Monitoring of the Extent of Surface Waters of an Inactive Post-Flotation Reservoir as an Element of its Safety Assessment

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Abstract

The post-flotation tailings yard is one of the important elements in the copper production process. An inseparable element of the operation of the landfill is closely related to it, systematically conducted research and control observations. These are mainly geodetic measurements of the embankment deformation and the surface of the land in the foreground of the landfill, hydrological observations of water levels in the embankment body and its close foreground. The article presents the methods and results of geodetic monitoring of the now closed "Gilów" mining waste dump and the technologies used in monitoring the extent of the overlying floodplain.

Keywords: *geodetic monitoring, measurements of the extent of the floodplain, facilities for the disposal of mining waste, mining waste*

1. Introduction

Hydrotechnical objects are an interesting field of experiments for surveyors. Predicting the influence of various factors on the behavior of dams, accompanying objects, ground and near foreground helps to develop the necessary and economic justification of the scope of geodetic observations [5]. Due to the variety of objects being the subject of research, it is necessary to use various geodetic technologies. In addition to careful and quick measurements of the deformation of the object, care should be taken to prepare appropriate numerical and graphic material that will suggestively show specialists from other fields what is happening with objects observed using geodetic methods. This material is also intended to indicate the benefits of modern geodetic technologies as well as the scope of their use in solving, for example, safety problems of hydrotechnical facilities, especially those located in mining areas [6].

2. Tailings and their disposal

Copper ore supplied from the mines of KGHM Polska Miedź SA is enriched in the flotation process at the installations of the Ore Enrichment Plant Branch located in the Lubin, Polkowice and Rudna regions. The level of mineralization of Polish copper ores, which does not exceed 2%, means that in the processes of their enrichment, about 94% of the extracted mass is separated as waste. This means that with the current extraction of approximately 32 million Mg/year, up to 30 million Mg of flotation waste is generated.

The tailings from the flotation process are finely ground gangue containing trace amounts of ore-bearing minerals. The basic components of the waste are quartz, dolomite, calcite and kaolinite. The waste from the Polkowice mine is dominated by carbonate rocks (mainly dolomite), and the waste from the Lubin and Rudna mines is dominated by sandstone. Differences in the composition of flotation tailings from individual enrichment plants result from different proportions of these minerals in the processed ore. In addition to the basic components, the waste contains small amounts of metal compounds and organic carbon in the form of bituminous compounds in mineralized shale rocks. Metals in flotation tailings occur in the form of compounds that are sparingly soluble in water, generally in the form of sulphides, sulphur salts, arsenides, and noble metals, partly also in native form.

A characteristic feature of the ores extracted and processed in the LGOM enrichment plants is the alkaline nature of the gangue, resulting from the presence of dolomite and calcite. The presence of carbonate minerals prevents the acidification of the environment and the oxidation of sulfides, and thus prevents the leaching of metals from waste both during ore processing and during transport. The specific nature of the LGOM deposit means that in the case of flotation tailings produced here, there is no risk of generating acid effluents, which are the main nuisance in the management of tailings from the enrichment of sulphide ores from other deposits. Due to the method of enrichment, the waste is in the form of a passable sludge, in which the bulk of the mass is a fraction with a grain diameter below 0.75 mm, and the size of the solid particles generally does not exceed 2 mm. [1]

3. Description of the Gilów tailings storage facility

The "Gilów" landfill put into operation in 1968 was located in the vicinity of the mining area of the Lubin Mine, on the slope of flat hills. It is limited by an embankment with a length of 6.76 km (Fig. 1). The body of the embankment (Fig. 2), which reached the elevation of 179 m above sea level, forms an arch line running from east to west, with its convexity facing south. The maximum height of the embankment is 22 m, the width in the crest is 4 m, and the maximum width in the base is 97 m.

The internal slope has a slope of 1:2 and is covered with concrete slabs 15 cm thick, and the external slope has a slope of 1:2 to 1:2.25 and is covered with grass. The drainage system of the embankment is a triangular gravel heap near the escarpment.

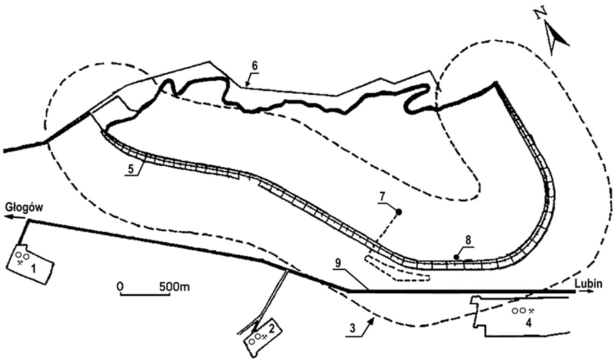

Fig. 1. A situational sketch of the "Gilów" landfill: 1. shaft PW; 2. shaft LZ; 3. boundary of the embankment of the protective pillar; 4. shaft LG; 5. pipeline distributing waste along the embankment; 6. pipeline distributing waste along the flood axis; 7. overflow tower No. 2; 8. overflow tower No. 1; 9. return water pipeline[2]

Rys. 1. Szkic sytuacyjny składowiska „Gilów": 1. szyb PW; 2. szyb LZ; 3. granica obwałowania filara ochronnego; 4. szyb LG; 5. rurociąg rozprowadzający odpad y wzdłuż obwałowania; 6. rurociąg rozprowadzający odpad y wzdłuż osi zalewu; 7. wieża przelewowa nr 2; 8. wieża przelewowa nr 1; 9. rurociąg wody zwrotnej[2]

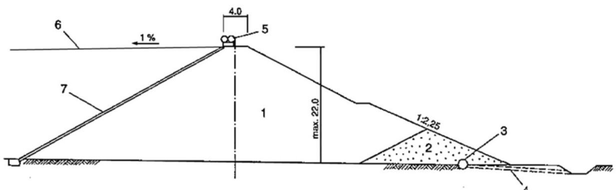

Fig. 2. Section of the embankment of the "Gilów" landfill: 1. mechanically compacted medium and fine sands; 2. partnership; 3. drainage; 4. concrete pipes; 5. distribution pipelines; 6. beach; 7. concrete slabs 6 x 6 m x 15 cm on lean concrete [2]

Rys. 2. Przekrój obwałowania składowiska „Gilów": 1.piaski średnie i drobne zagęszczone mechanicznie; 2. pospółka; 3. drenaż; 4. rury betonowe; 5. rurociągi rozprowadzające; 6. plaża; 7. płyty betonowe 6 x 6 m; gr. 15 cm na chudym betonie [2]

The body of the embankment was built of medium and coarse sand transported from the deposit. Its total cubic capacity is approximately 3.7 million m³. The area of the floodplain assuming the height of waste depositing is 176 m above sea level. was 5.4 km². In this case, the target capacity of the landfill was 51.7 million m³.

The bedrock of the landfill is made up of fluvioglacial sediments in the form of sands, gravels and clays of varying thickness from 30 to 50 m, resting on a layer of several dozen meters of Pliocene clays, which is the top of the Tertiary. Generally, the thickness of the Quaternary and Tertiary formations is about 300 m. Beneath it, there are Variegated Sandstones and Zechstein formations. Groundwater of the Quaternary level, fed by precipitation and infiltration from the landfill, has a runoff direction perpendicular to the embankment.

The reservoir is bounded by the ridge of the Trzebnica Hills from the north, and by an earth dam from the other sides. An earth dam (crown elevation +179.0 m above sea level) with a length of about 6.7 km and a maximum height of 22 m, it is shaped in the form of a strongly bent arch with its convex side facing south. The dam consists of two wings, the eastern one with the N-S course, approximately 2 km long and the western one with the SE-NW course, approximately 5 km long. The width of the crown, which also serves as a road to service the tank, is 4 m, and the width of the shelf is 2 m (Fig. 1). The dam is equipped with a drainage system. Through this system, water from the dam is discharged into the ring ditch. The overflow tower, located in the central part of the reservoir, rises to a height of +185m above sea level. The pipes that discharge water from the spillway tower are protected by a channel called a gallery. This channel has a segmental structure.

In order to deliver the waste to the landfill and to drain the supernatant water, the following devices were built (Fig. 1):

1. steel pipelines with a diameter of 500 mm, one running along the embankment crest and the other running along the flood line, for the discharge of waste,'
2. steel pipelines with a diameter of 1000 mm, running from the overflow tower No. 1 and No. 2 to the pumping station within the tunnel landfill, used for the discharge of supernatant water,
3. reinforced concrete overflow towers, one of which is located by the embankment in its southern part, and the other is located in the central part of the landfill, 500 m from the embankment.

In the first phase of operation of the landfill, the discharge of all waste produced in mining plants was carried out by the method of horizontal spreading from special open channels, arranged diagonally with an appropriate slope on the inner slope of the embankment. The channels were equipped with outlets that opened as the sediment level rose. A layer of water was kept above the settlements, the maximum depth of which was limited to 2.0 m.[2]

In the light of the consequences of the "Iwiny" landfill disaster, it was decided to ensure greater safety of the "Gilów" landfill. For this purpose, the method of waste storage was changed, consisting in moving the overlying water away from the embankment. This effect was achieved by discharge of waste onto the inner embankment with the use of terminals installed at 20 m intervals in the distribution pipeline running along the top of the embankment. This way of distributing the waste led to the deposition of coarser fractions at the embankment and finer fractions as they moved away from the discharge points.

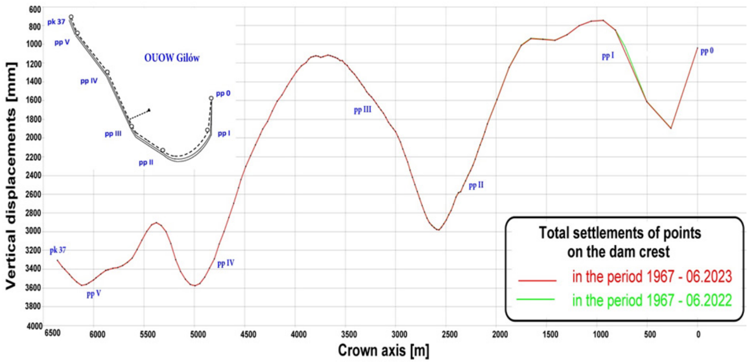

Fig. 3. Total settlements of points on the dam crest
Rys. 3. Całkowite osiadania punktów kontrolnych na koronie zapory

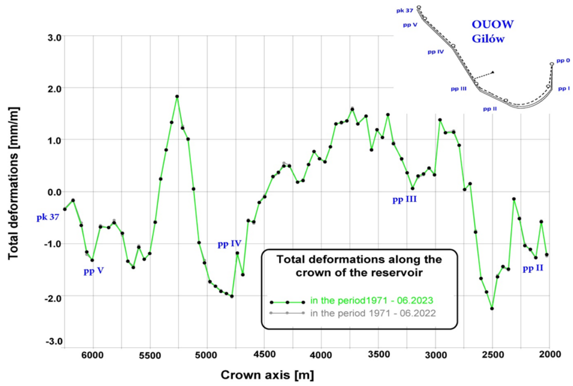

Fig. 4. Total deformations along the crown of the reservoir
Rys. 4. Całkowite odkształcenia poziome wzdłuż korony zapory zbiornika

The introduction of these changes was preceded by an attempt at the so-called "Mały Gilów", an experimental landfill built at that time in the eastern part of the "Gilów" landfill, [3]. As a result of these studies, data were obtained on the process of precipitation segregation depending on the different location of the overlying water discharge sites, as well as data on the possibility of sealing the bottom of the landfill with waste. It should be noted that the originally used waste discharge system caused flooding of the areas on the outside of the embankment, reaching the Lubin - Zielona Góra provincial road. This problem was eliminated after changing the waste discharge system by sealing the bottom of the landfill. Practically, the groundwater has decreased to its original state before the construction of the landfill.

Due to the production of two types of waste, i.e. sandstone and carbonate, significantly different in grain size composition, the next step towards ensuring greater safety of the landfill was their independent depositing. Sandstone waste, characterized by a coarser grain size and a greater degree of different grain size, was dumped from the embankment. On the other hand, carbonate waste, characterized by a finer grain size and a lower degree of heterogeneity, was discharged from the landfill flooding line (Fig. 1). In this way, it was beneficial from the point of view of maximum filling of the landfill and its safety, closing in the so-called ring.

The overlying water was continuously brought to the ore enrichment plants, and its periodic excess was temporarily discharged into the Oder River. Both overflow towers and pipelines, which ran in tunnels within the landfill, were used for this purpose. Tower No. 1 was operated only in the period when the discharge of waste was carried out from open channels, i.e. when water retention occurred at the embankment. When the method of discharge was changed, which resulted in the removal of the overlying basin, the collection of water was carried out with tower no. 2.

Another operational condition was the introduction of the principle of permanent maintenance of the sediment beach at the embankment with a width equal to or greater than 100 m [5].

4. Mining exploitation in the protection pillar of the Gilów tailings storage facility

The condition of maintaining the appropriate width of the sediment beach was related to the permit issued in 1975 for the mining of copper ore with roof caving directly under the landfill and in the embankment protective pillar, which has been carried out until now. It should be emphasized that this was possible thanks to the changes introduced in the method of depositing waste.

Despite the continuous exploitation of the deposit in the protective pillar, the height of depositing waste in the "Gilów" landfill was increased twice, up to the height of the embankment crown with the permissible ordinate of damming up the supernatant water at 177.5 m above sea level. As a result, approximately 68 million m³ of waste was eventually deposited in the landfill on an area of 5.7 km².

The "Gilów" landfill, after reaching the permissible water damming level in June 1980, served only as an emergency retention reservoir for the discharge of excess water from the neighboring, active "Żelazny Most" landfill and water intake for

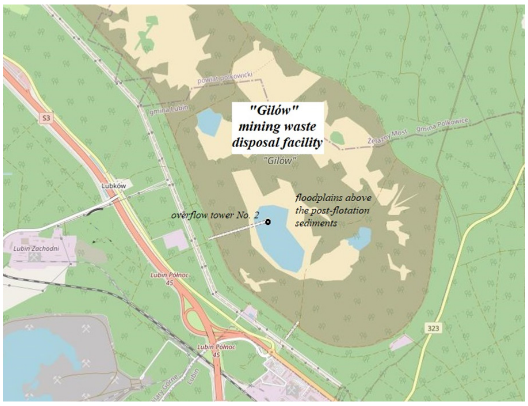

Fig. 5. Map of the location of floodplains above the post-flotation sediments
Rys. 5. Mapa lokalizacji terenów zalewowych nad osadami poflotacyjnymi

mechanical processing of the ore. The water level has been systematically lowered since 1980. The depth and size of the basin made it possible to keep the overflow tower in continuous operational efficiency. The observed phenomenon of meandering of the overlying basin was mainly related to surface depressions as a result of the exploitation of the protective pillar. The width of the beach along the entire embankment was always greater than the minimum allowable width of 100 m.

Due to the significant reduction of the basin, from mid-1989, overflow tower no. 2 ceased to operate automatically. If the basin periodically came closer than 100 m to the embankment, water was pumped out to the overflow tower, draining the water outside the landfill by gravity by means of a return water pipeline.

5. Geodetic monitoring of the Gilów tailings storage facility.

An inseparable element of the operation of the landfill was closely related to it, systematically conducted research and control observations. These were mainly geodetic measurements of the deformation of the embankment and the surface of the land in the foreground of the landfill, hydrogeological observations of water levels in the embankment body and its close foreground, and water flows in the ditch, as well as groundwater chemistry. Photogrammetric measurements of the landfill and meteorological observations were also carried out. Field geotechnical laboratory tests of sediments within the beach area were carried out on an ad hoc basis.

Geodetic stability studies of the over 6 km long dam limiting the reservoir from the south and east, as well as its close foreground and engineering facilities in its vicinity, were based on a geodetic monitoring project developed in the 1970s, consisting of the following control measurements: [4]

- the basic horizontal control network (currently determined by the GNNS satellite technology) consisting of 9 points (of which 6 are located on the dam crest),
- detailed control network in the form of polygon sequences developed between the points of the basic control network on the crown,
- high-altitude network, including benchmarks located on the dam crest, on the ledge, at the foot of the dam and in the close foreground, as well as benchmarks located on the "Gilów" supernatant water pumping station,
- deformations on selected sections along the crown and in cross-sections extending to its close foreground,
- a line of technical leveling with increased accuracy between benchmarks stabilized in the gallery to the overflow tower.

The lowering of the dam of the "Gilów" sedimentary pond in LGOM is an example of the overlapping of various factors influencing the lowering of the mining area [6]. These are:

- compression of the dam body due to compaction of the fill material, from which the dam is built;
- subsidence of the dam base due to the weight of the dam body;
- subsidence of the pond base together with the dam due to the pressure of deposited exploitation waste;
- large-area depressions caused by dehydration of the rock mass caused by underground exploitation;
- direct impact of the deposit exploitation on the dam and the pond.

On this object, in order to obtain parameters describing the deformations of the dam, observations are made all the time in annual intervals, including: GPS measurements, field measurements with the use of high-precision electronic total stations, leveling measurements of the crown, shelves and foot of the dam, and deformation measurements.

On the basis of the test results and control observations, periodic assessments of the embankment condition and assessment of the safety margin from the point of view of slip stability of external slopes are made. This procedure became necessary when the exploitation of the copper ore deposit in the embankment's protective pillar was introduced. Additionally, the so-called periodical confrontation of space-time forecasts of embankment deformations with the results of observations of actual deformations [2]. The forecast of deformations is updated each time, as the directions and locations of the current exploitation of the copper ore deposit change.

The surface of the landfill sediment beach was recultivated by afforestation of a large area. At the same time, all devices related to the hydrotransport of waste were liquidated.

The measurements from June 2023 show that the crown of the embankment has been lowered, reaching ordinates from 178.0 to 175.3 m above sea level. compared to the original elevation of 179 m a.s.l. (Fig.3)

Fig. 6. Photo of the disused overflow tower No. 2
Rys. 6. Zdjęcie nieczynnej wieży przelewowej nr 2

Fig. 7. Photo of the floodplain in the sediments of the Gilów mining waste disposal facility
Rys. 7. Zdjęcie powierzchni zalewowej w osadach obiektu unieszkodliwiania odpadów wydobywczych Gilów

Fig. 8. Photo of the shoreline of the floodplain in the settlements of the Gilów mining waste disposal facility
Rys. 8. Zdjęcie linii brzegowej zalewiska osadnika w obiekcie unieszkodliwiania odpadów wydobywczych Gilów

The horizontal deformations of the control sections, which are located on the section of the dam from 2500 m to its end, have been determined since 1973. They range between -2.25 mm/m in the vicinity of 2500 m (and this is the highest value of compressive deformations along the dam crest, slightly higher than the value found in previous observation periods) and +1.59 mm/m on the section of 3800 m (Fig.4) and do not pose any threat to this type of engineering structure what is an earth dam.

6. Studies of the extent of surface waters

Indirect impacts of mining exploitation are a wide group of often very complex geomechanical and hydrological phenomena occurring both in the rock mass and on the surface of the terrain. They can occur under the influence of: dewatering of the rock mass, transformations of the relief resulting from direct influences, mining seismic tremors [7]. Among the more important indirect effects of underground mining, the following should be mentioned:

1. Disturbance of water balance and loss of groundwater resources and degradation of drinking water quality.
2. Deformations of the land surface as a result of mining drainage. Among them, there are continuous deformations, resulting from the consolidation of the drained soil, and discontinuous deformations, related to the development of the suffosion process (suffosion funnels).
3. Degradation of agricultural and forest land as a result of lowering the groundwater table.
4. Flooding and swamps of the area and the formation of permanent or temporary floodplains.

They may form within the subsidence basin as a result of the relative lifting of the groundwater table, as a result of the formation of cesspools and a change in the direction of surface runoff, or as a result of deformation of watercourses, which prevents the gravitational discharge of their waters. In this way, agricultural and forest land is lost or the conditions for plant vegetation deteriorate. In addition, the geological and engineering properties of construction soils undergo negative changes [8].

In the case of post-flotation tanks, there is an additional concern that under the influence of mining activities, sediments may liquefy within the beach area.

Land flooding and the formation of permanent or temporary floodplains can also be caused by precipitation, especially in the situation of impermeable ground and lack of outflow.

Monitoring of the range of floodplains can be carried out using classic geodetic techniques, such as tacheometric me-

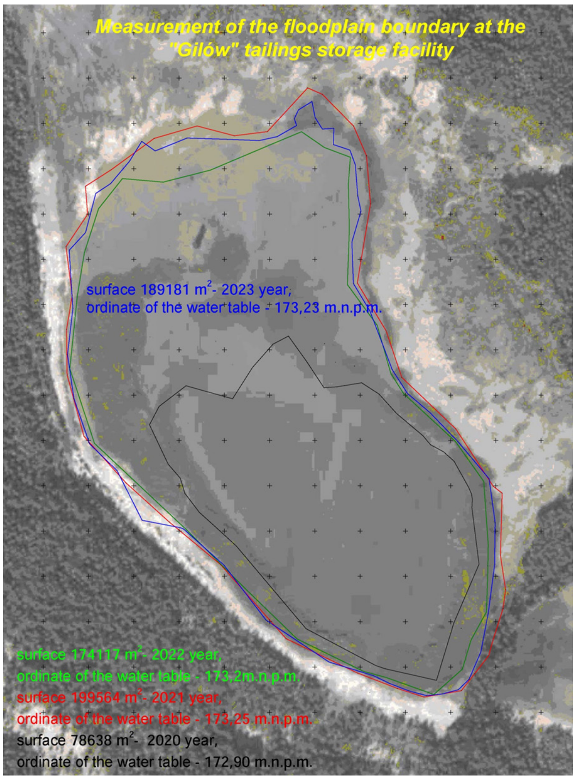

Fig. 9. Measurement of the floodplain boundary at the "Gilów" tailings storage facility
Rys. 9. Pomiar granicy powierzchni zalewowej na terenie składowiska odpadów wydobywczych „Gilów"

asurements (determination of coordinates of selected points based on the measurement of the angle and length) or satellite RTN (Real Time Network). The RTN method is one of the real-time satellite measurement methods. It uses surface corrections calculated on the basis of a network of physical reference stations (Continuously Operating Reference Stations – CORS) and virtual reference stations (VRS) generated by the computational algorithm.[12] It is also possible to use photogrammetric or remote sensing methods for monitoring floodplains using UAS - Unmanned Aircraft Systems. These are modern technologies effectively used in the preparation of maps, research of engineering structures or land surfaces, [13]. Unmanned ships serve as carriers for scanning devices, cameras and video cameras. They are an important element of aerial photogrammetry – methods of data acquisition using photographic equipment to generate orthophotos, topographic maps or 3D terrain models [14]. The effectiveness of the use of unmanned systems has significantly increased by equipping them with navigation technologies – a global navigation satellite system (GNSS) or an inertial navigation system (INS).

One of the elements of the deformation study of the Gilów tailings storage facility are site and height measurements to determine the extent of the floodplain around the inactive tower No. 2 (Fig. 5 and Fig. 6). From the methods of measuring the floodplain presented above, the RTN satellite technology was selected using the Topcon Hiper V receiver. Photos of the floodplain were also taken using a camera placed on an unmanned aerial vehicle - a multirotor (fig. 6, 7, 8) for documentation purposes.

Based on the measurements, the range of the floodplain and the average height of the water table were determined. Figure 9 summarizes the results from June 2020 to June 2023 (Fig. 9).

The average height of the water table reached its highest height in June 2021 and amounted to 173.25 m. In June 2023 it slightly decreased to 173.23 m (Fig.9). The lowest value was recorded during measurements in June 2020 and it was 172.90 m. Along with the increase in the height of the water table, the area of the floodplain increases from 78 thousand. m^2 in 2020 to 199,000 m^2 in 2021. In June 2023, the area of the floodplain is approximately 189,000 m^2. Analyzing changes in the area of the floodplain in comparison with the data of the Polish Institute of Meteorology and Water Management – National Research Institute, one can see correlations between the annual sums of precipitation in the vicinity of Lubin and the size of the floodplain. In 2019, the sum of precipitation was about 500 mm and in the following year, 2020, it was over 600 mm. The greatest rainfall was recorded in 2021, about 750 mm, which in the following year, 2022, amounted to 650 mm. In the vicinity of the Gilów. Reservoir, the highest rainfall occurs in June-July and on average it is about 80 mm/month.

7. Summary

During the entire period of mining exploitation, no threat to the embankment stability was observed in the embankment protective pillar, both in the phase of waste depositing, retention of mine water and landfill reclamation, despite the recorded lowering of the embankment crown of 3.58 m and the continuous movement of stretching zones in the embankment body along with the change of deposit exploitation fronts [3]. Moreover, the locally increasing intensity of paraseismic vibrations did not cause any traces of sediment liquefaction within the beach.

The currently used technology of testing the deformation of the dam and its foreground, based on the use of the most modern equipment, guarantees proper accuracy and unambiguous interpretation of the results. The basic network is still made up of points determined by GPS technology, although access to locations with a horizon suitable for satellite measurement is becoming more and more difficult.

The influence of the impacts caused by the drainage of the tertiary strata of the orogen by the Lubin O/ZG on the dam and its foreground remains at the level of the previous observation periods. Currently, periodic depressions caused by this phenomenon for the dam area are in the range of 4 to 6 millimeters. Changes caused by seasonality and, in particular, different amounts of precipitation in the pre-measurement period should be added to the picture of changes found annually.

The changes (total values of deformation indexes) found so far, which the dam has experienced against the background of the mining exploitation in its protective pillar, should be assessed as correct, and their course so far as regular and consistent with the results of the preliminary forecasts that have been carried out (within the accuracy limits of these forecasts).

Monitoring the extent of the floodplain and its impact on sediment liquefaction requires correlation of the measurements made with meteorological data for this region, which allows for rationally conducting safety analyzes of the sediment liquefaction status.

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Monitoring zasięgu wód powierzchniowych nieczynnego zbiornika poflotacyjnego jako element oceny jego bezpieczeństwa

Składowisko odpadów poflotacyjnych stanowi jeden z ważnych elementów w procesie produkcji miedzi. Nieodłącznym elementem eksploatacji składowiska jest ściśle z nią związane, prowadzone systematycznie badania i obserwacje kontrolne. Głównie są to geodezyjne pomiary deformacji obwałowań i powierzchni terenu na przedpolu składowiska, hydrologiczne obserwacje stanów wód w korpusie obwałowania i bliskim jego przedpolu. W artykule przedstawiono metody i wyniki monitoringu geodezyjnego nieczynnego już składowiska odpadów wydobywczych Gilów oraz technologie stosowane w monitorowaniu zasięgu zalewiska nadosadowego.

Słowa kluczowe: *monitoring geodezyjny, pomiary zasięgu zalewiska, obiekty unieszkodliwiania odpadów wydobywczych, odpady wydobywcze*