

Assessment of deformations in post-flotation earth dams of hydro-technical facilities exposed to the influence of underground mining activities

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Abstract

The energy crisis translates into the profitability of production, which requires the optimization of production processes in the mining industry. One of them is the optimization of the storage process and ensuring the safety of post-flotation waste. Large-scale objects are often artificially raised above the ground and consist of barriers separating the deposited material from the environment. Safe earth dams are a key element of the production cycle of mining plants. Due to the continuous development and deformation processes of the dam body over many years, geotechnical (also geodetic) monitoring is important. Underground mining activity (causing stress disturbances in the rock mass) increases the risk of excessive deformation of the body, which may lead to disruption of the dam's continuity and a disaster. Cyclical geodetic observations are carried out before the start of construction in order to determine the deformations of earth dams and accompanying structures, as well as during operation in order to determine the current spatial shapes, surfaces, and volumes of the structures. This is important for deformation analysis and verification of geotechnical data. The article analyses the deformations of two post-flotation reservoirs, which were additionally subject to the influence of underground mining. The degree of density of the earth dam slopes and the relationship between their vertical and horizontal displacements as a function of time under the influence of mining exploitation were also determined. This will allow the introduction of new technological solutions, increase the precision of forecasting, and more effectively counteract the threats generated by mining activities.

Keywords

safety of earth dams; influences of mining exploitation; geodetic monitoring, spatial stability, slope compression, dynamic instability hazards



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Introduction

Large-area industrial waste landfills are classified as special hydrotechnical facilities due to the need for maintenance of the water table inside the surrounding dams. Their area can be as much as several square kilometres, and their height above the surrounding area can reach up to 100 m. In connection with mining production (for instance, flotation of metal ores), liquefied material is continuously delivered to the landfill, where it is then deposited, and water is filtered out. This implies a constant need to expand and thus change the geometry of these objects, usually limited by earth dams, which are expanded throughout their active operation. Their construction involves preparation of an in-depth environmental impact assessment, starting with geological and geotechnical surveys of the subsoil to determine potential hydraulic flows, prevent uncontrolled outflows and punctures of the dam body, and identify impacts on the microclimate (dust) and methods of protecting slopes by covering with vegetation, and ending with analysis of the effects of object deformation and loss of stability. Hydrotechnical post-industrial waste tanks are most often built with washing technology, where post-industrial waste products (for instance, flotation sludge) also serve as an element of subsequent dam scarps.

Tailings dams are therefore complex earth structures that must take into account the fact that the shear strength of the slopes and the pore pressure inside them generate conditions that are difficult to predict (Martin and McRoberts, 1999). In order to understand the behaviour of flotation sediments, it is necessary to analyse the stability of slopes during shearing and changes in pore pressure, and to determine the probabilities of potential mechanisms triggering the risk of damage (Dezert et al., 2024; Talukdar et al., 2019; Meehan and Vehedifard, 2013; Courivaud et al., 2009; Zhong et al., 2021). To make this possible, the stresses and deformations to which the dams of the facility are subject should be taken into account. However, due to constant changes in shape and masses deposited in the reservoir, such analyses are burdened not only with model errors, but also with uncertainties resulting from outdated input data. For this reason, it is necessary to use real data obtained during in situ measurements (surveying, geotechnical) (Szostak-Chrzanowski et al., 2007; Szostak-Chrzanowski et al., 2006) and laboratory analyses. This is important because it is a strategic choice of technology, which in the case of poorly selected monitoring can result in functional safety (FS) threats or vulnerabilities, raising concerns about facility resilience (Szostak-Chrzanowski et al., 2003).

For this reason, embankment hydrotechnical structures should be checked in terms of EN 1997-2 (Geotechnical Design) (EN 1997-2 Eurocode 7) slope stability, filtration pressure gradients, as well as the amount of settlement (Osugwu, J. C., et al, 2017) of the structure body and subsoil, including the risk of shifting, slipping on the ground and in the ground, and the risk of displacement of weak soil from under the embankment. These safety criteria are related to the geometric assessment of the mutual position of the facility's parts, which is performed both on a macro scale using geodetic and geophysical methods, and on a micro scale using geotechnical monitoring sensors. Geometric assessment of the stability of the object is made on the basis of the development of geodetic studies (Guler et al., 2006) in order to determine so-called deformation indices (Pielok, 2002), which include vertical displacement, horizontal displacement, horizontal deformation, inclination, and radius of curvature.

From the point of view of deformation assessment, reference points that will guarantee the invariance of the reference system should first be established. A geodetic network of fixed points (a situational, height, or spatial network) established outside the unstable region (i.e., that region subject to the influence of mining exploitation) is usually regarded as stable. This means that it does not change in relation to the adopted frame of reference. According to the literature (Pielok and Piwowarski, 1996), the point coordinates of such a network of a static reference field form a vector:

$$X^T = [X_l, Y_l, Z_l, \dots, X_m, Y_m, Z_m] = \text{const} \quad (1)$$

More comprehensive possibilities occur when analyzing the deformation of the field in which changes are caused by the forces acting upon it. In such a case, we are dealing with a dynamic field of reference points, described by the relationship:

$$X_i = X(F_i) = X_0 + \varphi(X, F_i - F_0) \quad (2)$$

where: X_i – coordinate matrix of the field of reference points as a result of the action of the vector of forces F_i , X_0 – coordinate matrix of the field of reference points as a result of the action of the reference force vector F_0 , φ – dynamic modelling function.

As already mentioned, the accuracy requirements for control networks must take into account the purpose of the measurements and can generally be reduced to determining the accuracy of the coordinates of the observation points in order to determine the significance range of the determined movements (Pielok, 2002). The chosen method of performing geodetic measurements, and then their deployment in order to determine the distortions of

the object, will depend on the type of object in question and, therefore, on the geometric elements to be measured, the level of accuracy required, and the terrain on which they are located (Pielok et al., 2011).

Geodetic technologies used in determining the deformation of objects, in the form of field observations, and the development of these observations, evolve along with the development of technology. Currently, surface assessment techniques can be used (aerial photogrammetry, airborne laser scanning, InSAR, remote sensing tests using spectral cameras), as can point assessment techniques based on the designated current spatial coordinates of control points located throughout a facility. Use of these techniques should take into account their level of accuracy. The first type, surface assessment, is of lower accuracy but allows information to be obtained about the entire area covered by the study, which can be considered a quasi-continuous assessment of the object's condition. The second type, the discrete point model, enables the determination of current spatial coordinates to within a single millimetre, allowing us to identify significant changes in displacement above 3÷6 mm. These methods of obtaining information can complement each other thanks to multi-stage analysis, in which initial surface assessment may indicate the need to perform more precise follow-up research based on measurements of controlled points.

The geodetic monitoring project, which is discussed in this study, defines the shape of the geodetic network, the conditions for its continuous expansion, and adaptation to the changing conditions of the stability and expansion of the facility. It also includes a statistical analysis of the accuracy of the determined deformation indices in terms of the geodetic techniques used (Jóźwik et al., 2007). The expansion of the structure also entails expansion of the control network, in which the array of control points includes not only the points of the traditional control network but also a network of benchmarks on accompanying structures, deep benchmarks, and diametrical drainage. An important aspect is the inclusion of inclinometer heads in the discussed network, for which the determined displacements are used to update the displacements of the inclinometer tubes. Very often, the total number of precise geodetic measurements includes several hundred points, the coordinates of which should be determined in the shortest possible time. For this reason, the optimization of the performance of such measurements requires the use of techniques that accelerate the acquisition of overall observations. The introduction of satellite navigation technology (Global Navigation Satellite Systems - GNSS) changes not only the method of determining deformation indicators, but also offers the prospect of significantly increasing the accuracy of XY coordinates. Also of importance are: experience in using technology in solving geodetic issues, learning about the sources of errors (accuracy) that occur in a given technology, possibility of determining the accuracy of coordinates obtained, terrain conditions (requirements for the location of points), structure of the network (its shape), time constraints (related to obtaining information within one observation series), short-term, environmental factors.

Material and Methods

The geodetic monitoring project, which is discussed in this study, defines the shape of the geodetic network, the conditions for its continuous expansion, and adaptation to the changing conditions of the stability and expansion of the facility. It also includes a statistical analysis of the accuracy of the determined deformation indices in terms of the geodetic techniques used (Pielok, 2002; Szostak-Chrzanowski et al., 2006). The expansion of the structure also entails expansion of the control network, in which the array of control points includes not only the points of the traditional control network but also a network of benchmarks on accompanying structures, deep benchmarks, and diametrical drainage. An important aspect is the inclusion of inclinometer heads in the discussed network, for which the determined displacements are used to update the displacements of the inclinometer tubes. Very often, the total number of precise geodetic measurements includes several hundred points, the coordinates of which should be determined in the shortest possible time. For this reason, the optimization of the performance of such measurements requires the use of techniques that accelerate the acquisition of overall observations. Geodetic monitoring of large-area hydrotechnical facilities always requires an individual approach, which will depend on the specific characteristics of a given facility: its spatial and geological location, the type of structure and its interaction with the environment, and potential threats to the environment. Consideration of such factors allows us to carry out a spatial assessment of the current geometry of an object and its substrate, which, together with information about the geomechanical structure of deposited material, enables assessment of interactions and prediction of the object's stability model. Listed below are the most commonly used methods for conducting continuous and periodic tests within so-called geodetic monitoring.

Studied objects and periodical surveying

The article presents deformation analysis of two hydrotechnical objects located in southern Poland. These differ in terms of area, expansion method, and height above the surrounding area, but they represent the same type of mining hydrated tailings tank. They are already closed rather than expanding tanks, but, as during their period of active use, they remain in the impact zone of ongoing or completed underground mining. Due to data

confidentiality concerns, the authors cannot disclose certain sensitive data owned by facility management companies; therefore, the exact locations of the objects in question are not provided here.

Object A

This is the smaller of the two settlement ponds, with a total area of 78 ha, maximum dimensions of 1 km x 0.85 km, and a plateau area of about 20 ha (Figure 1). Due to the shallow mining operation conducted beneath it during its expansion, it is a particularly notable hydrological structure for having maintained its spatial and geotechnical safety since its commencement in 1966. It is an above-level reservoir (settlement pond) with a trapezoidal cross-section, with a target height of up to 60 m above ground level. The total capacity of the reservoir is approximately 38 million Mg, and the expansion of the reservoir was completed in 2009. The present sedimentary pond was created from the expansion of two smaller ponds, exploited in the years 1970–1984. The facility is built mainly of a fine-grained fraction of dolomite material, which is a waste product from the Zn-Pb ore flotation process. The outer part of the pond consists of embankments formed by silting, from the thickest fraction of waste. The internal part of the pond in the bottom part consists of compacted sediments of various granulations, decreasing towards the middle. The outer layer at the top of the pond is composed of the finest fraction, whose consolidation has not yet been completed. The major part of the pond's top was, until recently, a depression filled with overlying water.

The area where the reservoir dams are located is also covered with other anthropogenic formations in the form of mine heaps, railway and road embankments. This area is characterized by diverse morphology (Razowska–Jaworek et al., 2007; Herbich et al., 2003) and complex geological structure (Figure 1), including a fragment of the Triassic carbonate series covered with weathered formations. In addition to outcrops of Triassic (limestones, dolomites) and Carboniferous (sandstones), poorly permeable and insulating formations in the form of loess and deluvial loess, containing dusty and sandy clays and clays, can be distinguished. There are Quaternary formations (water-glacial sands and gravels, silt of valley bottoms, aeolian sands, river sands and silts) and numerous outcrops of older rocks. These include: Jurassic rocky and slab limestones, calcareous marls, glauconitic clays, sandstones, conglomerates; Neogene clays, claystones, mudstones, and sandstones. Despite the average depth to the first aquifer (5–20 m), the number of isolating formations and slopes significantly increased the time of seepage of water infiltrating deep into the aquifer. On the other hand, within the outcrops of Triassic rocks, with gentle slopes, the time of replacement of the field water capacity is shorter. A potential threat to the Quaternary aquifer is leachate water from the tailings reservoir, containing excessive or elevated levels of sulphates, zinc, and lead.

Mining exploitation under the reservoir was carried out about 180–200 m below the surface, the height of the exploited layers reaching as much as 4.5 m. The mine ceased operation in 2009 due to exhaustion of deposits (Figure 2). After the cessation of ore mining in mid-2010, the liquidation of the excavations began by flooding (as a result of switching off the drainage pumps) the dammed parts of the mine. All shafts were fitted with piezometers in order to observe the flooding process. The soil around the reservoir is contaminated with heavy metals (mainly zinc and lead) to the extent that agricultural activity is excluded. Ongoing reclamation of the reservoir, as well as stabilization of the slopes, is carried out by covering the slopes of the landfill with topsoil, planting trees and shrubs, spraying the slopes of the reservoir, and recirculating water from the pond. All of these activities also reduce the emission of dust pollutants on an ongoing basis. Currently, the settler is owned by a private company that has obtained a permit for the extraction and recovery of 380,000 tons of waste.

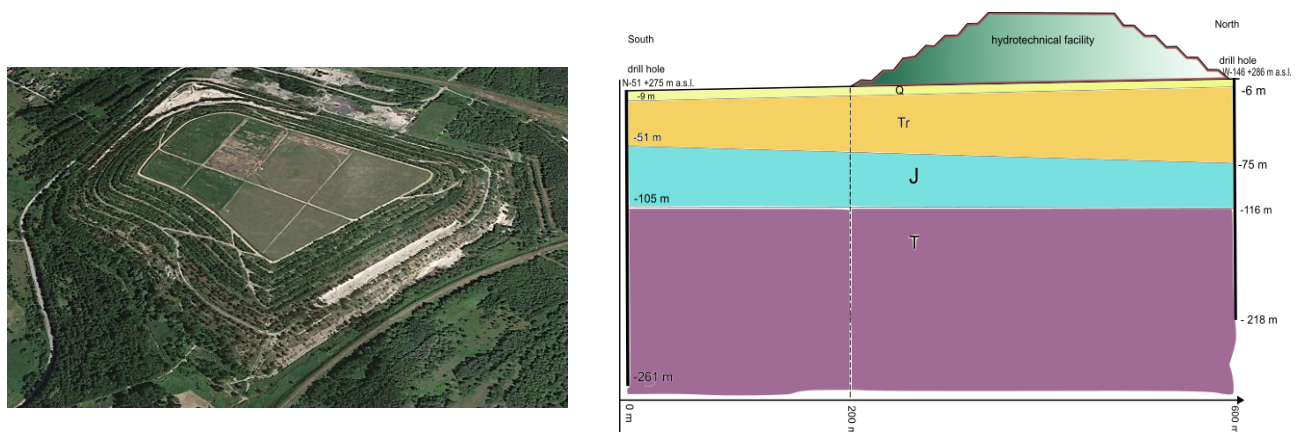


Fig. 1. Left: The Shape of the Object A - earth dam; Right: Geological cross-section. Facility dimensions: 1 km x 0,8 km.

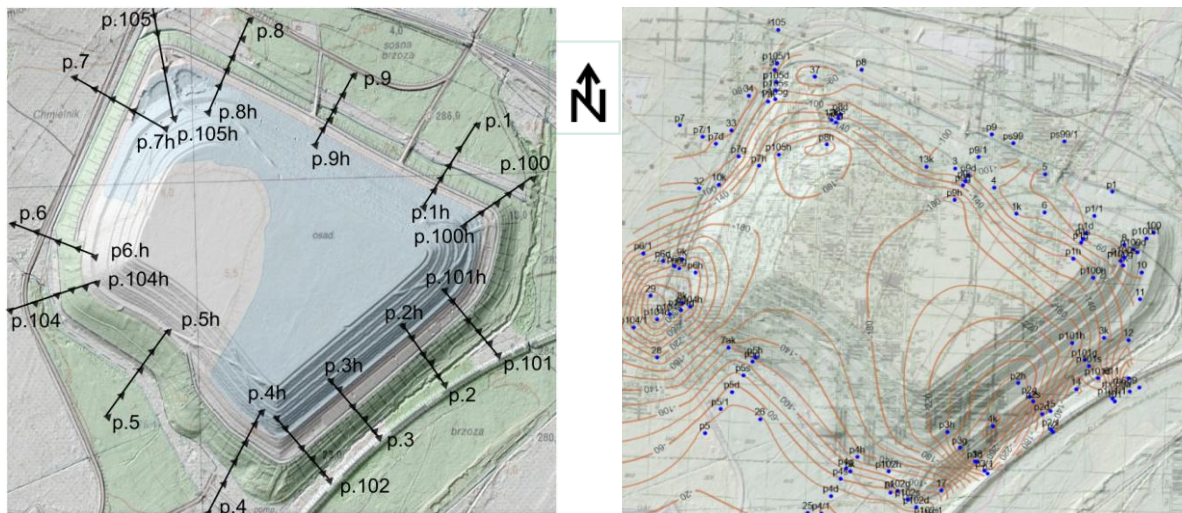


Fig. 2. Left: Location of geodetic control network on ledges and slope profiles; Right: Map of total subsidence isolines (max 300 mm in years 1991 – 2000). The mining area under the reservoir is shown in black: chambers and pillars with hydraulic backfill. Blue dots – the control network.

Object B

This tailings pond is an earthen dam over 6.7 km long with an area of approximately 4.8 km² (480 ha). In the years 1966 to 2000, over 60 million m³ of sediments were deposited in this reservoir. This facility is situated within an established protection pillar in an area that has been subject to mining exploitation since the 1970s and continues to be so. The earth dam (crown elevation +179.0 m above sea level) with a maximum height of 22 m is shaped in the form of a strongly bent arch with the convex side facing south (Figure 3a). The maximum width of the foot of the dam is 97 m, and the width of the crown is 4 m. The upstream slope is secured with a dilated concrete slab, and the downstream slope is secured with grass on a layer of topsoil. The tank was filled by sedimentation on the principle of gravitational fall of suspension particles. The excess of the settled water was transported to the ore processing plant for reuse in the production process or discharged to surface watercourses. Transport activities were carried out using technical devices of the dam, namely overflow towers, galleries, and pumping stations. The dam is equipped with a drainage system in the form of a stone and gravel filter at the base of the dam, through which water from the dam is discharged into a surrounding ditch. The overflow tower, located in the central part of the reservoir, rises to a height of +185m above sea level. Pipes draining water from the overflow tower, as critical elements, are protected by an underground canal (gallery) with a segmental structure. The reservoir was put into operation in 1968, and the deposition of waste was completed in 1980. Due to its location near industrial plants and an expressway, as well as mining operations, the facility is constantly monitored by geodetic and piezometric measurements.

The sedimentation dam is located close to the border of two geological units: the Fore-Sudetic Block and the Fore-Sudetic Monocline, which are separated by the dislocation of the central part of the Oder River, generally NW-SE. The Fore-Sudetic Block is made up of Precambrian and older Paleozoic rocks formed in the form of metamorphic shales as well as granites and granite gneisses. Similar series build a deeper substratum of the Fore-Sudetic Monocline, on which monoclinial sediments of mainly red Sced and Zechstein (sandstones, limestones, dolomites with copper-bearing shales, claystones, anhydrites) and variegated sandstone (arkose sandstones with clay inserts) are monoclinial (Drozdowski et al., 1993, Staško, Malinowska-Pisz, 1997) – Figure 3b. The sub-Cenozoic substratum is cut by numerous faults and eroded. As a result of these processes, the relief of the substrate is varied. Tertiary formations lie on it throughout the area. Tertiary sediments (approx. 150 ÷ 200 m thick) are represented by clays, dusts, sands, gravels, and lignite deposits. They form a poorly diversified sediment complex. The ceiling parts of the Tertiary locally show structural disorders such as erosion washouts (erosion trough) and are glacial in nature. The thickness of the Quaternary ranges from 20 to 60 m. Quaternary formations are formed mainly in the form of sand-gravel sediments, clays, and dusts, stratigraphically represented by the South- and Central Polish glaciations.

Quaternary and Tertiary aquifers, associated with the thicker complex of Cenozoic sediments, and Triassic and Permian aquifers associated with lower sediments of the Fore-Sudetic monocline structural unit can be distinguished here. Studying the quality of the Quaternary usable aquifer, it should be stated that these waters have been degraded. The values of chlorides, sulphates, and dry residues have increased, although the above-mentioned indicators do not exceed the limit values in most cases. The near-surface aquifer is particularly vulnerable to anthropogenic pollution and shows poorer quality than the main levels. The tailings landfill located in the area, where waste and salt mine water of the Cl-Na-SO₄-Ca type have been deposited, poses a significant threat to the

environment. Contaminated water infiltrating into the ground and through dams has seriously threatened the quality of groundwater. Therefore, groundwater from the areas under the post-flotation sediment landfill was excluded from the aquifers used.

Based on geodetic observations (Figure 4) collected over tens of years, subsidence and horizontal deformations specific to the points of the dam crown are determined every year. These observations were, specifically, the spatial coordinates of the control points and the lengths of the control network sides on the dam crest. The first situational and height measurements were made in 1971, and the first length-of-side measurements in 1973. Every year, updated values of deformation indices are determined from measurements, which are then compared to the indices calculated according to the Knothe-Budryk theory (Knothe, 1984), taking into account current data on underground mining. This theory is based on certain relationships between the selected seam space and observed deformations on the ground surface. The exploited space of the seam and existing deformations of the terrain surface are related to a function of influences (Ostrowski, 2015). The data verified in this way were and are the basis for analyses of reservoir slope stability performed using numerical methods by geotechnical services.

Periodic changes in the dam geometry are determined in relation to the period preceding mining exploitation in the protective pillar of the dam. Vertical displacements (depressions), which are at once the most reliable and the most sensitive indicator of deformation, have been determined based on height measurements since 1967, when the initial state of the height control network was determined. The picture of these changes is supplemented by that of horizontal displacements, which were also assessed before mining in the protective pillar of the dam and reservoir.

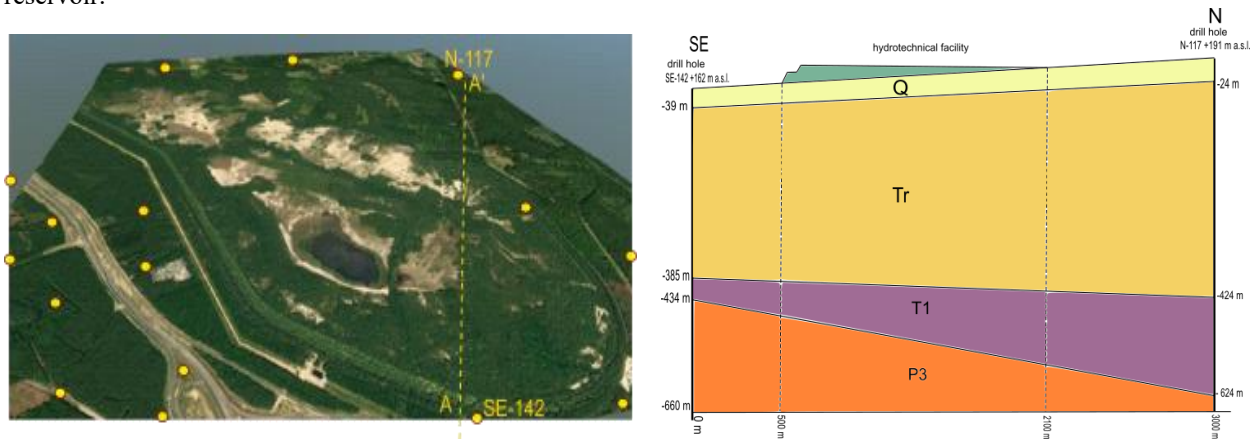


Fig. 3. Left: The shape of the Object B - earth dam with location of research and piezometric wells (yellow points); Right: A geological cross-section A-A'

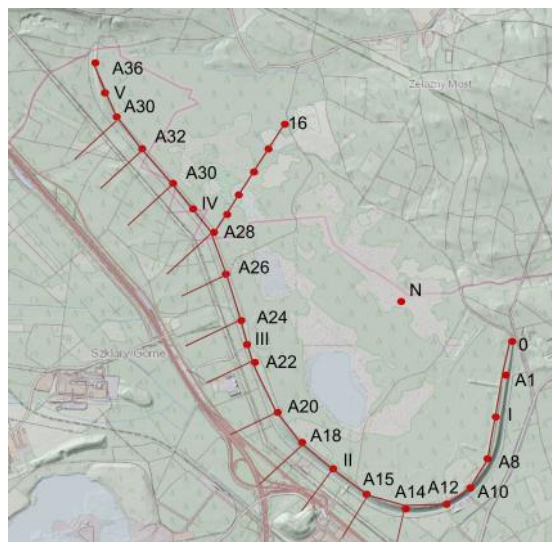


Fig. 4. The Object B dam with location of the main control points in the geodetic network (only the nodal points are shown - the rest are spaced 48 meters apart)

Methods of Surveying

The presented analyses are based on periodically performed geodetic observations, which must be designed to obtain the highest possible level of accuracy. This is related to the differential assessment of the control tests carried out, taking into account the measurement uncertainty of each test cycle. Therefore, the methods described below must always ensure the indicated accuracies.

GNSS technology

The use of Global Navigation Satellite Systems (GNSS) is a basic technology in the observation of the control points of large-area objects. Due to the requirement to determine changes in the spatial position of control points at the level of ± 5 mm (horizontal) and ± 2 mm (vertical), measurements can only be made using the static method, in relation to permanent stations (Figure 5). This means that measurement sessions must be specially prepared (Pluciński et al., 2003), taking into account the availability of satellite signals, obscurations, the number of vectors, the distance to the reference points, and the state of the ionosphere. GNSS monitoring stations can also work in a permanent mode, constituting the basis for continuous geomonitoring, in which they ensure the unambiguity and validity of the adopted spatial reference system. This also allows the assessment of changes in the position of other control points as a function of time.

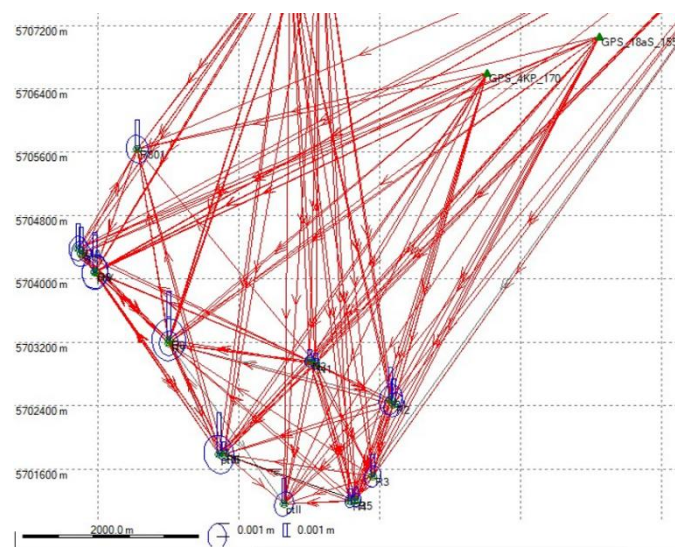


Fig. 5. GNSS vectors and the localization errors (least squares method) for the geodetic control points of the hydrotechnical facility (ellipses - horizontal errors, bars - vertical errors) in relation to permanent GNSS stations – RMS horizontal and vertical $\pm(3\div 5)$ mm.

Angle and distance measurement technology

In cases where control points are unfavorably located for GNSS observations, such points and inclinometers can be measured using classical techniques for determining horizontal angle and length. To achieve a level of accuracy similar to satellite measurements, instruments were used to measure angles and distances to a very high degree of accuracy, as listed in Table 1. Angular-linear observations are used to form a network, which is adjusted in order to determine the best estimates of XY coordinates. This is the so-called exact least squares (LS) adjustment, meaning the simultaneous adjustment of all observations, taking into account the weights of these observations, which are a measure of their accuracy. At the stage of designing the control and measurement network, when it was not possible to rely on an actual statistical assessment of the distribution of measurement errors, elementary error analysis was used to determine these accuracies and observation weights. It was then possible to evaluate each activity performed during the measurement and determine the impact of its accuracy on the value of the average error of the measured angle or distance. For example, the average measurement error of the horizontal angle, calculated based on elementary errors, was presented for two instruments used in the control observations of geodetic networks. The values are shown in Table 1 below:

Tab. 1: Accuracy of horizontal angle measurement based on the analysis of the impact of elementary measurement activities

Instrument	Aiming error	Direction error	Levelling error	Instrument centering error	Target centering error	Angle measurement error (2 series)
TCA2003	$\pm 6''$	$\pm 1.5''$	$\pm 0.1''$	$\pm 3.6''$	$\pm 1.3''$	$\pm 5.1''$
TMS50	$\pm 6''$	$\pm 1.0''$	$\pm 0.2''$	$\pm 3.6''$	$\pm 1.3''$	$\pm 5.1''$

The analysis presented above, allowing determination of the accuracy of measurement of the horizontal angle, turned out to be fully consistent with the results obtained from measurements carried out in the control network of the objects discussed below.

The accuracy of distance measurement using electronic total stations is defined by manufacturers of surveying equipment as the standard deviation of the measurement (the mean distance measurement error). These values for individual instruments used during the research are as follows (Table 2):

Tab. 2: Distance measurement accuracy using exemplary measuring instruments

Instrument	Distance RMS error	Example: average measurement error of a 250m section
TCA2003	$\pm(1\text{mm}+1\text{ppm})$	$\pm 1.25\text{mm}$
TMS50	$\pm(0.6\text{mm}+1\text{ppm})$	$\pm 0.85\text{mm}$

Height difference measurement technology

One of the most important ways to control the geometry of a large-area object is to determine the height differences necessary to determine the value of vertical displacements (so-called depressions or uplifts of controlled points). With hydrotechnical facilities and their environs, this is most often done using the geometric levelling method. Altitude determination by means of, for example, GNSS using the static method, even more so in the RTN (Real Time Network) or RTK (Real Time Kinematic) mode (Borowiec et al., 1999), is insufficient in terms of the reliability of the measurement results obtained. For this reason, i.e., the level of accuracy required in determining the height of control points, precise digital levels (for instance, NA3003 and DNA03 by Leica) with a set of precise leveling rods (with bar-code) are used for geometric levelling. Intermediate points on the lines, established between the control points, are temporarily marked with a steel levelling pin driven into the ground.

Levelling measurements are carried out in the form of closed levelling lines with a total length of up to 25 km. Each test series (every 3 months) includes the measurement of points controlled in relation to fixed benchmarks, located outside the impact area of the post-flotation tank. In the case of unstable areas (for instance, mining areas), the current heights of reference benchmarks should be obtained on each occasion. Elevation measurements also included inclinometers in order to determine the actual spatial position of the wellhead.

For precise levelling, this error should be within $\pm(0.5 \div 2)$ mm/km. As in the case of obtaining horizontal coordinates, the determined height differences between the control points are subject to adjustment (LS). Statistical analyses of cyclic observations carried out by the authors showed mean square errors of ± 0.9 mm/km, and maximum mean errors in height determination of $\pm (1 \div 1.5)$ mm.

To sum up, using geodetic technologies typical for precise measurements, the situational coordinates of control points can be obtained with an average error of $\pm(3 \div 5)$ mm (1σ) and height in the range of $\pm(1 \div 2)$ mm (1σ). On this basis, it can be concluded with a confidence level of $p=95\%$ (2σ) that situational changes of points can be determined if their value is greater than $6 \div 10$ mm and vertical changes above $2 \div 4$ mm.

Results

Object A

Geodetic measurements were made in the form of observations of permanently stabilized points of the geodetic control network, located in the foreground of the reservoir, along the foot, and along selected intermediate and upper shelves. These measurements used angle-linear observations, GNSS measurements - static and RTK, as well as precise levelling along the embankment shelves under construction and in profile lines, transversely to the reservoir slopes. The accuracy of the measurements obtained was in accordance with those described in Chapter 2 above. A visualization of the reservoir and the location of the geodetic control network are presented in Figures 2a and 2b.

Based on geodetic monitoring carried out by the team (including the authors of the publication) in the years 1991 to 2000, assessments of changes in the spatial geometry of the reservoir were performed. Graphs and maps presenting the values of total vertical displacements of the control points against the background of mining exploitation are presented in Figure 2b. A subsidence of the entire structure under the influence of mining activity is discernible, reaching -320 mm in the south-west corner of the reservoir foreground in 2000. The embankment subsidence ranges from -100 to -300 mm (in the south-east part), depending on the location and intensity of the excavation of the underlying deposit.

Changes in the height of the embankments in the period 1992÷1999 are presented in the example of profile lines surrounding the reservoir from the N-W side through S-W, S-E, and again to N-E (Figure 6). The overlapping of the phenomena of the impact of underground exploitation and embankment compaction is visible. The greater the distance from the reservoir's foreground to the dam crest, the greater the subsidence values, despite the similar scope and duration of mining excavation in both the foreground and under the reservoir. The difference in the intensity of subsidence can be seen even more clearly in Figure 7, which shows depressions of the profile points controlled as a function of time, including points in the downstream (foreground), toes (foothills), intermediate

shelves (berms), and the currently highest one during the measurements. In the initial phase of berm formation, compression reaching -30 mm/6 months is visible, and the reaction of all slopes to exploitation is greater than that of the points in the foreground. In the period May÷December 1997, it even reached a value of about -100 mm. At the same time, the dam toe lowered by only about 20 mm. This analysis can be supplemented with a comparison of the behavior of the uppermost berms of the dam: +297.5 m and +307 m, between which the analysis of height differences in the period 1995÷1999 clearly shows discrepancies in the rate of depression growth, which consists of compression and post-mining subsidence (Figure 8). These differences are within the range of -40 to -110mm in 1999, which again demonstrates an initial common rate of settlement under the influence of material compaction (period 1995÷96) and then its diversification under the influence of additional factors (mining influence).

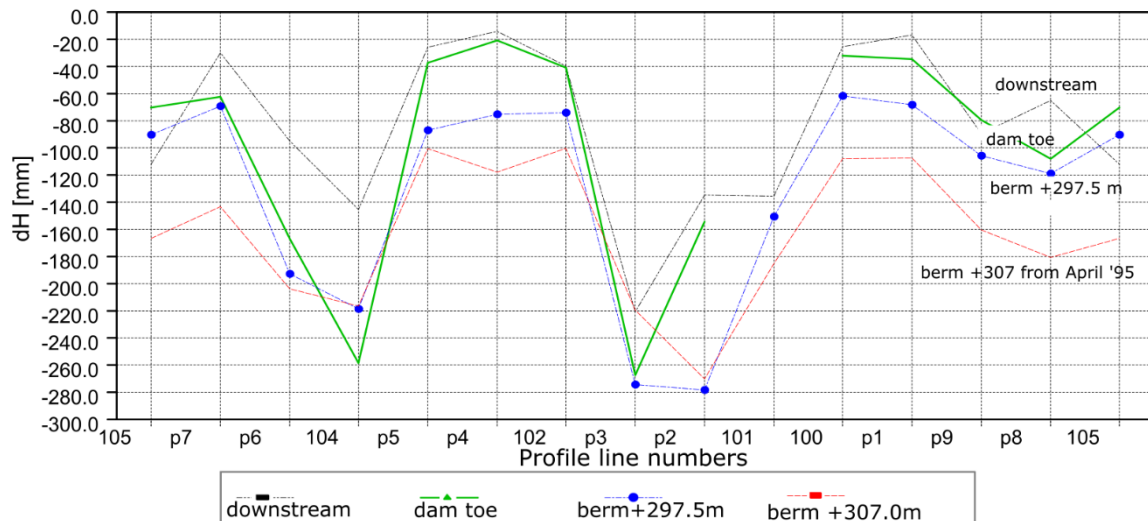


Fig. 6. Changes in height of points of downstream, toe, and selected berms in the period 1992–1999

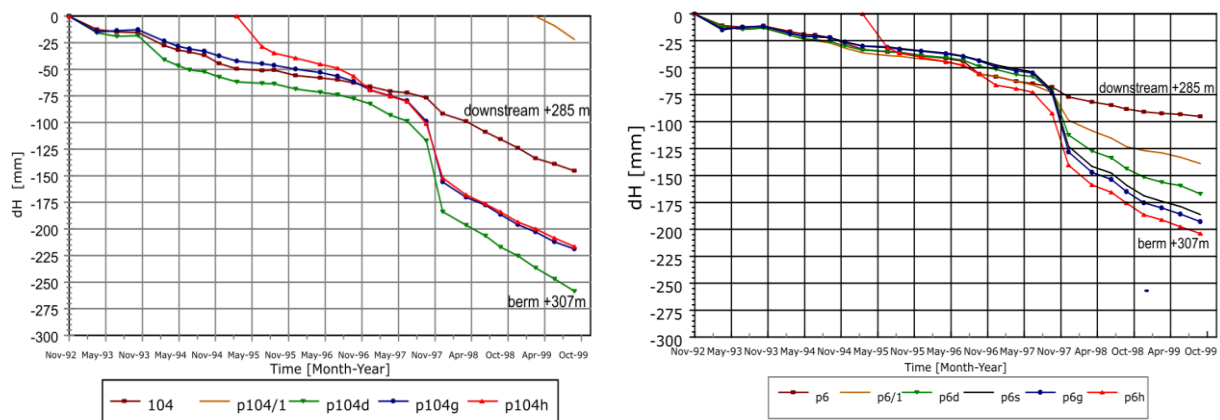


Fig. 7. Changes in height of points of selected controlled profiles 104 (left) and p6 (right) (S-W) over time.

Total changes in the length of the sides of the network (period 1993÷1999) are presented in the development along the embankments (Figure 9). These testify to horizontal displacements of these embankments, and thus to compressive and tensile deformations. These changes depend on the phase of kinematics forming the post-mining trough under the tank. In individual profiles, changes extending the sides up to +50mm can be observed (upper berm 307.0 - tensile deformations ϵ^+), and the sides at the lower levels and in the foreground are shortened (ϵ^-) by up to 140 mm throughout the entire test period. Due to the similar behavior of all lower levels of the research profiles, these changes should be associated with the impact of mining. Only the highest part of the berms behaves differently (stretching), which suggests the influence of another phenomenon (compression) and is probably the result of the pressure generated by the stored masses inside the tank.

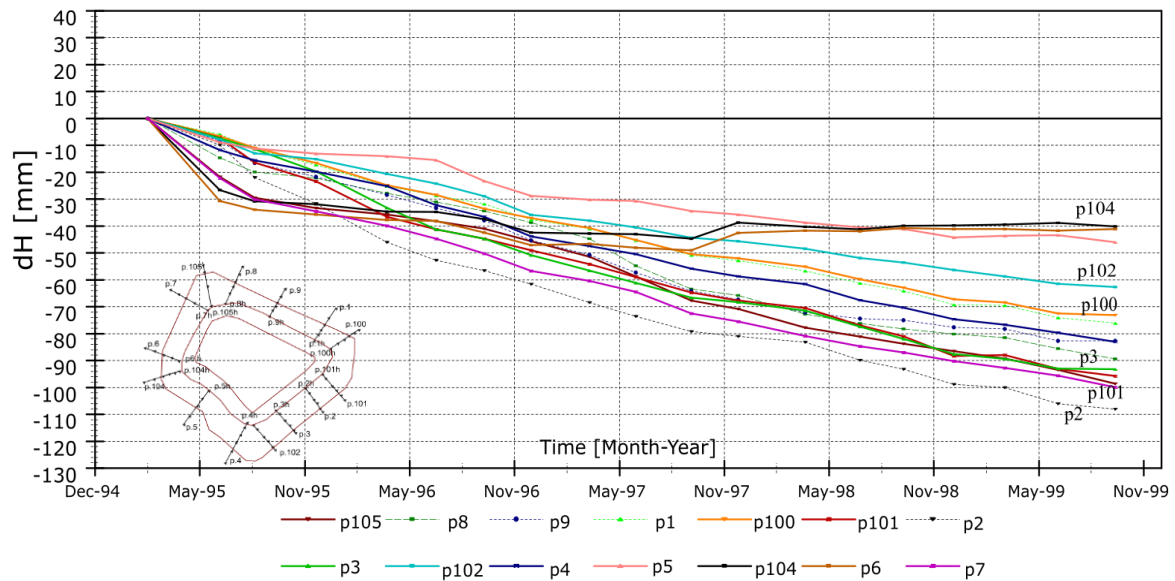


Fig. 8. Changes in the difference in height between the highest shelves of the controlled profiles (berm +297.5 and +307 m) of reservoir embankments as a function of time.

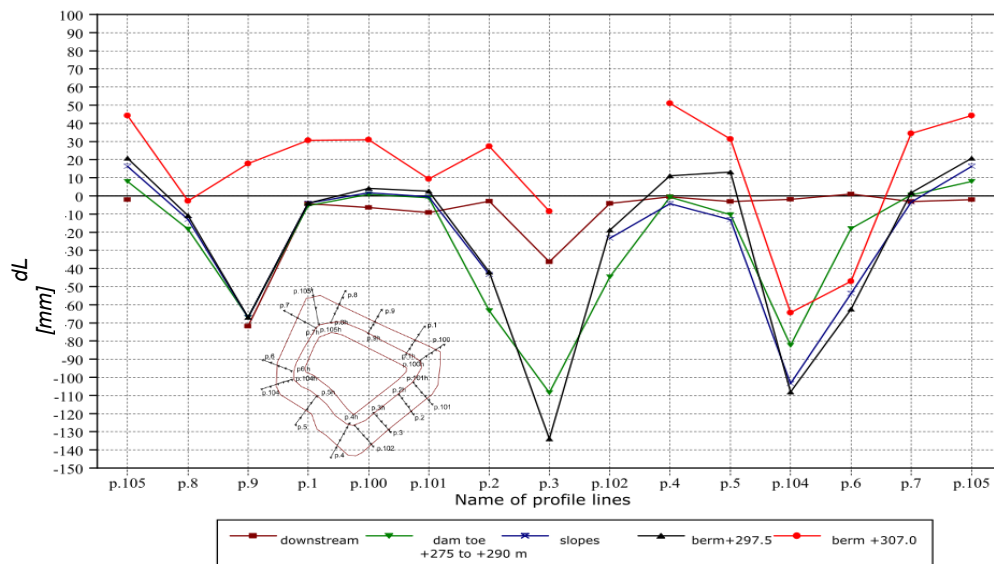


Fig. 9. Total (1993–1999) changes in length of control network sides from starting points of profile lines.

Changes in the distance between points in two selected cross-sections (p6 and p9) through the reservoir slopes are even more clearly visible in Figure 10. The red line marking the uppermost part of the profile indicates its stretching (influence of compression), and below it, only the phenomenon of side compression is observed (post-mining trough). Taking into account the distances between the points, the total values of horizontal deformations (ϵ) are in the range of +1.0 to -1.2 mm/m, which is still a range indicating that small values of deformation of the slopes of the hydrotechnical facility are generated.

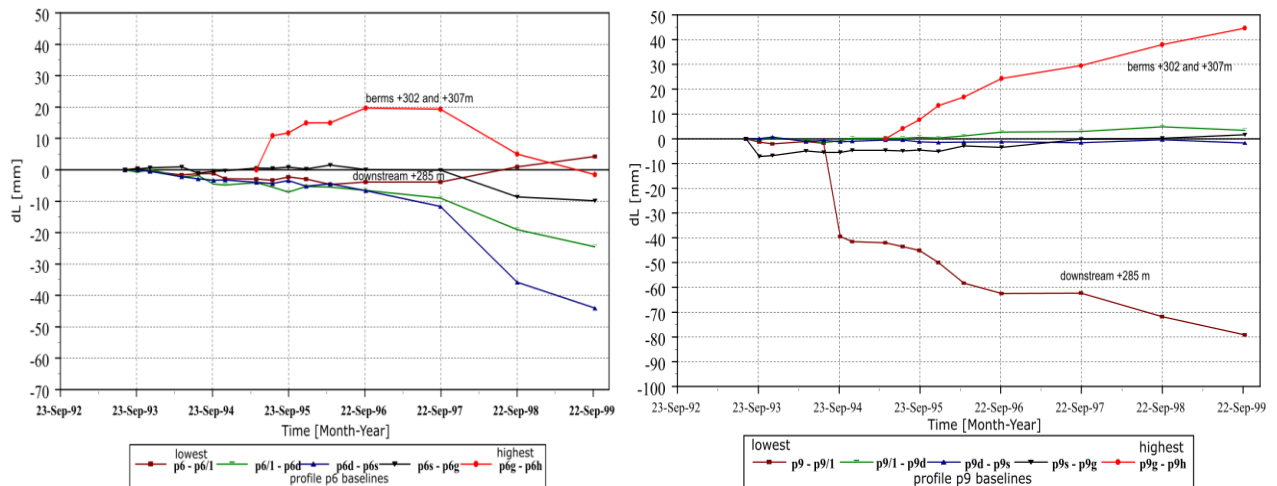


Fig. 10. Changes in length of sections in transverse profiles (p6-left and p9-right) through reservoir slopes – showing different behaviour (extensions) of sides on the highest slopes.

Following the complete cessation of reservoir and mining activities, systematic monitoring of the reservoir has been completed. However, thanks to the EGMS (European Ground Motion System - egms.land.copernicus.eu) system of the Copernicus program, further analyses of its stability can be performed using InSAR radar interferometry analyses. Figure 11 below shows the maximum depressions at the top of the reservoir (Figure 11a) and the characteristic behavior of the foreland (Fig. 11b). The continuous operation of the upper slopes in relation to the practically immobile foreland is clearly visible, which indicates the end of mining impacts and the slopes subjecting themselves to the natural compaction of the soil, which is probably related to the process of its continuous drainage after the end of the reservoir's operation as an active reservoir. In the period from 2018 to 2022, the maximum crown displacements are estimated at 40 mm (8-9 mm/year).

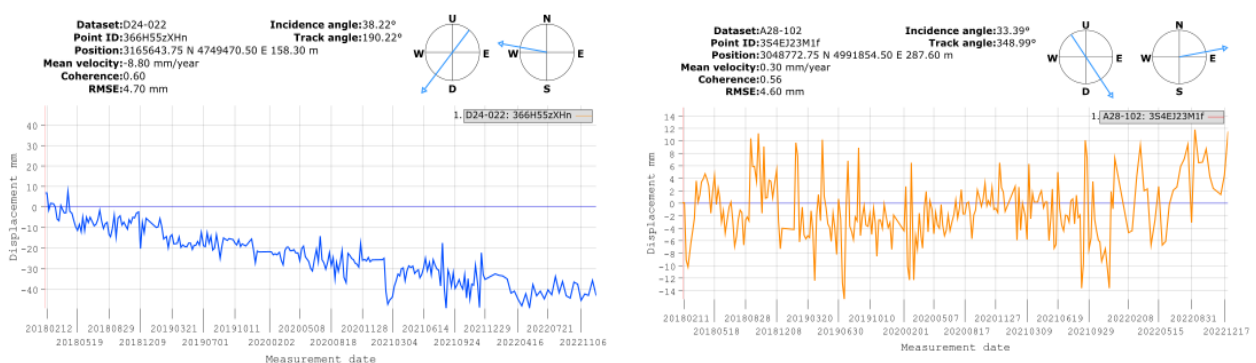


Fig. 11. Subsidence of the Object A dam berm (left) and dam toe (right) (EGMS services – <https://egms.land.copernicus.eu>) – period (Feb. 2018 – Dec. 2022)

Object B

All analyses were carried out in a similar way as for object A; however, the presented graphs are consistent with the characteristics of the object, better approximating its change in geometry over 50 years of geodetic monitoring. The vertical displacement (Figures 12, 13, 14), horizontal displacement (Figure 14), and horizontal strains (Figure 15) of this tailings pond dam demonstrate how various factors can interact to influence the settlement of a hydrotechnical structure. 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, along with the dam, is due to the pressure of deposited exploitation waste.

The total impact of the above-mentioned reasons can be observed in the revealed values of the differences in subsidence up to 384 mm (Figs 12 and 13). The next factor, directly connected with mining exploitation, involves large-area depressions caused by the dehydration of the rock mass and the direct impact of deposit exploitation on the dam and sedimentary pond, resulting from underground exploitation. This has led to subsidence values of up to 3500 mm over 54 years of monitoring (Figs. 12 and 14).

The Knothe-Budryk theory (Knothe, 1984; Pielok, Piwowarski, 1996) was used to estimate the range of horizontal strains (Fig. 15) allowed, based on the identified exploitation plots, depth, and thickness of exploitation,

to calculate its impact on the analyzed reservoir of post-flotation waste. These data (-4.2 to +2.5 mm/m) indicate the convergence of forecasts with measurements, which verify their accuracy but also allow for specifying the parameters of subsequent forecasts. This allows for the optimization of exploitation in the vicinity of the reservoir and minimization of subsequent impacts.

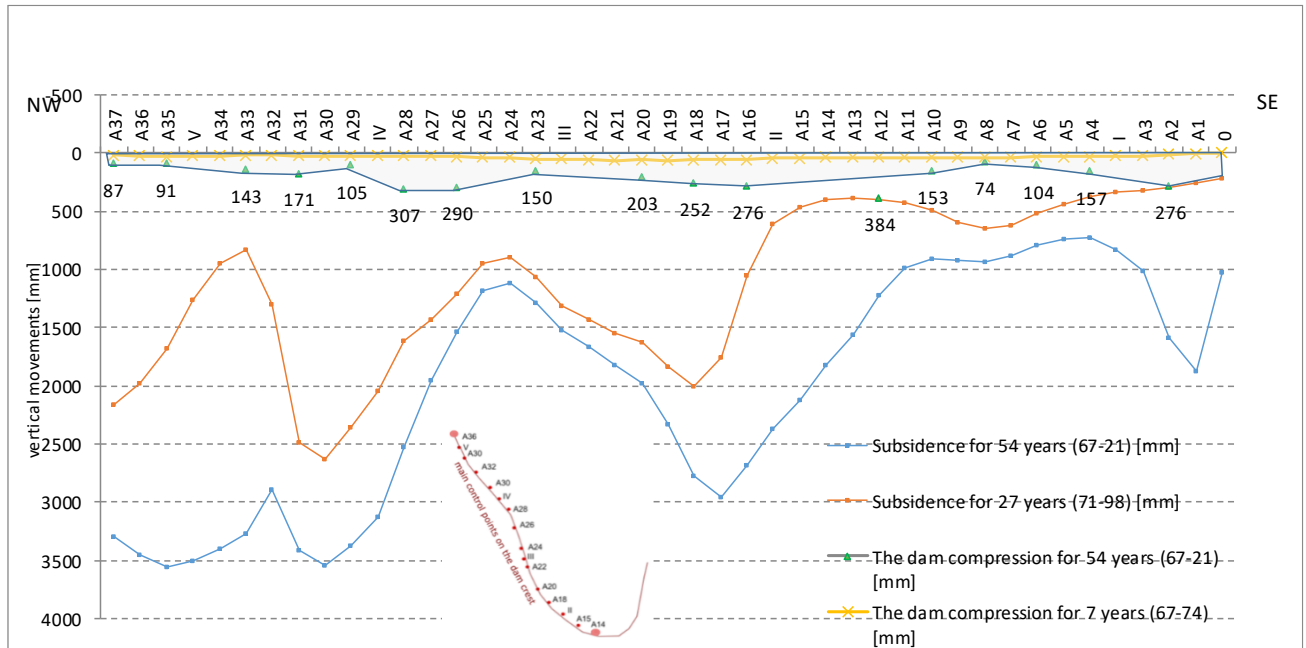


Fig. 12. Subsidence and dam compression throughout its lifetime (years 1967 – 2021). Left side of the legend – map of the control points.

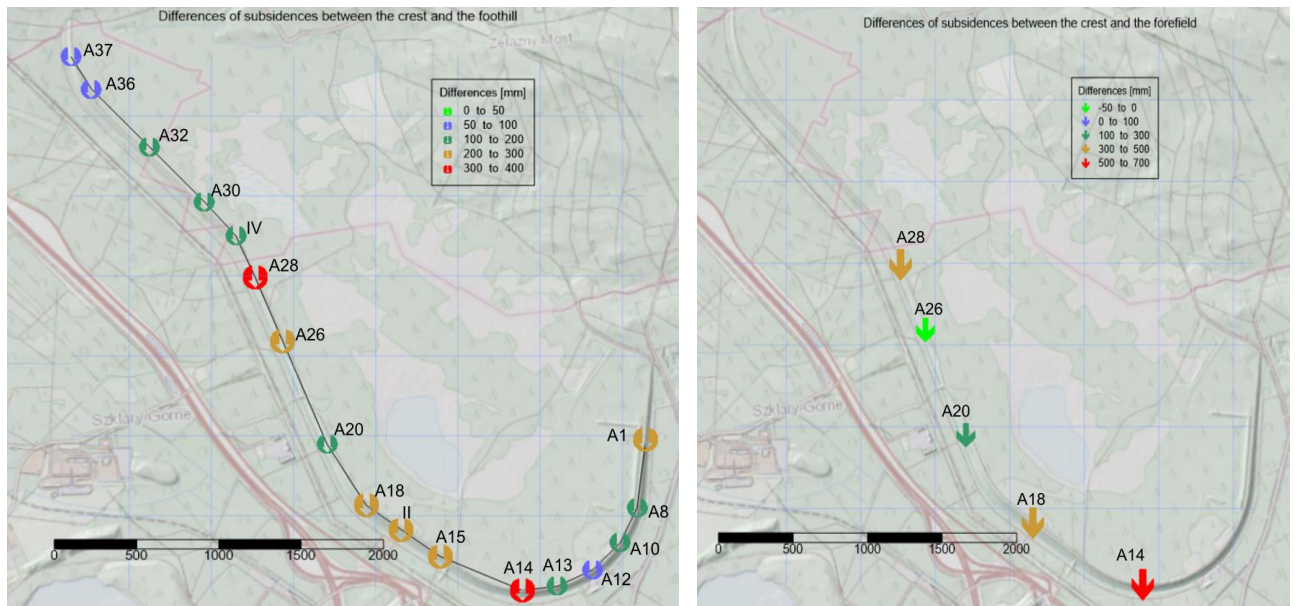


Fig. 13. Differences in subsidence of the crown in relation to (left) the foot (toe) and foreground (downstream) of the dam (right). The subsidence of the crown is greater than that of the foothills and foregrounds (the values are given in the legend).

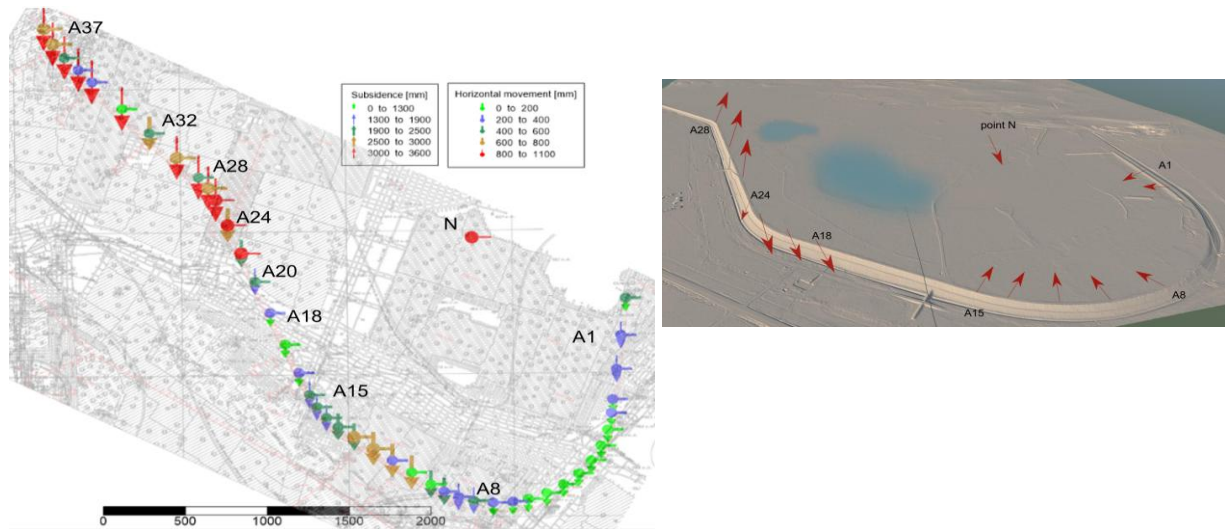


Fig. 14. Left: Total subsidence of the dam crest and its displacement under the influence of cumulative factors deforming the dam. In the background, the scope of mining exploitation is presented. Right – the direction of movements of the dam crest based on 54-year-old monitoring

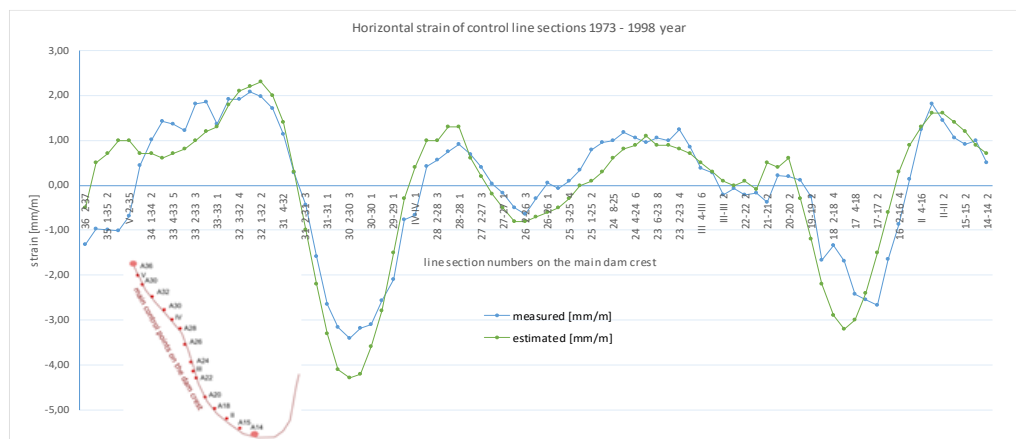


Fig. 15. Example of horizontal strain of control line sections (A36 – A14) on the dam crest (brown color), 1973-1998 (real and estimated, using Budryk-Knothe theory (Knothe, 1984, Pielok, Piwowarski, 1996)).

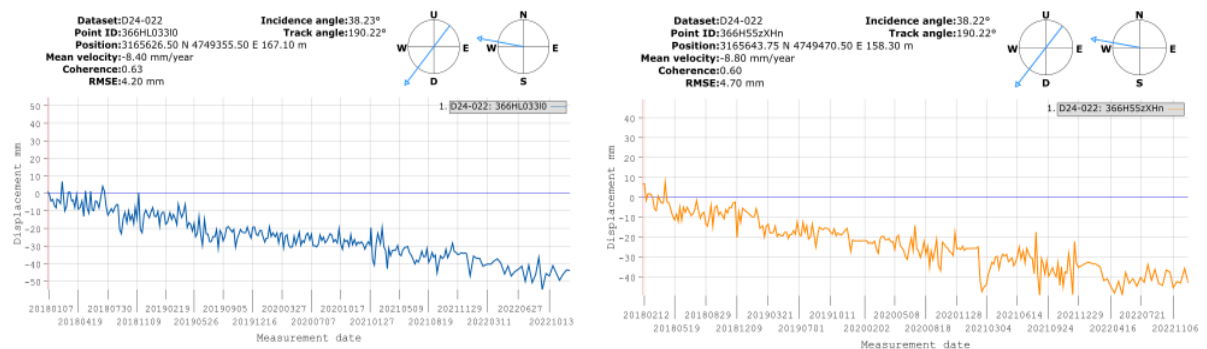


Fig. 16. Subsidence of the Object B dam berm (left) and dam toe (right) (EGMS services – <https://egms.land.copernicus.eu>) – period (Feb. 2018 – Dec. 2022)

The analysis presented below, based on InSAR measurements (EGMS - Copernicus), indicates similar behavior of the dam crown (Fig. 16a) and its foreland (Fig. 16b). The revealed movements in the period 2018-2022 reach a value of 50 mm, which means the rate of change is 8-9 mm/year. Thus, it can be concluded that the process of revealing the influences affecting the dam has not been completed, despite the similar behavior of the slopes as in the case of structure A. However, considering the dam's twice lower height in structure B and the continuous movement of the foreland, despite the dam's end as a large-scale tailings storage facility, geodetic monitoring is still carried out on an ongoing basis.

Discussion

Based on the geodetic observations of both reservoirs, which have been analyzed over many years, it is possible to observe significant vertical and horizontal displacements of the dam body, which are significant from the point of view of changes in geometry. First of all, the very process of expansion and formation of slopes by washing or adding generates a process of displacement. The analyses conducted indicate a high intensity of compression in the first months of slope construction, reaching a peak of about 10mm/month. However, this compression does not end after a few months but continues with the ongoing expansion and increase in weight of the overlying slopes. In Object A, built with the use of washing, one can notice settlement of the highest berm, "+307.0", in relation to the lower berm "+297.5", at a level of 10 mm versus 30 mm / 3 months around the entire perimeter of the reservoir (Figure 7). In subsequent measurement series, these values either remain similar or the process slows down, as shown in Figure 6. The same can be seen in Figure 6, which includes the lowering values for the foreground, the foot of the escarpment (dam toe), the intermediate berms, and the highest berm, "+307". There, one can observe differences in the rate of subsidence of the top shelf in relation to the others. This difference is an indicator of the compression process, which distinguishes the typical process related to post-flotation material compaction from the other depression values. Within 4.5 years (March 1995–September 1999), the values of these differences are within the range of just 70 to 140 mm, which indicates an average change of 10 to 20 mm per year ($1 \div 2$ mm/month). Comparison with previous analyses confirms this change in the rate of compression over a longer period and that all dam berms behave in basically the same way.

Figure 6 shows that the object experiences much greater deformations and vertical displacements, which are related to the above-mentioned mining exploitation under the reservoir and its impact on the formation of subsidence basins in the region of the reservoir. The total values of lowering points of the foreground and reservoir slopes located on the ledges reach values from 90 to 280 mm over a period of 7 years (September 1992–September 1999). This means that, in relation to the impact of compression, the value was as much as twice as large and affected all slopes of the transverse profile, not just the highest.

In Object B, whose height is only 22 m and whose escarpment was constructed in one stage, compression affects the entire body and can be determined based on differences in settlement of the dam crest relative to its dam toe (Figures 12 and 13). The figures attest to this phenomenon over more than 50 years of geodetic monitoring. The compression value separated from all displacements was in the range of 87 to 384 mm in the period 1967–2021 (54 years), meaning an average monthly density of up to 0.6 mm. This value is similar to that obtained for Object A, but it is worth noting that the highest value for this type of subsidence typically occurs at the beginning of the dam construction process. The analysis indicates that the values of the largest compressions are related to the height of the dam above the adjacent terrain (Figure 13), confirming its correctness. However, this process may locally be accelerated again under the influence of external factors (excessive soil watering, mining tremors, the impact of mining exploitation, etc.). The exploitation carried out for a very long time at a depth of about 800 m under the sediments deposited in the reservoir led to a significant lowering of the dam crest, its foot, the interior of the reservoir, and its foreground. The values of total subsidence, determined from 1967–2021, reach 3.5 m, while during its operation and depositing of sediments until 1998 (18 years after the end of the facility's use), these values reached a level of subsidence up to 2.6 m. Despite ten times greater subsidence than in the case of Object A, resulting from the influences of exploitation, the values of compression for Object B are comparable and do not lead to excessive deformation of the dam. It should be noted that despite such significant subsidence, both objects retained the ability to safely deposit and store flotation sediments, and the dams did not and do not show any dangerous changes in the structure of the dam body.

The second important indicator of deformation, related to the assessment of geometry, is horizontal displacement, and this was based on the determination of the horizontal deformation (relative change in length) of the sides. The values of horizontal displacements in both objects were determined. As in the case of subsidence, the values of horizontal displacements are primarily related to the emerging impact of underground exploitation, but there is also a residual impact of compression on the recorded changes.

In Object A, due to the different distances between the points of the control network, deformation values were not determined, and only the values of horizontal displacements from (initial) points in the foreground were compared, divided into individual vertical profiles surrounding the reservoir slopes (Figure 9). The values of these changes over a period of 6 years range from +50 mm to -140 mm. It is significant that the positive values, indicating stretching of the measuring sides, are located on the top shelf (red line - Figure 9). Other locations show shortening of the individual sides of the control network. In other words, in principle, most of the profile points located on the slopes and foothills approach the points in the foreground, while the points on the highest slope move away from the starting point. Such contrasting behavior indicates a different type of impact than just underground mining and is probably also related to the compaction of the top berm (compression) and its subsidence towards the interior of the reservoir. This tendency is seen more clearly in the graphs presented in Figure 10, where the sides of the top berm "307" (red line) lengthen over the period February 1994–September 1999. In the case of the "p6" profile (Figure 10a), this elongation disappears after 3.5 years, while in the "p9" profile (Figure 10 b), it increases

successively all the time. The values of length changes at the remaining profile points oscillate within a range of 0 to -50 mm, at different rates of change, depending on the impact of mining exploitation. However, a significant impact of mining exploitation is also evident in the rapid shortening of the side distance in the foreground over a very short period (brown line - Figure 10b). A positive finding of this analysis is that the observed changes in length testify to the compaction of berm material, which increases its density and prevents loosening. Thus, the slopes of the reservoir were not (apart from on the highest shelf) threatened by discontinuous deformations. This conclusion is further confirmed by many years of visual observations, which likewise found no evidence of such phenomena on the dam's embankments.

Object B is characterized by a control network spaced at equal distances on the dam crest and foot (every 24 and 48 m); hence, apart from the determined horizontal displacements, it was possible to determine the values of horizontal strains. Displacements (vertical and horizontal) are shown in Figure 14, which also presents the mining operation in the background, while the deformation values are shown in Figure 15. A change in the dam geometry is visible in the form of horizontal displacements of up to about 1 m in selected regions of the dam (Figure 14a), but most significant is the observation of opposing directions of displacement, which indicate the phenomenon of dam stretching. These values reached the level of 2.0 mm/m within 25 years (Figure 15). In addition to the compressions and stretches of the sides of the dam crest determined from geodetic measurements in this period, the predicted values of deformations caused by mining activity, determined during prognostic modelling (Knothe, 1984), are also presented. There is a high level of agreement between the predictions and the observed values, and at the same time, it can be seen that the values of the maximum stretches found (+2.0 mm/m) are lower than the maximum compression (-3.0 mm/m). The presented data are, of course, variable in time due to the dynamics of mining operations, but the values presented for the period of 25 years are representative of the object in question. Also, in this case, the fact is confirmed that the deformations generated by exploitation are rather of a clamping type, which is a more favorable form of geometric change for a large-area earth hydrotechnical structure.

The analyses carried out indicate a certain proportionality of vertical to horizontal displacements, which is a natural effect of deformation and described in much of the literature (Puniach et al., 2023; Tajduś, 2018). Therefore, these relations, vertical (dH) and horizontal (dU) movements, were determined for Object B, striving to identify the characteristics of the size of changes in statistical terms. For this purpose (Table 3), the annual and total changes in the horizontal and vertical displacements of the control network points were summarized and, on this basis, basic statistics describing the data sets were determined. Based on the ordered sets, histograms of the frequency of occurrence of coefficients with similar values were also determined, which indicate that the phenomenon of horizontal displacement in relation to vertical displacement is dominant in a given object. These results are presented in the graphs shown in Figure 17. Different characteristics of the phenomenon are visible, which are related to the intensity of the impact of mining exploitation, but above all to its depth and development over time. Also not without significance is the method of building the slopes of the reservoir, which, in different ways, determines the reaction of the object to the revealed influences of exploitation. Taking into account the probability of occurrence of the phenomenon at the level of 80% (dashed blue line in Figure 17), it can be seen that in annual changes, the values of vertical displacement dH are most often in the range [0.4 to 2] in relation to the horizontal displacement dU. In the case of complete changes, a relationship in the range [2 to 8] clearly dominates in 80% of cases, with the predominance of depressions in relation to the value of horizontal displacements. Such variable coefficients are, of course, related to the impacts of mining exploitation, which manifests itself primarily in reductions that are visible primarily in changes longer than 1 year. In annual periods, the deformation process may sometimes be characterized by greater horizontal displacements in relation to depressions ($dH/dU < 1$).

Tab. 3: Object B - Frequency of occurrence of ratio of vertical (dH) to horizontal (dU) displacements for (a) total changes over 54 years and (b) periodic change between the years 2019 and 2020

(a)		
Classes of dH/dU	Incidence	Summary %
2.0	1	2.3
7.6	34	79.5
13.3	6	93.27
19.0	2	97.7
24.6	0	97.7
30.3	0	97.7
More	1	100.0

(b)

Classes of dH/dU	Incidence	Summary %
0	1	2.2
0.2	0	2.2
0.4	3	8.7
0.6	6	21.7
0.8	4	30.4
1.0	6	43.5
1.2	5	54.3
1.4	6	67.4
1.6	3	73.9
1.8	5	84.8
2.0	1	87.0
2.2	0	87.0
2.4	1	89.1
2.6	1	91.3
2.8	2	95.7
3.0	0	95.7
3.2	0	95.7
3.4	1	97.8
3.6	0	97.8
More	1	100.0

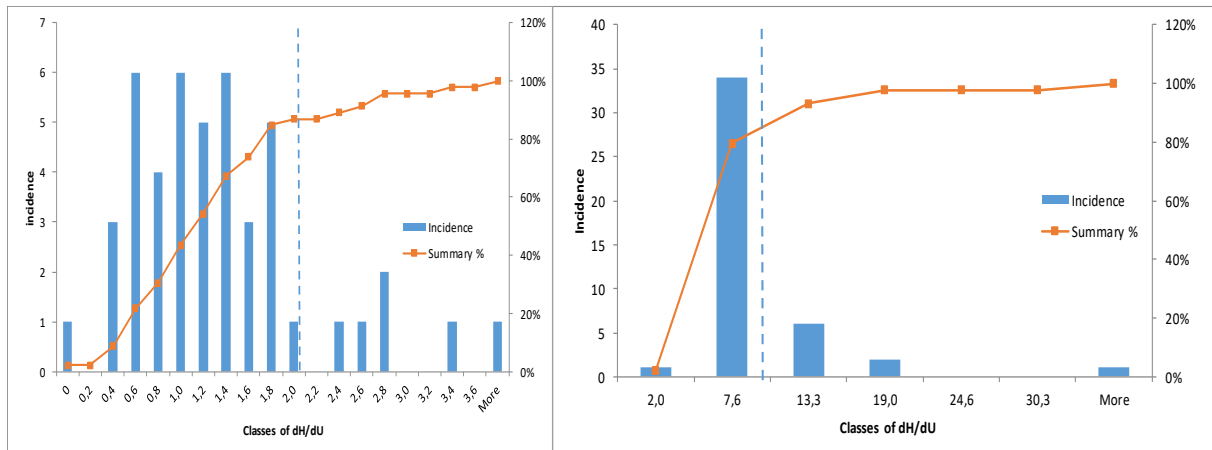


Fig. 17. Object B - Histograms of dH/dU relations for annual changes (a) and total changes (54 years) (b).

Conclusions

Periodically performed geodetic surveys allow ongoing monitoring of the current state of the geometry of an object and, at the same time, enable ongoing control of the impact of mining operations and their conduct in such a way that the stability of a facility can be maintained at all times. Confirmation of the need for such procedures is provided by the fact that a safe state can be preserved despite very significant subsidences of the objects in question, provided that the methods of protection and stabilization of slopes are properly selected (Róžański et al., 2022; Rodríguez et al., 2021). Such protections are provided not only by typical geotechnical measures to strengthen the body of the dam, such as planting of trees and shrubs and use of a watering network on the slopes of the reservoir, but also based on geodetic measurements and remote sensing (Che et al., 2018). Thanks to these, mining technology under the tanks can be selected in such a way as to minimize the horizontal strains, especially stretching deformations, which occur.

Throughout the expansion of the dams, the impact of the process related to sedimentation and compression of the material from which the slopes of the dams were built is visible. In the analyzed objects of different types and constructions, a similar compression value was found, reaching 10 mm/month. In the case of other impacts, the impact of compression is less visible due to a much greater increase in deformations related to land subsidence under the influence of, for instance, mining exploitation. Since the start of waste storage in large-area tanks, the pressure generated by the stored masses is also important. These masses cause the formation of local subsidence troughs, whose size and range of impact depend on the amount and location of the deposited material. The more accumulated waste material and overlying water, the greater its impact on the subsoil and the crest of the dam. The pressure falls most heavily on the centre of the pond and decreases towards the periphery. The phenomenon of rock mass dehydration should not be overlooked, as it significantly influences the measured increase in subsidence, particularly in rock masses drained by mining activity. The above-mentioned factors were determined cumulatively, showing the value of the dam body lowering reaching up to 3.5 m during 54 years of monitoring,

which still does not constitute a dangerous condition for the geometry and strength of the post-flotation reservoir dam.

The examples cited and methods of conducting periodic geodetic surveys discussed in this paper do not exhaust this subject. Therefore, the authors, using the example of another object, intend to investigate the cooperation of geodetic monitoring with other kinds of survey carried out by other industries in order to protect a still-functioning hydro-technical object which plays a similar role to Objects A and B above.

It should be emphasized that regardless of the size of this type of facility, geodetic control measurements are among the most basic activities for monitoring the safety of large-area hydrotechnical facilities (Rico et al., 2008) and indicate their effectiveness in minimizing energy expenditure in the process of maintaining the correct production cycle. However, each facility requires an individual approach and the implementation of control measurements, proceeding from an individual observation project and the selection of appropriate measurement technologies to the cyclical interpretation of results and the exchange of information with all services in order to secure the proper functioning of the structure.

The tests and analyses performed have served since the beginning of their operation for the ongoing assessment of the safety of the foundation and functioning of earth hydrotechnical dams. The results of the determined periodic and total deformations are subject to assessment by specialists in underground mining and geotechnical and hydrotechnical protection, scaling their theoretical models and adjusting them to the current mining situation and the location of post-flotation waste.

The examples cited and methods of conducting periodic geodetic surveys discussed in this paper do not exhaust this subject. The authors conducted a literature review but did not find suitable studies on long-term post-flotation earth reservoirs. For this reason, the presented article will probably be a valuable contribution to expanding knowledge on the decades-long monitoring of these types of earth objects subjected to the impact of mining exploitation. Therefore, the authors, using the example of another object, intend to investigate the cooperation of geodetic monitoring with other kinds of survey carried out by other industries in order to protect a still-functioning hydro-technical object which plays a similar role to Objects A and B above. It should be emphasized that regardless of the size of this type of facility, geodetic control measurements are among the most basic activities for monitoring the safety of large-area hydrotechnical facilities (Szostak-Chrzanowski et al., 2007) and indicate their effectiveness in minimizing energy expenditure in the process of maintaining the correct production cycle. The demonstrated values of deformation of facilities indicate that it is possible to safely use earthen flotation waste tanks with large total deformation values, provided that proper and very extensive geo-monitoring is carried out.

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