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Research paper

Evaluation of the functionality of seepage prevention structures of dam bodies after a long period of operation – a case study of Otmuchów and Nysa reservoirs

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Abstract: The article reviews the technology of construction and functioning of watertight elements of hydrotechnical embankments. A case study of two reservoirs located in the middle course of the Nysa Kłodzka River is described: (1) Otmuchów reservoir functioning since 1933, (2) Nysa reservoir functioning since 1971. The effectiveness of the applied impermeable screens, i.e. a clay screen of the Otmuchów reservoir and a concrete screen of the Nysa reservoir, was assessed and compared. Data from piezometers located at the height of the dam crest along its entire profile were analysed for measurements taken in the years 2020–2022. Indicators such as the distribution and depth of the water level in the dam body and changes in pressure in piezometers under the influence of water level fluctuations in the reservoir were considered. In addition, the scale and frequency of repair and maintenance activities carried out on both facilities were analysed, especially in aspects of the dam body sealing and the need to repair the upstream slope structures, which are directly exposed to filtration and wave action. It was found that, despite the long period of operation of both facilities, they maintain proper water tightness, and the depth of the water level in the embankments reacts only slightly to fluctuations in the amount (height) of stored water. This correlation is more evident closer to the middle part of the dam of the Nysa reservoir, where an abrupt increase in damming height caused a vertical movement of the water table in the embankment, but with a delay of about a week. It was pointed out that both sealing technologies adopted were associated with the need for numerous revitalisation measures, mainly due to dynamic degradation of the stone paving in the area of fluctuations in the level of dammed water in the case of the Otmuchów reservoir and loss of watertightness at expansion joints of concrete slabs protecting the upstream slope of the Nysa reservoir dam.

Keywords: dam, hydrology, reservoir, seepage prevention structures, upstream slope revitalisation

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1. Introduction

Dam reservoirs function as one of the more effective methods of artificial water retention for economic or social purposes. Since ancient times, people have dammed rivers to store and accumulate water by delaying runoff, thus creating zones of permanent flooding to reduce the risk of water scarcity during dry and rainless periods [1–3]. The vast majority of reservoirs were built in the second half of the 20^{th} century; however, there are still many older structures built in accordance with the construction techniques of the time, which in some cases are far from today's standards, especially in terms of structural safety. One example is the Edenville Reservoir Dam formed in 1920 on the Tittabawassee River in the USA. After a century of operation, it suffered uncontrolled failure during increased water damming, and the cause turned out to be liquefaction of the embankment structure, which was formed without proper geotechnical parameters and using technology that is outdated by today's standards. In this case, no layered body formation was used, the slopes were too steep, and, above all, no technological solution was assumed to regulate the filtration through the embankment apart from a primitive drainage system [4]. Internal erosion is the second most common cause of reservoir disasters and failures, just after the circumstances that cause water to overflow the dam crest [5, 6]. Sometimes its effects are already observed in newly constructed facilities, as it happened in the case of the Lapão reservoir dam in Portugal, where cracks and subsidence of the crest occurred just after the first filling in 2002 [7].

Proper modelling of the potential filtration path through the dam body is not a trivial issue, which includes the frequent occurrence of factors such as inhomogeneous (anisotropic) embankment zones where filtration velocities reach different values, as well as the need to take into account the initial moisture content of the soil and the problem of saturated or unsaturated seepage (when the pores of moist soil are only partially filled with water) [8, 9]. However, advances in modelling studies and information technology make it possible to determine more and more precisely the water filtration path through a dam still at the design stage and, in addition, to determine which parameters of the earth embankment have a key influence on the safety of the entire structure, examples being the selection of the appropriate thickness of the impermeable core, the slope gradient or the filtration coefficient of the materials assumed to be used [10]. Of great importance is the drainage that leads the seepage water through the embankment, or more precisely its shape and technology of construction. The selection of proper drainage dimensions, including the ratio of its length and height, makes it possible to significantly influence the shape of the filtration curve and the reduction of water pressure inside the dam [11].

Currently constructed earth dams, even of detention reservoirs (storing water only during flood event) are always equipped with watertight elements, such as cohesive soil screens, reinforced concrete screens, steel screens, etc. The adoption of a particular technology is determined primarily by the location and the availability of materials, including the type of soil from which the dam body is made of and on which it is placed [12–15]. Infiltration protection takes many different forms and – despite the established patterns – there are many innovative and unique examples, such as the diagonal steel core in the Rurtal Dam [16] or a flexible Gepath dam core formed in layers from diluvial soils, also with the addition of bentonite [17]. In the dams analysed in this article, a clay or concrete screen was used as an embankment sealing element successively for the Otmuchów and Nysa reservoirs. Already on the basis of literature data, the basic problems and risks associated with the application of the two technologies mentioned can be identified. Examples include the need for regular and extensive measurements to assess the possible degradation of the clay screen [18] or the problem of selecting the right concrete formulation, the phenomenon of corrosion and the vital importance of the precision of the reinforced concrete slabs [19]. In both cases, after a long period of operation , there is the issue of selecting an appropriate method of repairing the upstream slope, generating the assumed effect of improving the technical condition and safety of the structure, while maintaining a reasonable cost and scale of the undertaking [20–23].

Events, such as the Edenville Dam disaster described above, not only provoke stricter requirements for newly constructed structures, but also prompt a more thorough monitoring of the condition of the already existing hydraulic structures. The regular carrying out of assessments of the technical condition and safety of these structures is subject to legal regulations, which in their details depend on them being formulated in a given country, including the accepted guidelines and practices of the supervising institutions [24, 25]. In Poland, there are guidelines formulated by the Institute of Meteorology and Water Management, indicating the recommended scope of tests and measurements to be carried out in order to comprehensively assess the technical condition and safety of water damming structures [26]. It should be emphasised that such monitoring also allows an important contribution to engineering knowledge as the thousands of reservoirs that have been in operation for years are an excellent field for research that can show which solutions (accepted at a given time as the most advantageous, modern, or economically sound) actually work decades later or what operational, financial, or environmental problems have resulted from the decision to implement a particular design. The main objective of the paper is (1) to present and characterise the different solutions for waterproofing the dam body of the two reservoirs that have been in operation for more than half a century; (2) to analyse piezometric studies conducted between 2020 and 2022 to determine the effectiveness of the impermeable barriers used; (3) to recognise the scale of the operation, repair, and maintenance activities that have been carried out on the two facilities under study; and (4) to compare the technologies adopted for the construction of the two dams in terms of safety and quality of construction.

2. Materials and methods

The reservoirs being the case study within the research described herein are located on the Nysa Kłodzka River in south-western Poland, in their immediate neighbourhood. The central points of the bowls of the two facilities are approx. 10 km apart, with the Otmuchów reservoir located above the Nysa reservoir, as shown in Figure 1. Both facilities played an important role during the 1997 flood, which was the largest natural disaster of this kind in Poland since World War II, commonly referred to as the “millennium flood” [27]. Despite the lack of proper preparation of the reservoirs in question for the incoming wave, they had a flood reserve of approx. 90 million m^3 in total, reducing the maximum flow on the Nysa Kłodzka River from 2594 m^3 to 1500 m^3. The coordination of water discharges and ongoing efforts to secure the breaches created at the base of the Nysa reservoir's downstream slope made it possible to avoid major damage that could result in the loss of safety of this facility, the risk of which occurred [28].

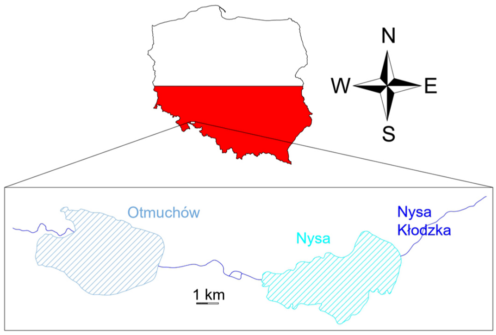

Fig. 1. Top view of the Otmuchów and Nysa reservoirs

2.1. Otmuchów reservoir

The Otmuchów reservoir was commissioned in 1933; since then, it has performed an important flood control, retention, power, and navigation function in the region. The basic parameters of the facility are: capacity – approx.. 130 million m^3, floodplain area – 1975 ha. The main element of the reservoir is the 6.5 km long dam body, rising 20 m above the bottom of the Nysa Kłodzka River bed. It was founded directly on the lower quaternary layers, on a bed of gravels with pebbles and a few interbeds of sands and clays. The body itself has been divided into zones of varying permeability. Looking from the downstream side, the embankment is dominated by permeable soils, gradually changing to more cohesive soils up to a clay screen, immediately behind which the compacted soil has been placed. The frontal part of the upstream side of the embankment was formed from sand and gravel material and its slope was reinforced with one or two 40–60 cm thick layers of crushed stone and a 20–30 cm thick layer of gravel and gravel sub-base. Water drainage from the embankment is by means of a granite drain located at the base of the downstream slope, which is furthermore drained by siphons and stones directing the water into the bund ditch [29]. The cross-section of the upstream slope is illustrated in Figure 2.

The primary impermeable device is therefore a clay screen with a slope of 1:1.6 and a thickness of approx. 1.5 m, additionally supported by cohesive soils located in the middle part of the dam. As part of the control of seepage through the dam body, it was equipped with dozens of measuring devices (piezometers) located in fifteen cross sections, the location of which is shown in Figure 3. In order to determine the level of the water table in the embankment, readings from piezometers located across the width of the dam crest were selected for two characteristic periods in the years 2020–2022, i.e., the maximum and minimum water levels in the reservoir. Six of the above piezometers installed in cross sections II and V (left side), VII and X (middle section), and XIII and XIV (right side) were selected to assess the performance of the impermeable protection.

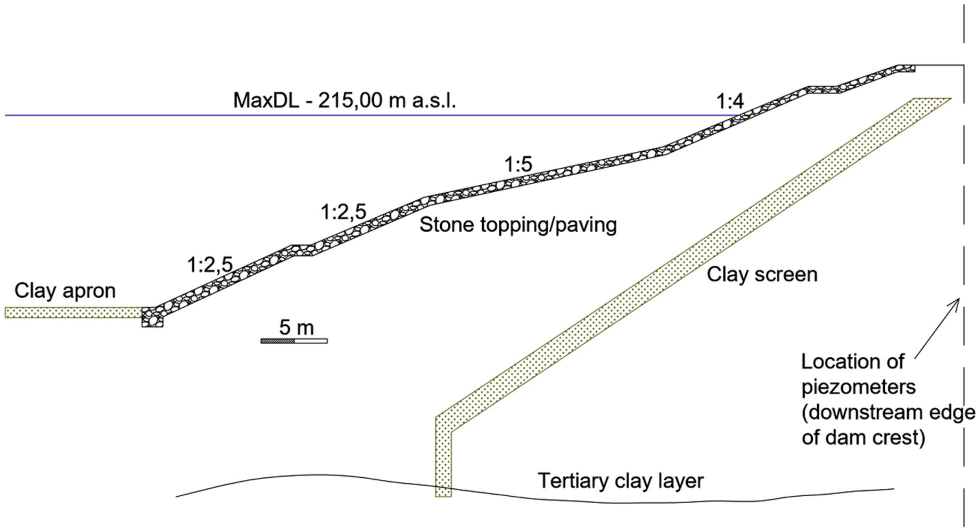

Fig. 2. Cross-section through the upstream side of the Otmuchów reservoir dam (based on [29])

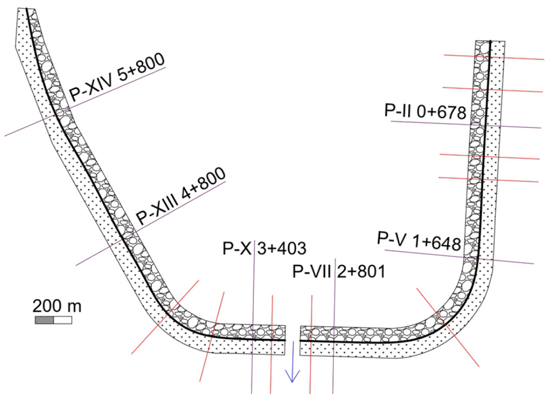

Fig. 3. Location of piezometric cross-sections of the Otmuchów reservoir head dam (based on [29])

2.2. Nysa reservoir

As in the case of Otmuchów, the primary tasks of the Nysa reservoir, which was built in 1971, include flood protection and water storage for agriculture and shipping. In addition, the facility was built to allow aggregate extraction from the bottom of the reservoir. The basic technical parameters are: capacity – approx. 122 million m3, floodplain area – 2068 ha. The dam body of the Nysa reservoir has been founded largely over a layer of impermeable Miocene Tertiary sediments (clay and clay, locally with sand lenses). The maximum height of the structure is 13.7 m and the embankment has been formed as a single zone embankment of gravels and gravels with an addition of pebbles and clay. Material extracted from the site in the future reservoir bowl was used. The drainage of water from the embankment is carried out with a 300–350 mm diameter perforated vitrified clay pipe drain located at the base of the downstream slope in a reverse filter. On the drainage every 50 m there are collection pits from which pipelines divert water to the band ditches [30]. No additional insurance other than sod was used on the downstream slope, while the upstream slope was fully reinforced with a concrete screen together with a clay apron and clay screen, as illustrated in Figure 4.

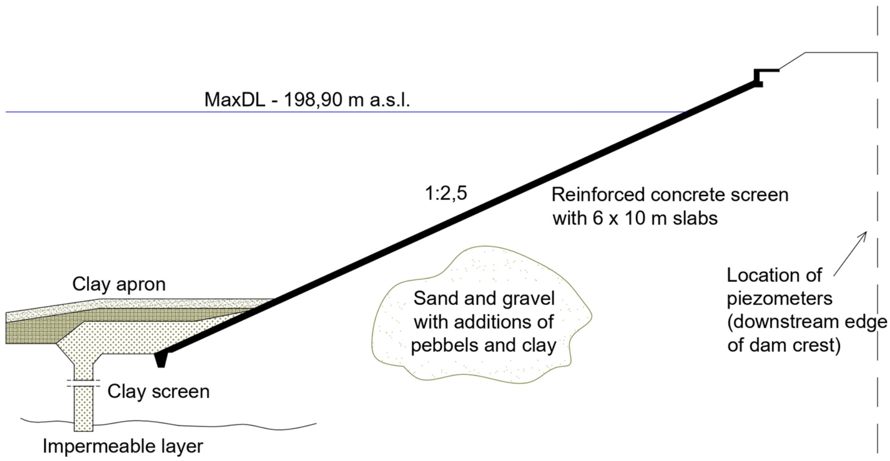

Fig. 4. Cross-section through the upstream side of the Nysa reservoir dam (based on [30])

The dependence of the water level in different parts of the dam on the water level in the reservoir and the rate of change was analysed. A significant correlation and the occurrence of large-amplitude dynamic fluctuations of the water table in the embankment could indicate areas with potentially lost impermeability, more exposed to the influence of seepage water and ultimately posing a threat to the safety of the entire facility. In order to properly assess the aforementioned relationship, statistical analysis of Pearson's correlation coefficient was applied to individual cross-sections of the Otmuchów and Nysa reservoirs. Due to the clay additions in the dam body, the embankment itself is characterised by limited filtration; however, the aforementioned $15 \times 6 \times 0.2$ m concrete screen of reinforced plates plays a key role here. Its topping, in the form of a reinforced concrete spike, reaches 1.1 m below the ground surface and connects to a clay apron that continues into a clay screen that is up to 30.7 m deep (14.4 m on average) and reaches impermeable layers. In order to control filtration through the dam body, it was equipped with 118 piezometers in 29 cross sections, the location of which is shown in Figure 5. Analogously to the case of the Otmuchów reservoir described earlier, in order to determine the water level in the embankment, readings from piezometers located at the width of the dam crest were selected for two characteristic periods between 2020–2022, i.e., maximum and minimum water damming in the reservoir. Seven of the above piezometers installed in cross sections II, V, and X (left side), XIII and XVIII (middle section), and XXII and XXVII (right side) were selected to assess the performance of the impermeable protection.

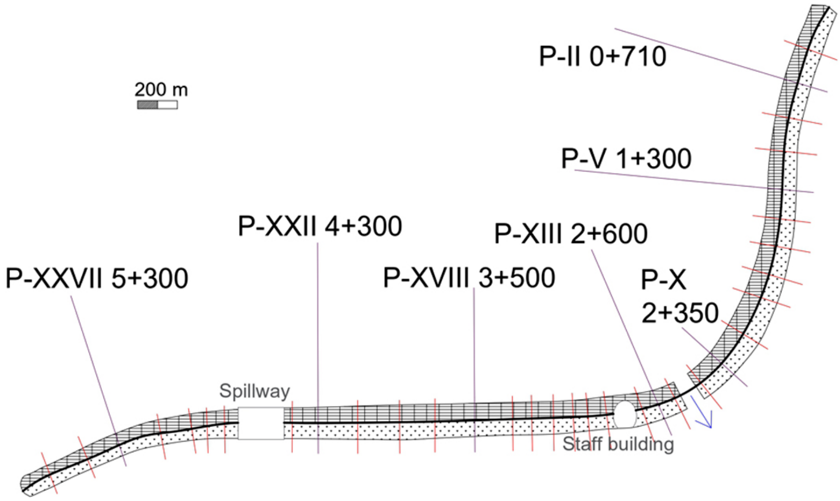

Fig. 5. Location of piezometric cross-sections of the Nysa reservoir head dam (based on [30])

In order to establish the scale and frequency of the repair and maintenance activities carried out on the two facilities, particularly in aspects of waterproofing the dam body and the need to repair the upstream slope stability assurance directly exposed to filtration and waves, a field inspection was carried out, searches of archival and current technical and operational documents were made, and a dialogue was held with individuals responsible for the management of the facilities under study.

3. Results

3.1. Water level in the dam body

In order to determine the level of water seeping through the dam body, the results of pressure measurements at piezometers located across the width of the dam crest were collated at all available control cross sections. For the period from the beginning of 2020 to the end of 2022, two points in time were selected where the water level in the reservoir was highest and lowest. For the Otmuchów reservoir, these were on 1 July 2020 and 3 November 2021, and for the Nysa reservoir – on 19 October 2020 and 13 October 2021. The results are presented in Figures 6–9.

Pressure measurements in piezometers indicate that the water level in the dam body of the Otmuchów reservoir remains constant regardless of the volume and height of water stored in the reservoir. In the section from 0+000 to 1+100, the water level is high, decreasing along the embankment between 7 and 10.5 m below the ordinate of the dam crest. The water level then drops sharply to a depth of approx. 21.5 m in the vicinity of the bottom outlet, after which it gradually rises up to cross-section 4+800 reaching a depth of approx. 16 m. The water level in cross-section 5+800 fluctuates considerably (further on in Figure 11) which, due to the lack of correlation with the height of the water table in the reservoir, may be directly related to fluctuations of the groundwater level in the vicinity of the right end of the embankment or is the result of a malfunctioning measuring device. Incorrect (in relation to

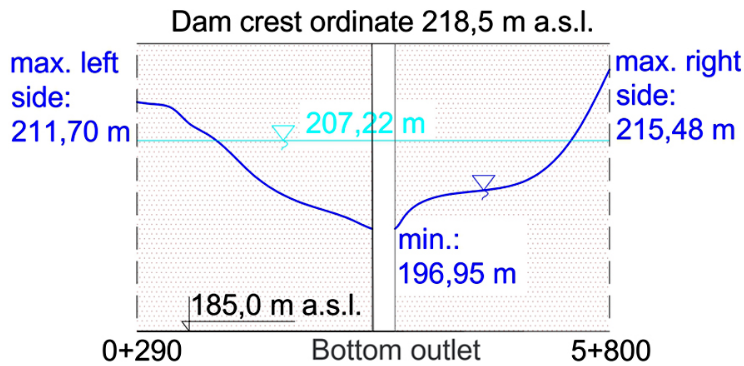

Fig. 6. Water level at the Otmuchów reservoir dam on 1 July 2020

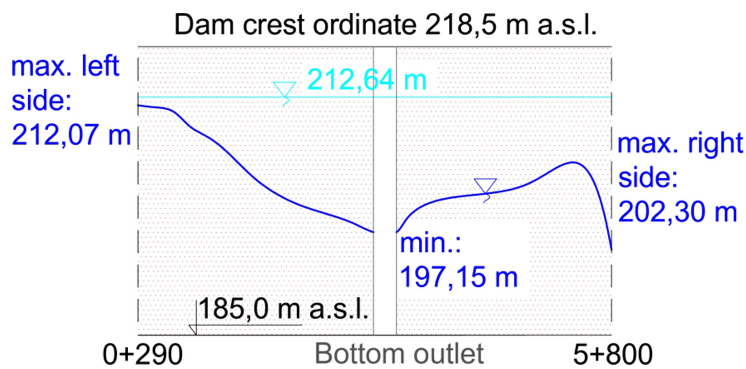

Fig. 7. Water level in the Otmuchów reservoir dam on 3 November 2021

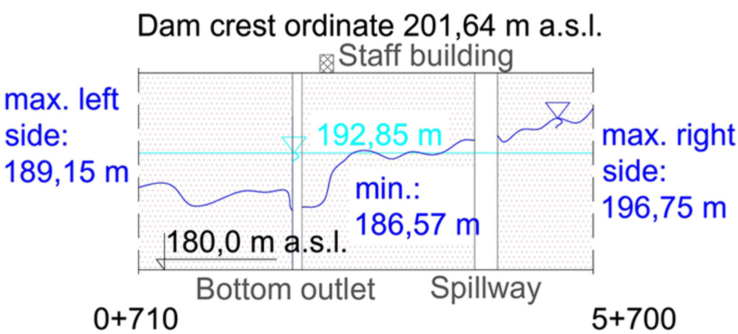

Fig. 8. Water level at the Nysa reservoir dam on 19 October 2020

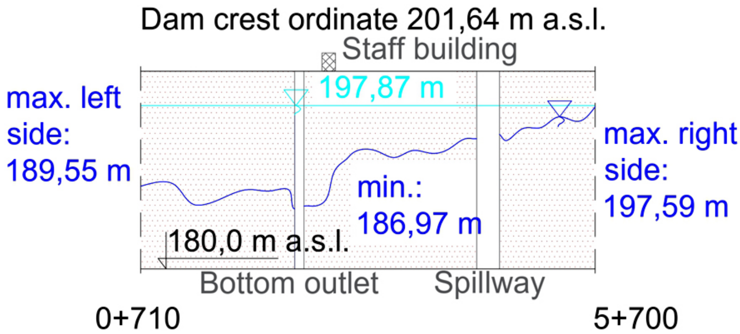

Fig. 9. Water level at the Nysa reservoir dam on 13 October 2021

the actual state) piezometric readings are a sporadic phenomenon. In the study carried out for 82 piezometers of the Koronowo reservoir dam between 2010 and 2015, statistical tests revealed 56 outlier observations, which accounted for 0.2 ‰ of all results. Potential causes were identified as a mistake by the person carrying out the test, incorrect choice of measurement method, unfavourable weather conditions or mechanical damage to the piezometer [31].

As in the case of the Otmuchów reservoir, for the Nysa reservoir, no significant changes were observed in the shape of the water level distribution in the dam body depending on the height of the water table accumulated in the structure's bowl. The depth of water in the embankment in the section from 0+000 to 2+700 ranges from 12.5 to 15 m, with the lowest point reached at the height of the bottom outlet, the latter circumstance corresponding to the situation in the Otmuchów reservoir. A sudden jump in the water level of 3.8 m was observed between cross sections 2+700 and 2+800, i.e., at the height of the technical facilities building. Subsequently, until the end of the dam at cross-section 5+700, a rounded linear drop in depth is recorded, with no significant interference of the surface overflow, finally stopping at a level of approx. 5 m below the crest ordinate.

3.2. Fluctuation of water level in the dam body depending on the height of damming

In order to assess the impermeability of the studied dams and, above all, the effectiveness of the applied impermeable solutions, the fluctuation of the water table level in the embankment depending on the amount (height) of water stored in the reservoir was analysed for the period from the beginning of 2020 to the end of 2022. For both sites, characteristic piezometers located along the width of the dam crest in cross sections located in the left, right, and centre of the embankment were selected. The results of the measurements are shown in Figures 10, 11 and 12.

In the case of the Otmuchów reservoir, only a slight correlation was observed between the fluctuation of the water level in the reservoir and the vertical displacement of the water level in the dam body. A sudden change in the amount of water in the reservoir does not cause sudden jumps in pressure in the piezometers, but only a gradual increase or decrease. During the observed period, the damming height ranged from 207.22 to 212.64 m above sea level, remaining at 210.42 m above sea level on average. In the piezometers on the left side, the situation was different for cross-sections II and V, where for the former, the water level was above the water level in the reservoir most of the time, indicating a connection with the general groundwater level in the area and the absence of a significant influence of seepage on the recharge of the ground. In cross-section V, the difference between the lowest and highest water levels was 1.5 m. The lowest level of filtered water was maintained in the middle part of the body, and the highest pressure values for cross-sections VII and X were reached on

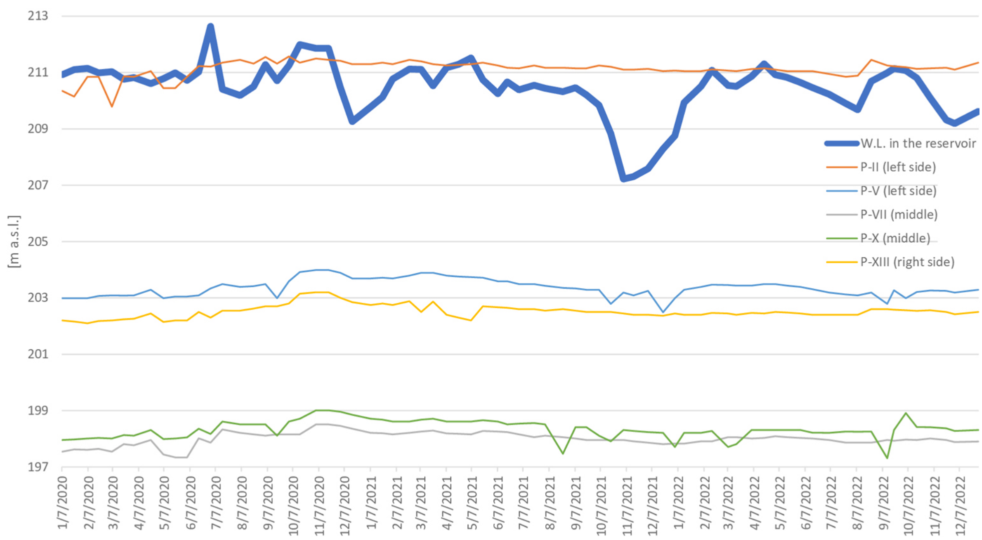

Fig. 10. Data from selected piezometers at the Otmuchów reservoir dam between 2020 and 2022

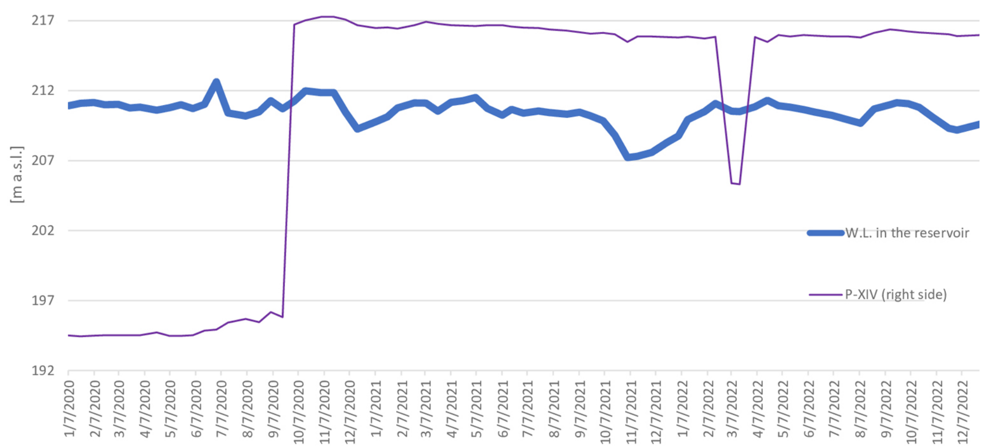

Fig. 11. Piezometer data from cross-section XIV of the Otmuchów reservoir dam for the years 2020–2022

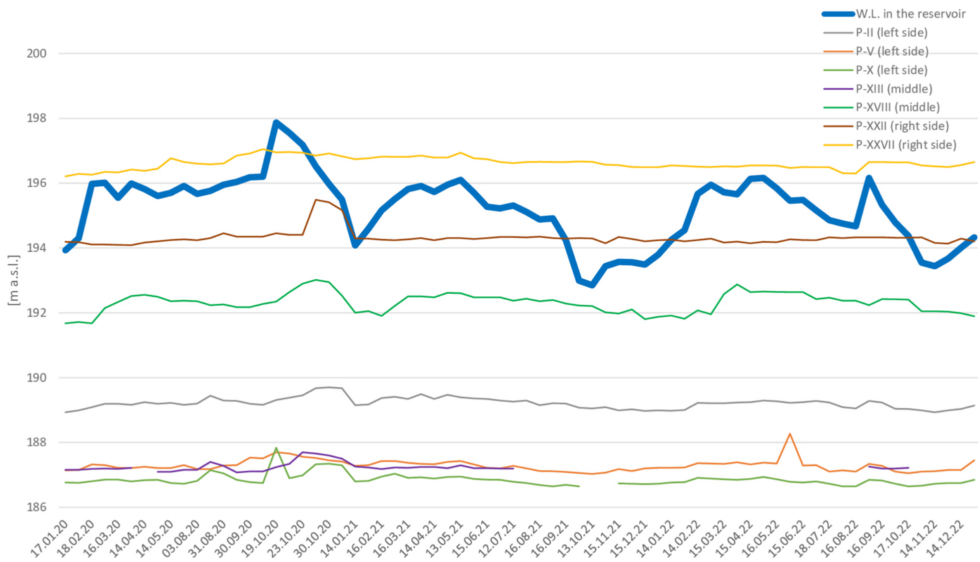

Fig. 12. Data from selected piezometers of the Nysa reservoir dam between 2020–2022

18 November 2020, i.e., after a period when the amount of retained water was noticeably higher. Subsequently, the level gradually decreased from that day onwards; however, without any apparent relation to the changes in the water level in the reservoir and only in the range of 0.6 m for cross-section VII and 0.7 m for cross-section X. On the right side, in cross-section XIII, a similar shape of pressure distribution was recorded as for cross-sections II, V, VII, and X. Statistical analysis of the correlation between the water table level in the reservoir and the water level in individual cross-sections showed a low positive correlation (Pearson coefficient <0.2) for all cross-sections except V, where it was slightly higher, but did not exceed the Pearson coefficient of 0.37.

The anomalies apply to cross-section XIV, as indicated in separate Figure 11. The sudden jump in pressure in the piezometer at cross-section XIV, indicating an increase in the level of seeping water in the embankment of approx. 21 m, is not related to a fluctuation in the amount (height) of water stored in the reservoir. Such a circumstance could be explained by a local rise in the groundwater level, but a jump from 195.82 m above sea level to 216.73 m above sea level within a maximum of 14 days would have to be indicative of sudden and intense rainfall, which is not confirmed by the data on the weather conditions occurring at the time. Furthermore, the subsequent persistence of such a high water level for a period of approx. 1.5 years, the sudden drop to an ordinate of approx. 205.00 m above sea level on 7 September 2022 and 17 September 2022, followed by a return to the previously read high values of approx. 216.00 m above sea level. The lack of rational justification for this phenomenon leads to the conclusion that the measuring device in section XIV is malfunctioning [31] and should be repaired or replaced once this hypothesis is confirmed.

The Nysa reservoir experienced fluctuations in dammed water levels between 2020 and 2022, ranging from 192.85 m above sea level on 13 October 2021 to 197.87 m above sea level on 19 October 2020. At all analysed measurement cross-sections, except for cross-section XXVII, a response was observed to the sudden surge in water height that took place in October 2020. On the left side, this response did not result in significant changes in the water table level, and in the piezometer pressures for cross-sections II, V, and X indicated fluctuations of 0.77 m, 1.24 m, and 1.19 m, respectively, for the entire analysed period. In the middle section, especially for cross-section XVIII, the correlation between the water level in the reservoir and the water level in the embankment is clear and indisputable, and the piezometer reacted to both increases and decreases in the amount of water retained. In the case of cross-section XIII, the measuring device ceased to function properly after 12 July 2021, which is a circumstance indicating some wearing out of the functioning control and measurement system. On the right, the water level in cross-section XXII rose markedly after the water level peak on 19 October 2020, after which it stabilised at a height of approx. 194.30 m above sea level and did not react further to further movements of the water level. The readings for the piezometer in cross-section XXVII showed no significant correlation with the water level in the reservoir.

There is also a noticeable delay in the peak height of the water table in the embankment in relation to reaching the maximum damming height in the reservoir, as illustrated in Figure 13 on the example of cross sections XVIII and XXII for the period from 15 September 2020 to 29 January 2021.

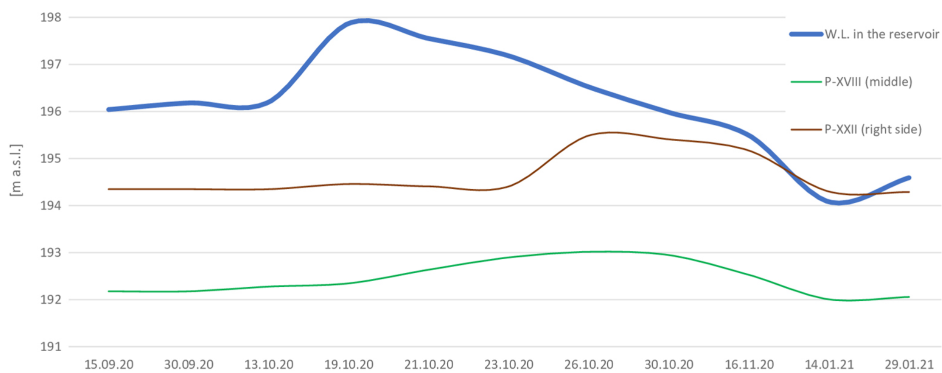

Fig. 13. Data from piezometers at cross sections XVIII and XXII of the Nysa reservoir dam during the period after increased damming height

The sudden increase in water level from 196.2 m above sea level to 197.87 m above sea level between 13 October 2020 and 19 October 2020 caused movement of the water level in the dam body resulting in its rise by approx. 1 m in cross-section XXII and 0.7 m in cross-section XVIII. The peak heights in both of these cross sections were reached at most on 26 October 2020, when the amount of retained water was already lower. This indicates that approximately one week is needed for the seeping water to get from the upstream slope to the width of the downstream edge of the dam crest. This is also confirmed by statistical analysis of the relationship between the water table level in the reservoir and the water level in cross-section XVIII. When values from the same day are adopted for both of these heights, a graph with an indistinct linear relationship and a Pearson correlation coefficient of 0.58 is obtained. Examining the same relationship, however, adopting the values of the water level in the embankment with a delay of about 14 days, a graph indicating an indisputable linear relationship with a Pearson correlation coefficient of 0.76 is obtained. The graphs are presented in Figure 14.

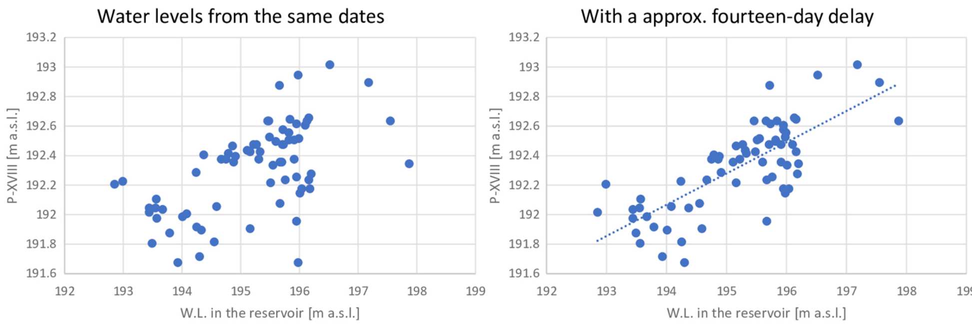

Fig. 14. Diagrams of the dependence of the water level in section XVIII on the water level in the reservoir

3.3. Repair measures due to functioning of seepage prevention structures

As the clay screen, which is the impermeable protection for the Otmuchów reservoir dam, is located inside the embankment, a simple organoleptic assessment of its condition is not possible, and it will be very difficult to carry out a direct repair of this element. In the event that a local disturbance of the water level in the dam or an increase in the flow velocity of the seeping water is observed, it would be necessary to introduce an alternative technological solution to seal the facility.

An indirect effect of the choice of an impermeable solution not located on the upstream slope is the need for additional strengthening of the body in a place exposed to the movement of the water table. In the case of the Otmuchów reservoir, this slope was reinforced with one or two layers of crushed stone 40–60 cm thick, and throughout the entire period of operation was subject to revitalisation measures, which are summarised and described in Table 1, where the inventoried scale of damage in individual years is also indicated.

The need for repairs to the reinforcement of the upstream slope of the Otmuchów reservoir has existed for a short period of time since its creation, with different technologies being adopted over the decades, ranging from filling potholes with stone rubble and pouring concrete over the existing reinforcement, to laying a stone lining embedded in concrete poured over a geotextile separating it from the aggregate filter layer (sub-base). According to the inventory carried out in 2021, 10 years after the renovation using this technology, the repaired areas are in good technical condition. Regardless of this, it was found that the sum of damages on the upstream slope requiring revitalisation again exceeded 10,000 m^2, indicating a high rate of degradation of the existing reinforcement. Between 1997 and 2011, it averaged less than 1,000 m^2 per year, which is a similar value to the period 2011–2021 (1,100 m^2/year).

Table 1. Damage and revitalisation activities on the upstream side of the Otmuchów reservoir dambody [32, 33]

Year	Damaged surface [m^2]	Scope of the renovation
1933–1944	n.a.	Filling of breaches with stone rubble
1949–1955	n.a.	Pouring concrete into the paving joints in a 5 m wide strip between the water level fluctuation ordinates
1965–1969		
1972	n.a.	Setting down stone paving on a ballast base
1978		
1984	6,000	–
1986–1988	n.a.	Laying of wedged stone overlay on aggregate filter
1994	2,150	–
1994–1996	n.a.	Ongoing repairs (no exact data available)
1997	1,850	–
2000	2,000	–
2004	6,400	–
2010–2011	15,000	Stone facing on concrete, geotextile, and gravel sub-base
2021	11,000	–

The situation is different in the case of the Nysa reservoir, where the element with an impermeable function, i.e., a screen made of concrete slabs, also constitutes the main reinforcement of the upstream slope. This solution generally improves the operation by reducing the frequency of actions taken to reverse the negative effects of damming water, however, it poses the risk of losing the integrity of the facility as a result of damage to the reinforcement in question. In addition, due to the complex nature of the concrete screen revitalisation works, these are works of a larger scale, generating greater costs and requiring more extensive preparations. The remedial measures carried out on the dewatering side of the Nysa reservoir are summarised and described in Table 2.

The main problem associated with the operation of the upstream slope stability assurance for the Nysa reservoir is the loss of integrity at the expansion joints between the concrete slabs, which was identified as early as the first decade after the construction of the facility. Initial repairs using asphalt compounds proved to be ineffective in the long term, and after several years most of the rehabilitated expansion joints had degraded. Despite the 2005 remedial measures covering the most damaged areas of the screen, the progressive deterioration contributed to the need for a major refurbishment that began in 2013, i.e., 42 years after the facility began operating. It covered almost the entire expansion joints (in the above-water part) and a total of approx. 3,640 m^2 of concrete slabs, which, despite the significant scale

Table 2. Damage and revitalisation activities on the upstream side of the Nysa reservoir dam body [34,35]

Year	Scale of damage	Scope of the renovation
approx. 1982	Damage to the edges of slab expansion joints (above water level) as a result of filling them with mortar; local loss of screen integrity	–
1987	95 expansion joints permanently under water were inventoried; numerous damages to the concrete cover, 11 joints in poor condition	Repair of expansion joints above water level using mineral-asphalt compounds
1989–2005	Gradual degradation of the used asphalt compounds; damage to the screen plates in the water fluctuation zone	–
2005	–	Repair of some expansion joints and slabs above water level (including complete replacement)
2012	Slabs to be replaced – 2300 m^2 Deep cavities – 370 m^2 Shallow cavities – 970 m^2 Cracks – 1,040 m Damaged expansion joints – 14,000 m	–
2013–2016	–	Repairs to the entire slope (above water level); dislodging of damage and replenishment of concrete; removal of asphalt from expansion joints and their reprofiling; replacement of significantly damaged slabs
2019	Cracks in repaired areas; surface peeling of concrete – 440 m^2	–

of the project, represents only approx. 3% of the total fortification (including the underwater part). The inventory carried out 3 years after the repair, however, showed the appearance of cracks and scratches in the places of the performed repairs (especially on expansion joints), which may indicate the worsening load capacity of the soil under the screen. The identification of numerous areas of peeling surface concrete suggests the possibility of deeper defects in subsequent years of operation of the reservoir. It should also be emphasised that the repairs were only carried out for the zone above the water level, and the inventory of the underwater area carried out back in 1987 showed some damage to the expansion joints located there. This circumstance may prompt consideration of a revitalisation of the strengthening of the upstream slope in the underwater area as well, or at least a reassessment of its current condition.

4. Discussion

The analysed results of piezometric measurements confirm the effectiveness of the applied impermeable solutions for both studied objects. The movement of the water table in the body of the Nysa reservoir dam is more clearly correlated with the level of damming than in the case of the Otmuchów reservoir, but these fluctuations are considerably delayed and their extent does not indicate the occurrence of local leaks threatening the safety of the structure. A deterioration in the condition of the measuring equipment has, however, been observed, which concerns the piezometer in cross-section XIV of the Otmuchów reservoir dam, indicating readings of questionable reliability and in cross-section XIII of the Nysa reservoir dam, for which since mid-2021 only sporadic results have been obtained. Such a circumstance may have a negative impact on the proper determination of the actual state of leakage at the various dam locations and is particularly unfavourable for the operation of the Otmuchów reservoir, where there are only 15 piezometric cross-sections over the entire dam length of approx. 6 km.

Both facilities, due to their long period of operation, experience damage problems on the upstream side of the dam body. They have different characteristics and it can be seen that the approach to ongoing repairs has evolved over the years, resulting in the identification of ineffective measures and the development of solutions that are most favourable for use on this type of reinforcement. Nonetheless, it must be assumed that damage will continue, and more and more resources will need to be committed to the necessary repairs. Progressive climate change and the consequent more frequent occurrence of extreme weather events and more intense fluctuations in water levels in reservoirs may increase the rate of damage. At the same time, milder winters may paradoxically reduce the scale of damage, particularly in the case of the Otmuchów reservoir, where fragments of the ice cap freezing to the stone pavement under the influence of wave action tear away less firmly stuck stone blocks. Regardless of this, wave action alone has a destructive effect on the strengthening and future consideration should be given to revitalising a larger area of the upstream side than just the damaged areas, which would, however, involve a significant one-off cost that is often difficult for the user to afford. Of concern for the safety of the Nysa reservoir is the suspected degradation of the soil under the concrete screen on the upstream side, which should be subject to an appropriate expert opinion. Experience with problems of maintaining the proper condition of expansion joints suggests that special emphasis should be placed on the quality and technology of their construction in newly built structures. In addition, a reduction in the size of the slabs could be effective to reduce deterioration. Such a solution was used during the revitalisation of the concrete screen of the Jeziorsko reservoir on the Warta River, where the old slabs were used as a base for new ones with a four times smaller surface area [21].

5. Summary

After a considerable lapse of time since the completion of construction of the Otmuchów and Nysa reservoirs, no significant leaks resulting from poor functioning of the applied impermeable solutions have been identified that could pose a threat to the safety of the structures. The water table in the dam body of Otmuchów reservoir is at least 7 m below the dam crest level, and its movement is not significantly correlated with a change in the water level, with the highest Pearson correlation coefficient calculated for cross-section V and equal to 0.37. For the Nysa reservoir, the minimum water depth in the dam is approx. 5 m below the dam crest and some piezometers closer to the middle part of the body reacted to a sudden increase in the amount of retained water. A significant dependence of the water level in the embankment on the water level in the reservoir was observed in cross-section XVIII, for which the Pearson correlation coefficient reached a high value of 0.76, but the peak in pressure height was not alarmingly dynamic and occurred with a delay of about a week. Both sites required frequent repairs to the upstream slope reinforcement. For the Otmuchów reservoir, a higher frequency of rehabilitation activities was assumed on a smaller scale, and there is currently a significant rate of degradation of the stone paving of approx. 1,000 m2/year. Repairs to the concrete screen of the Nysa reservoir mainly concerned leaking expansion joints. The use of asphalt masses to repair them proved ineffective for prolonged operation, which, among other things, contributed to a major overhaul carried out 42 years after the construction of the facility. Three years after its completion, cracks and nicks were found on the completed repairs, which may indicate that the ground beneath the concrete screen is degrading and that more or all of the slabs need to be considered for replacement.

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Ocena funkcjonalności elementów wodoszczelnych korpusu zapory po długim okresie eksploatacji – studium przypadku zbiorników Otmuchów i Nysa

Słowa kluczowe: hydrotechnika, rewitalizacja skarpy odwodnej, urządzenia przeciwfiltracyjne, zapora, zbiornik

Streszczenie:

W artykule dokonano przeglądu technologii wykonania i funkcjonowania elementów wodoszczelnych nasypów hydrotechnicznych. Opisano studium przypadku dwóch zbiorników retencyjnych znajdujących się w środkowym biegu rzeki Nysa Kłodzka: (1) Zbiornik Otmuchów funkcjonujący od 1933 roku, (2) Zbiornik Nysa funkcjonujący od 1971 roku. Poddano ocenie i porównano skuteczność pracy zastosowanych przesłon przeciwfiltracyjnych, tj. ekranu iłowego zbiornika Otmuchów i ekranu betonowego zbiornika Nysa. Przeanalizowano odczyty z piezometrów znajdujących się na wysokości korony zapory wzdłuż całego jej profilu, dla pomiarów wykonywanych w latach 2020–2022. Rozpatrzono takie wskaźniki jak rozkład i głębokość zwierciadła wody z zaporze oraz zmiany ciśnienia w piezometrach pod wpływem wahań poziomu wody w zbiorniku. Ponadto przeanalizowano skalę i częstotliwość działań remontowych oraz konserwacyjnych przeprowadzonych na obu obiektach, szczególnie w aspektach doszczelniania korpusu zapory oraz konieczności napraw ubezpieczeń skarpy strony odwodnej – bezpośrednio narażonej na filtrację i falowanie. Stwierdzono, że mimo długiego okresu pracy obu obiektów zachowują one prawidłową szczelność, a głębokość zwierciadła wody w nasypach jedynie nieznacznie reaguje na wahania ilości retencjonowanej wody. Ta korelacja wyraźniejsza jest bliżej środkowej części zapory zbiornika Nysa, gdzie skokowy wzrost wysokości piętrzenia spowodował pionowy ruch zwierciadła wody w nasypie, jednakże z ok. tygodniowym opóźnieniem. Wskazano, że obie przyjęte technologie uszczelniające wiązały się z koniecznością licznych działań rewitalizacyjnych, głównie w związku z dynamiczną degradacją bruku kamiennego w obszarze wahań poziomu piętrzonej wody w przypadku zbiornika Otmuchów oraz utratą szczelności na dylatacjach płyt betonowych zabezpieczających skarpę odwodną zapory zbiornika Nysa.

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