a pool in the beach zone, increased water filtration into the circumferential drainage and the deposition of an increased amount of fine particles deposited on the beaches close to the external dams. KGHM counteracts these threats through regular and post-construction inspections.

Despite keeping the beach slope towards the pond, the water infiltrates into the beaches towards the TSF foundation, adversely affecting the strength parameters of the tailings. In order to drain the beaches, the circumferential drainage surrounding the entire structure is developed. Currently, there are 5 floors of drainage in the form of filter walls arranged parallel to the dams, spaced approximately every 10 m in depth. The material used for the construction of filter walls is slag from copper smelters, thus in line with the closed-circuit philosophy used by KGHM. Due to the homogeneous particle size and high porosity, slag is a material that is difficult to compact and has a very high permeability coefficient. During the OUOW exploitation period, the filtration walls work properly and fulfill their tasks, which is confirmed by periodic inspections of the drainage discharge.

Water from the circumferential drainage flows into the ditch around the TSF, similar to the starter dam’s drainage. The water flows to the filter reservoirs at the Kalinówka and Tarnówek pumping...
stations, from where it is pumped into the KGHM process water system. Drainage discharges are monitored by gauge weirs, flow meters and reservoir filling sensors.

Fine fractions of spigoted tailings on the beaches flow towards the pond and, together with carbonate slurries from OEP Polkowice, remain in the central part of TSF. The tailings lying under the water pond contain over 90% of silty and clay fractions. This material settles to the bottom of the pond which contributes to low permeability under the pond. The tests of tailings pumped from the depth of up to 5.5 m below the water level, showed that after consolidation and drying, it has a permeability coefficient in relation to the temperature of 10 °C in the range from 2.9x10⁻⁹ to 6.4x10⁻¹⁰ ms⁻¹ [4]. Pursuant to the law in force in Poland [5], these parameters allow for the recognition of fine-grained material as suitable for the construction of a geological barrier sealing the ground for all types of landfills: inert, non-hazardous (Żelazny Most) and hazardous. The tests carried out on the laboratory model of the dam sealed with material collected from TSF also confirmed the high usefulness of fine-grained material from copper ore flotation for the production of anti-filter screens in structures made of water-permeable materials [6].

3.2. TSF monitoring
TSF Żelazny Most is designed using the observation method, which requires an extensive monitoring system [7, 8]. Geological, seismic, hydrological, hydrogeological, geodetic and environmental surveys and measurements are carried out at the repository. Monitoring is carried out mainly by KGHM services, but is subject to control and verification by independent research centers. In the scope of hydrological measurements, water and waste balance in the system is performed. The amount of water is checked daily by means of the readings of the staff gauge at the marina of TSF, and at least twice a year geodetic bathymetry of the entire reservoir is performed. The flow rate of ditches is constantly monitored by the means of flow meters visualized in the KGHM control system (SCADA).

KGHM has a specialized team that carries out hydrogeological measurements on more than 2,000 open stand pipe piezometers. About 300 vibrating wire piezometers (VWPs) were also installed at TSF, whose task is to control the pore pressures in tertiary clays in the foundation. Depending on the validity class of the device, piezometers are subject to periodic tests and measurements in some cases every day.

In recent years, at TSF Żelazny Most, an innovative study of the position of the phreatic line in the cross-hole technology has been carried out, consisting in the use of seismic wave reflection between two holes, one causing vibrations and the other one working as a listening device, equipped with a geophone. These studies have shown that the zone of full saturation with water is deeper than originally assumed, which increases the safety of the surrounding dams. The monitoring systems and advanced research carried out on Żelazny Most are described in more detail in the publications [9–11].

3.3. Barrier of drainage wells and numerical modeling
Despite the number of treatments and solutions limiting the migration of technological water beyond the TSF, a small amount of water leaks beyond the drainage system. Water quality tests in piezometers installed downstream the TSF allow to determine the zones polluted by technological water containing some portion of salt (Fig. 1). In order to reduce the zones contaminated with salt, KGHM built 44 drainage wells to capture polluted water and pump it into a circular ditch (Fig. 2). The barrier of drainage wells limits the impact of the facility on quality of groundwater around the TSF and despite two-fold increase in the salinity of technological water over a 6-year period and an increase in the elevation of facility, no significant increase in the air pollution of polluted waters was recorded [4].
Planning of the location of new drainage wells is supported by hydrogeological models of the TSF area. The first two-dimensional model was developed for the state of the TSF Żelazny Most in 1996. The models have been developed and expanded over the years. KGHM, in order to make forecasts related to the expansion of the TSF with the Southern Extension, commissioned the development of a three-dimensional numerical model balancing the circulation of groundwater and surface water in the repository and foreground. The model covers an area of 154.8 km² and is discretized with a grid of variable dimensions from 25x25 m to 100x100 m [12]. As a result of the analyses, it was found that the expansion of TSF will cause a slight progression of the area of influence of technological waters, without a significant threat to the environment [13], however, methods of its further reduction are still being sought. An example of such activities is the project "Development of an innovative technology for limiting the migration of saline groundwater to surface watercourses in the area of the Tailings Storage Facility (TSF) Żelazny Most" financed by KGHM and the National Center for Research and Development. Currently, the first phase of the project has been completed, in which, among others, feasibility study, evaluation of activities carried out until 2017, series of meteorological, hydrological, hydrogeological and geological surveys were completed. The obtained data will be used in the second stage of the task to develop a three-dimensional, multi-layer model of groundwater and pollution movement. The model will be used to test new installations limiting infiltration from TSF [4].

4. Protection of air quality - reduction of dust emissions

Mine tailings storage with tailings of fine particles have a significant tendency to dusting, i.e. entrainment of the smallest fractions by the wind [13]. KGHM’s experience shows that the wind speed above 10 m s\(^{-1}\) and the lack of precipitation create a high probability of dusting. Meteorological forecasts are monitored in order to conduct effective measures to protect TSF against emission. In the event of expected unfavorable weather conditions, KGHM intensifies the activities of the multi-level anti-dusting protection system for the facility developed over 40 years of operation, consisting of:

- maintenance of the crest geometry
- sowing downstream slope of the dams
- spraying beach with film-forming agents
- water curtains
- wetted beaches.
The TSF dam rises from 2 to 4.5 m above the water level in the pond. The appearance of any hole between the sand of the scattered pipeline causes air to penetrate under the pipe, where there is a rapid acceleration and avalanche entrainment of even large particles that would not normally be exposed to wind. Due to the destructive effect of wind on the crest, any damage is repaired on an ongoing basis. The upstream technology used means that the downstream slope, once built, is not subject to later changes. It is preferred technology to use permanent protection against both air and rain erosion by covering the tailings with sand followed by hydro-seeding or turfing.

Due to the most common wind directions, selected sections with a high risk are stabilized with film-forming agents during the periods of leaving to dry and consolidate. Originally, an asphalt emulsion was used for this purpose, applied from tracked vehicles and a helicopter. The protection in this technology lasted about 8 to 12 weeks and after this period, the solar radiation destroyed the stabilization structure. The asphalt emulsion formed a dense coating on the beach and it was destroyed by sudden separation of the stabilization sheets. For this reason, KGHM launched a program to search for more effective coatings [14].

The following coatings were tested: polymer-cellulose (lower durability), based on hydrated lime (lower durability and higher costs), and various types of polymer. Eventually, asphalt stabilizers were replaced by polymer emulsions with the addition of the dye shown in Figure 4. The change is due to full biodegradability, water solubility (which facilitates machine maintenance) and less storage requirements (no need to heat the tanks with emulsion). Due to the shape of the beach and the crest, the air stream carrying entrained fine particles moves low (approx. 1 m) over the pipeline. This observation was used by KGHM employees to develop a proprietary water curtain solution [14]. The installation is made of HDPE pipes with drilled holes and sprays the water mist to a height of about 1.5 m.

The small openings point towards the TSF pond, which is designed to counteract the force of the air stream. The solution originally used in selected sections of the eastern dam was also installed in the west of the facility due to its high efficiency in reducing dust emissions beyond TSF. The disadvantage of this solution is the deposition of beach-borne particles on the crest, which may need to be removed. The operation of the solution is presented in Figure 5.

![Figure 4. TSF beach protected with a polymer layer](image1)

![Figure 5. Water curtain during operation without dusting](image2)

The dry section on which the dusting process begins can be prevented from dusting by starting rinsing and wetting the fine particles. The TSF operation manual allows for temporary wetting of the section with waste for up to 3 days [3]. At the same time, up to 4 sections can be protected in this way, but this method of stabilization is temporary.

A wide range of methods of reducing dust emissions from TSF is designed to reduce the nuisance for the inhabitants of the nearest towns. KGHM implements a policy of full transparency by providing current results of dustiness measurements for the local population. In Tarnówek and Rudna, boards (figure 6) displaying selected air parameters in the localities were installed.
Figure 6. The current air parameters in the village of Tarnówek (first row on the left: date, on the right: time, second row: PM10, third row: wind speed, fourth row: air temperature, fifth row: air humidity).

5. Innovations increasing the reliability of the installation

TSF Żelazny Most could not function without extensive hydrotransport and technological water networks. Although both installations operate in difficult conditions of high water salinity and local mining damage, they definitely differ in terms of the dominant destructive processes. The hydrotransport installation sends flotation tailings from the ore enrichment plants to TSF. The main factor that degrades pipelines is abrasion caused by slurry particles. As a result of the crushing and grinding processes, particles with significant edge sharpness are formed, which increases the destructive effect on the pipes. In sections made of steel, a material loss of 1-3 mm is observed annually, mainly in the field part of the cross-section. This results in a short service life of the pipelines and the need for costly replacements. In the process of water installation, it is most exposed to various types of corrosion. In order to rationalize material management in pipelines, KGHM uses many solutions to reduce operating costs, including:

- systematic pipeline thickness measurements,
- rotation of pipelines,
- replacement of sensitive sections with pipelines with lining,
- construction of new pipelines with wear-resistant linings.

Pipeline thickness measurements are performed in each department that deals with pipeline networks. The basic method of non-destructive testing of pipe thickness is the use of ultrasonic thickness gauges, mainly Olympus 38DL PLUS. Before the measurement, the surface layer of the pipe is cleaned and the thickness gauge is calibrated. Pipelines are cross-section tested at the beginning and end of each pipe section, typically 8 m long. The basic measurement of cross-section consists of 8 points. Additional measurements are made on expansion joints and around the bends. The zone of greatest abrasion is located in the lower part of the pipe with the flow through full cross-section, and at the border of the bottom sediment layer, using only part of the cross-section. The distribution of measurement points and zones of increased abrasion is shown in figure 7. The pipeline inspection is documented in paper form, indicating the areas requiring observation and intervention. The required thickness and parameters of the zones depend on the working pressure of the pipelines and the consequences of a potential failure.
The measurement results are also recorded by the thickness gauge and periodically downloaded to the database.

**Figure 7.** Pipe cross-section with marked thickness measurement points (a) and areas of increased abrasion at full (b) and partial (c) flow.

On the basis of the measurement results, the pipe sections are rotated in zones with high wear. The angle of rotation is selected so that the most abrasive part of the cross-section is in the zone of lower exposure. Typically, the angle of rotation is from 120 to 180 °. The process requires cutting pipes for approx. 25 m sections, engaging 2 cranes and reassembling. Pipelines that have been turned twice before or whose wall thickness is less than the limit for a given section are designated for replacement.

Particularly prone to abrasion pipeline sections such as discharge manifolds in pumping stations, bends and tees are protected with a cement-based abrasion resistant lining from Densit. The application requires fixing the reinforcing mesh on the inner surface of the reinforced material, preparing the lining in a concrete mixer and applying a smooth layer, several centimeters long with a construction trowel. After the drying period, the element is ready for installation. The disadvantage of the previously made prefabricated elements is the necessity to enter the pipeline in order to fill in the gaps in the lining left for joints by welding.

The pipelines produced as part of the investment are built on the experience of the full-scale test program. The suitability of the material for installation in networks is tested by incorporating a 20 m long section into the existing pipeline, including several connections. The test section is periodically inspected for any wear sight. Usually, the weakest element of the pipelines tested are the pipe connections. Currently, the tests have been positive for HDPE pipes, ductile iron pipes with linings, and linings made of: Densit, cement mixtures, poured and spray polyurethanes. So far, about 60 km of HDPE pipelines and 4 km of lining have been built. The use of abrasion-resistant materials significantly reduced the failure rate of the network and reduced the need for time-consuming and cost-intensive pipeline rotation operations.

**6. Summary**

TSF Żelazny Most is one of the largest mining waste landfills in the world and is located close to human settlements and wildlife. Numerical tests and analyses indicate a slight impact of TSF on the natural environment. KGHM implements a policy of corporate social responsibility through consultations with local communities and a number of activities reducing the impact of TSF. Hydrogeological monitoring increases the number of tests that are used to validate the numerical seepage model. Analyses and research show the effectiveness of the adopted solutions. Protection of air quality through the development of technologies limiting the emission of fine particles is carried out in full transparency for local residents who have the opportunity to view the measurement results on information boards. KGHM implements a pipeline condition monitoring program based on wall thickness measurements. Worn pre-
emptive sections are turned or replaced. Modernized pipelines are made with the use of abrasion-resistant materials that have been previously tested. Currently, over 60 km of installations have been modernized, mainly using HDPE. The costly monitoring and modernization of installations undertaken by KGHM are aimed at running the TSF with the least possible impact on the natural environment.

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