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ANALYTICAL VERIFICATION OF OUTLET DEVICES CAPACITY OF LUBACHÓW STORAGE RESERVOIR ON THE BYSTRZYCA RIVER

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Abstract: The Lubachów storage reservoir was built in the 1920's. It is equipped with a relatively complex outlet installation, operating in variable hydraulic regime. The discharge deviations curves elaborated by German engineers for individual devices, after verification turned out to be burdened with a comparatively big error. This concerns especially the front spillway as well as intermediate outlets, and to a smaller degree the bottom outlets. The authors made a detailed analytical verification of the outlet installations and found great deviations from the currently valid discharge curves for these devices. Based on the analysis of conditions of computational discharges passage through the reservoir, they proved a high potential threat of water flow over the dam crest.

1. INTRODUCTION

The Lubachów storage reservoir on the Bystrzyca River was designed for the needs of flood protection of downstream areas as well as electric energy production by a small hydro power plant located downstream. In the 1970's to previous tasks a water uptake for industry was added, which in the 1990's was changed to serve municipal aims. Because the reservoir storage is small and water needs are great, the flood protection function was delimited by splitting an insignificant flood control storage in the reservoir. This brought about certain fears if with the moment of flood wave inflow, for example design wave, into reservoir there is a real possibility of its failure-free transformation to tailwater, without any damage to the object itself and to downstream area.

In the first phase of this study the authors carried out an analytical verification of capacity of existing outlet devices, because of more and more frequent opinions about their possible over-dimensioning by German engineers. In the paper, the results of calculations are presented.

2. OBJECT DESCRIPTION

The Lubachów storage reservoir [1] was formed as a result of river partitioning at 80+143 km of its watercourse by stone dam. Reservoir capacity at water level corresponding to the dam crest elevation of 352.0 m a.s.l. equals V_{zb} = 9.1 mln m^3, with reservoir area of about 51 ha and resultant backwater length of about 3 km.

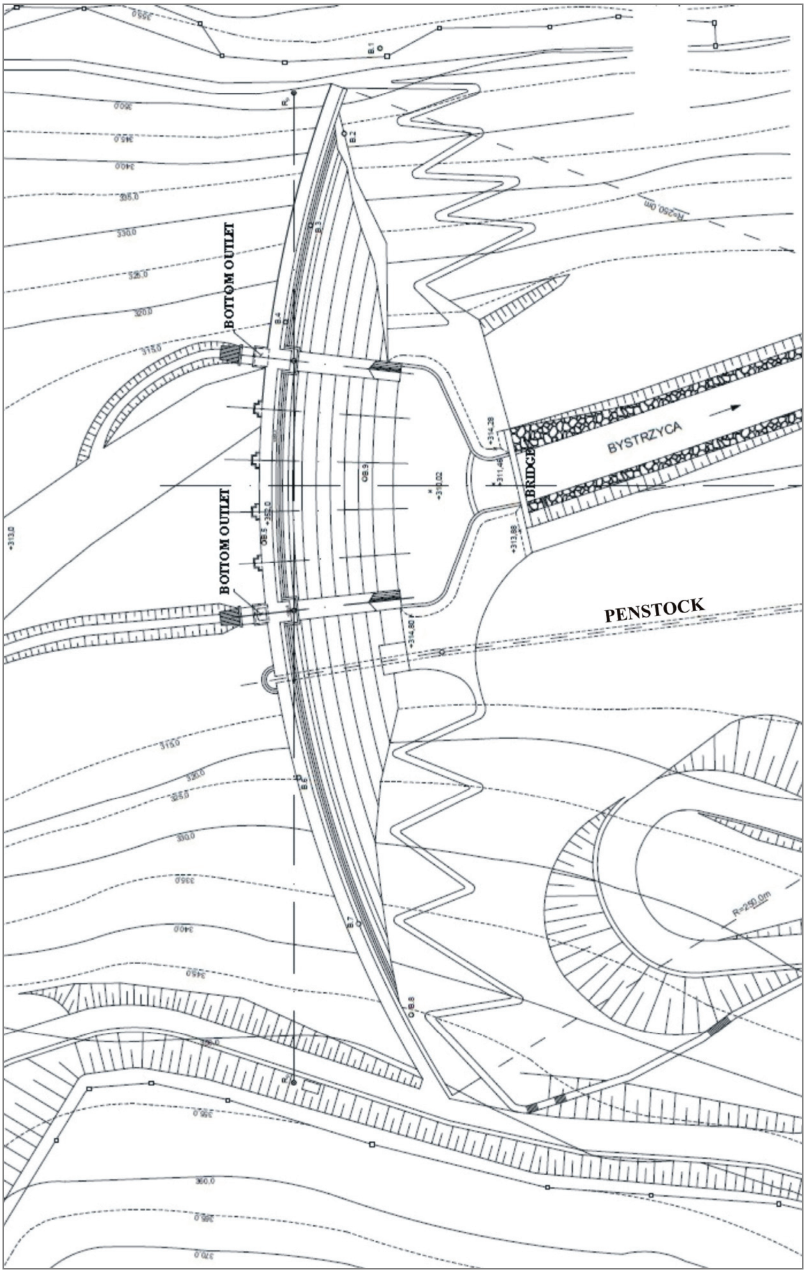

Fig. 1. Functional plan of the Lubachów storage reservoir dam

The dam body was built with natural local stone on cement mortar as monolithic structure without expansion joints. It was founded on concrete layer, levelling the ground of biotite gneiss. The average dam width at the base equals 29 m. The radius of the dam circular arch at the crest level is equal to 250 m (Fig. 1). Upstream dam body slope up to elevation of 343.50 m a.s.l. is covered by cement mortar of 6.50 cm in thickness, above this level it is covered by protective stone pointing by cement mortar. Downstream dam body slope is faced with local stone pointing by cement mortar. The dam crest width is equal to 3.50 m and its elevation is 352.0 m a.s.l. The dam length at crest equals 230.50 m, and at a base about 80 m, a minimum foundation elevation is 308.0 m a.s.l. The dam crest is topped with service road, with pavement made of granite cubes on concrete layer.

The powerhouse is located about 1.0 km downstream from the dam. It is founded on rock, which is a support for dam body. In a turbine room there are three turbine sets installed, conduits that supply water to the turbines are laid perpendicularly to longitudinal wall of the building and are a branching of the main supply conduit of 1800 mm in diameter. The penstock fulfils a double function; it delivers water from the reservoir to the hydro power plant and to the intermediate pumping station for water supply purposes.

3. RESERVOIR OUTLET DEVICES

Outlet devices of Lubachów reservoir consist of front spillway in the form of 10 orifices, 4 intermediate outlets, 2 conduits of bottom channel, water intake for small hydro power station and potable water intake, stilling basin joining a trained by erosion-control step the Bystrzyca River bed [1].

Spillway consists of 10 orifices located in the central part of the dam. The shape of opening cross-section is close to a semicircle with the weir crest elevation at 350.0 m a.s.l. (Fig. 2). The width of each opening in its lower part equals 3.60 m, and maximum height is 1.30 m. Because of spillway cross-section shape, height position of upper and bottom edge, and also irregular changeability of its cross-section area as a function of height from weir crest (bottom edge) the spillway works in variable hydraulic regime. When a water level in reservoir reaches an elevation of 351.40 m a.s.l., the upper edge of spillway becomes submerged and the character of flow changes from overflow to outflow from big not submerged orifice [1], [2].The capacity of overflow spillway (according to archival German data) was estimated to be about 200 $m^3 s^{-1}$ for water level in reservoir corresponding to dam crest elevation at 352,0 m a.s.l. A view of the front spillway is shown in Fig. 2 and a spillway cross-section is shown in Fig. 3.

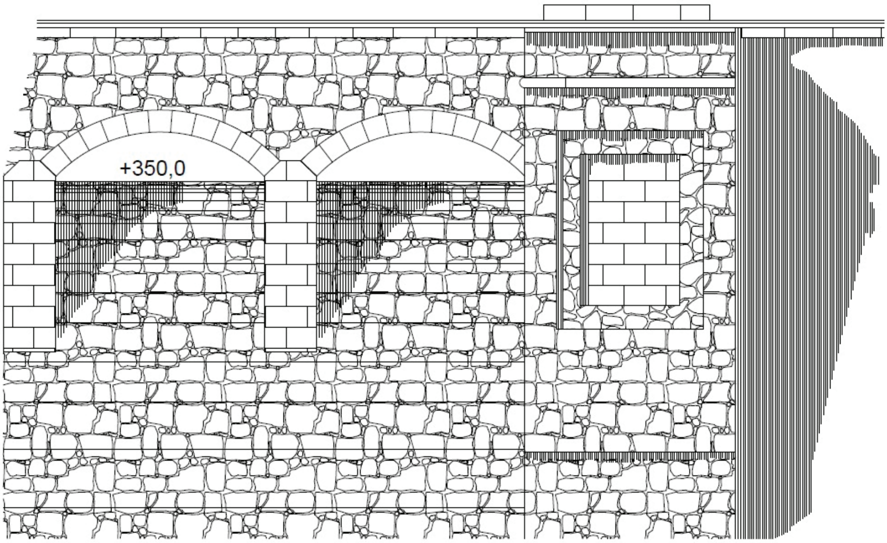

Fig. 2. View of the Lubachów storage reservoir free spillway

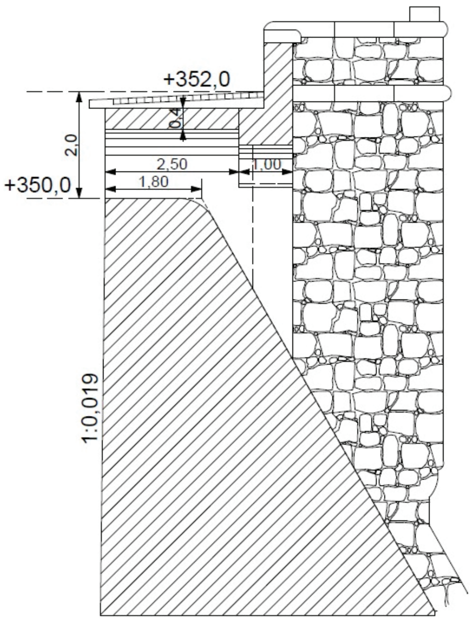

Fig. 3. Cross-section of the Lubachów storage reservoir free spillway

Four conduits of intermediate outlet are placed in the middle part of the dam body. Each inlet conduit, with dimensions of 1.60 m in height and 1.0 m in width and edge elevation of 332.0 m a.s.l., is being closed by a vertical lift gate with electric drive, that is placed on the dam crest. The mouths of intermediate outlets are placed on the downstream face of the dam, on the flowing off surface of ogee spillway. The upper edge elevation of each conduit's mouth is at 327.80 m a.s.l. [1], [2]. At water level in reservoir at 352.0 m a.s.l. the capacity of each conduit, taking into account a possible damping of an outflow by a spillway jet (according to archival German data) equals 24.0 $m^3\ s^{-1}$; the capacity without damping equals 28.40 $m^3\ s^{-1}$. A cross-section of one of the intermediate outlet conduits is shown in Fig. 4.

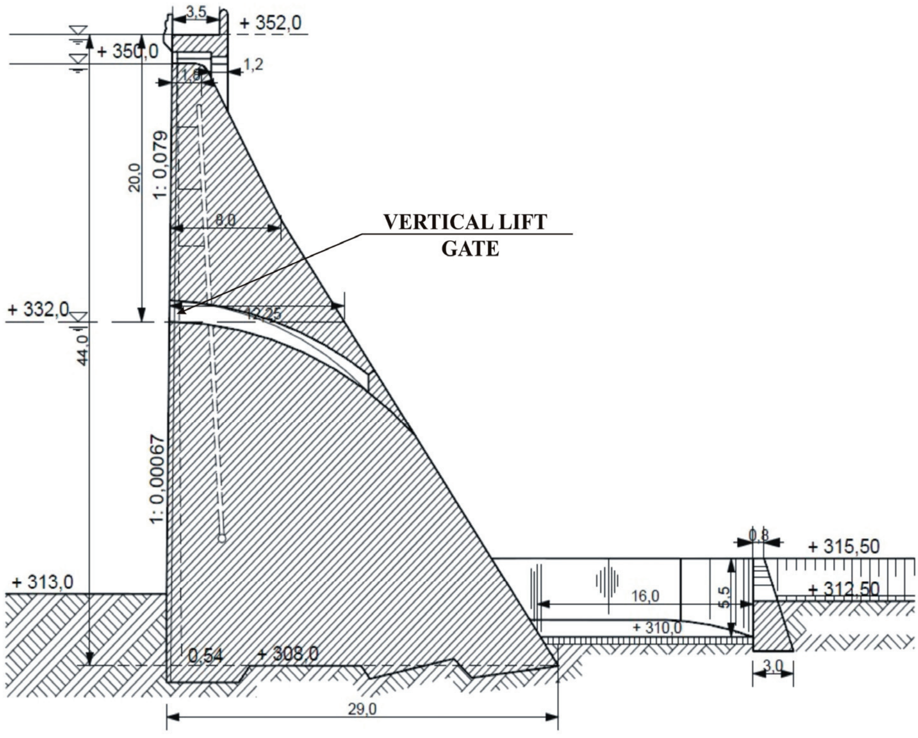

Fig. 4. Cross-section of the Lubachów storage reservoir intermediate outlet

Bottom outlets are placed at the left and right dam abutments. They consist of two conduits with a diameter of 800 mm and axis elevation at 313.70 m a.s.l. Both conduits are equipped with gate valves from headwater and tailwater. Inlet gates have also the manual operations, which are placed on dam crest. Gates at conduit mouths have also same manual operations, which are placed in stone buildings located at downstream dam base. Behind the gate valves the bottom outlets end by 90º bend inward into stilling basin. Bottom outlets are placed in tunnels of dimensions 2.50 by 2.50 m and length of 31.0 m. From headwater tunnels are closed by concrete stoppage [1], [2].

The capacity of each conduit (according to archival German data) was estimated at 11.50 $m^3\ s^{-1}$ for water level in reservoir at 352.0 m a.s.l. Cross-section of the one of the bottom outlets is shown in Fig. 5.

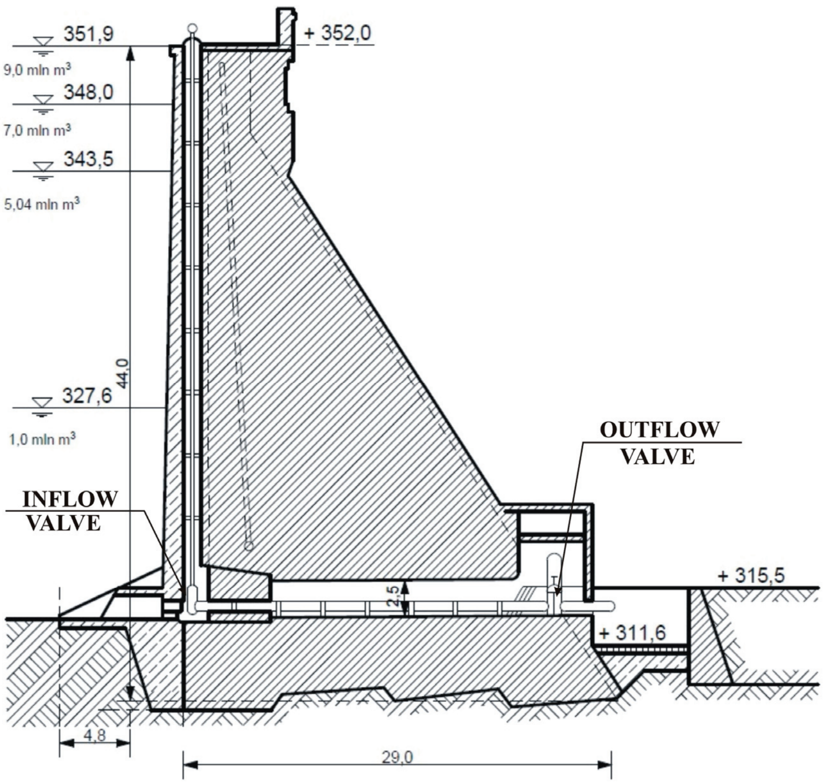

Fig. 5. Cross-section of the Lubachów storage reservoir bottom outlet

Water is delivered to three turbine sets by one penstock with a diameter of 1800 mm, whose axis elevation from the side of an inlet is at 323.00 m a.s.l. The conduit of total length equal 968.50 m is made of steel plate with riveted joints. The penstock is equipped with inlet and outflow gates. Manual operation from headwater is placed on dam crest, and manual operation from tailwater is located in special shaft at tailwater dam base. In the hydro power plant three turbine sets are installed, equipped with Francis turbines, placed in a spiral cast-iron casing with generators on a common shaft and nominal head is equal to 40.0 m. Total installed electric power of turbine sets is equal to 1.150 MW, and their total capacity is estimated at 4.60 $m^3\ s^{-1}$ for water level in reservoir at 346.0 m a.s.l.

The stilling basin is located downstream of the outflow face from spillway and intermediate outlets, also mouths of bottom channel are placed in it. Stilling basin is bowl shaped, the narrower part of which is closed by erosion-control step and is turned in flow direction. Stilling basin width at dam base equals 50 m, at 16 m downstream it narrows to 10 m in width, joining an outflow channel and the Bystrzyca River bed. Elevation of stilling basin bottom is at 310.0 m a.s.l., erosion-control step at 312.50 m a.s.l. Left and right sides of outflow channel and the Bystrzyca River bed downstream the stilling basin are protected by broken stone revetment (Fig. 1). Bottom width of both the outflow channel and the river bed is equal to 12 m.

In the currently valid exploitation and maintenance instruction for Lubachów storage reservoir, the capacities of outlet devices designed by German engineers are contained. In further period many times attention was paid to possible overdimensioning, especially of the front spillway [1], [2], but finally it has never been accepted for use by the object owner.

4. HYDROLOGICAL DATA – COMPUTATIONAL DISCHARGES

Hydrological data that are necessary for verification of capacity of reservoir's outlet devices, were taken from Jugowice gauging station, which is located at 85 + 044 km of the Bystrzyca River watercourse, on the right bank. Second gauging station is located in Lubachów, at 78 + 970 km of the Bystrzyca River watercourse, about 120 m downstream the mouth of outflow channel of hydro power plant, on the right river bank [4].

The Bystrzyca River catchment was flooded quite frequently in the past. According to historical records and sources major floods occurred in: 1464, 1496, 1530, 1560, 1585. In the years 1950–2010 the worst floods were in 1964, 1965, 1968, 1977, 1979, 1997, 2001, 2006 and 2010. The 1997 flood was the most extensive in the postwar history. The biggest floods in the Bystrzyca River basin occur most often in July and September, seldom in April. It is difficult to assess a scale of phenomenon, because historical records are not much precise and focus mainly on flood range and damage it caused. It was only at the beginning of the 20th century that daily observations of the Bystrzyca River water stages started.

Technical class of importance of reservoir is determined on the basis of Directive of the Poland's Minister of Environment of April 20, 2007 on technical conditions of hydrotechnical structures and their location [3]. At present, the main structures of Lubachów reservoir should be classified to the first technical class because damming up height H is higher than 30 m and simultaneously number of population L on flooded area, resulting from hypothetical failure of structure, is greater than 300 people.

Below, the values of design and control discharges for the first class of importance are given, assuming simultaneously that for hydrotechnical structures located on mountainous river, control discharge should be set with the upper extension α. Computational discharges for Lubachów reservoir are then:

$$Q_m = Q_{0.5\%} = 310 \text{ m}^3 \text{ s}^{-1},$$

$$Q_k = Q_{0.1\%} = 567 \text{ m}^3 \text{ s}^{-1},$$

$$Q_k^a = Q_{0.1\%}^{\alpha} = 801 \text{ m}^3 \text{ s}^{-1}.$$

5. THEORETICAL HYDRAULICS BASIS OF OUTLET INSTALLATION

In analytical calculations of capacity of outlet devices, first the operating conditions of a given device should be established, which are connected with mutual water level elevation and spillway crest elevation, also a hydraulic scheme determining a flow character – orifice, spillway, outlet submergence or lack of submergence. Because a capacity is a function of device parameters and flow velocity, that is why an acceptance of proper hydraulic scheme have the most significant impact on final determination the capacity of given device. Simultaneously, because some of devices are equipped in movable gates, hence, again a flow character should be set – over or under a gate and principles of its operation [5]–[9].

The above approach was applied for determination of capacity of Lubachów reservoir's outlet installations.

5.1. BOTTOM OUTLETS

The bottom outlets of Lubachów reservoir work under relatively favourable hydraulic conditions, an inlet from headwater is entirely submerged, mouth from tailwater is free [5], [7]–[9]. However, it should be mentioned that mouths of bottom outlets work as free till moment when front spillway starts its working, since even intermediate outlets work entirely, a river outflow is not significant to submerge the mouths of bottom outlets. In analysis of bottom outlets operations it is important to take into account the losses, both local and longitudinal as well, the more as a velocity will be considered, caused by water column of height over 35–40 m. It is also important to determine hydraulic characteristics of each conduit under conditions of changeable position of valve at its mouth [8].

5.2. INTERMEDIATE OUTLETS

The intermediate outlets of Lubachów reservoir also work under favourable hydraulic conditions. Their mouths remain free till the moment the spillway starts to work, as water flowing on dam face can damp an outflow from intermediate outlet. Another matter is the cross-section of intermediate outlet, it gradually decreases along its length from inlet to outlet; and also the fact that each conduit is drawn in arch with radius adjusted to curvature, resulting from orifice free water jet. Also a determination of its capacity variability with the change of opening degree of inlet gate is significant for this device operation. Hence, is was necessary to take into account in calculations of small discharges only inlet cross-section, whereas in calculations of big discharges the outlet cross-section. A determination of the moment of cross-section change from inlet to outlet was the most difficult, moreover a fact of a certain flux aeration, and also an impact of front spillway operation on outflow conditions from intermediate outlets [5], [6], [9].

5.3. FRONT SPILLWAY

On the basis of preliminary analysis of the capacity of this device, one might think that Lubachów reservoir's spillway works under the most favourable hydraulic conditions. However, precise analysis of this device cross-section parameters allowed to state that not under all conditions, related to water levels in reservoir, the spillway works as not submerged. When water level reaches the spillway crest and water starts to overflow its cross-section, a work of weir is defined as front spillway with a straight insert on its crest; with further rising of water levels the spillway is defined in the same way but with changeable width, whereas when water level reaches weir's upper edge the flow character changes and spillway works as big, not submerged orifice (Fig. 2) [5]–[7], [9].

6. ANALYTICAL VERIFICATION OF OUTLET DEVICES CAPACITY

6.1. BOTTOM OUTLETS

Assuming first the bottom outlet operation with not submerged mouth, the capacity of a single conduit can be expressed as follows [5], [7], [8]

$$Q = \mu\, A\, \upsilon = \frac{1}{\sqrt{1 + \lambda \dfrac{L}{D} + \xi_{kr} + \xi_{wl} + \xi_{zg} + \xi_{zd} + \xi_{k}}}\, A \sqrt{2\, g\, H} \tag{1}$$

where:

- Q – discharge in bottom outlet conduit; m^3 s^{-1},
- μ – discharge coefficient of conduit,
- A – cross-section of conduit; m^2,
- υ – flow velocity in the conduit; m s^{-1},
- g – gravitational acceleration; 9.81 m^2 s^{-1},
- H – hydraulic head, calculated as difference between water level in reservoir and axis of conduit; m,

λ – hydraulic friction factor, determined on the basis of the Colebrook–White equation, for iron pipes with a long period of exploitation $\lambda = 0.0250$ is assumed,

L – length of conduit; $L = 31$ m,

D – conduit diameter; $D = 0.80$ m,

ξ_{kr} – loss coefficient on grate at conduit inlet, $\xi_{kr} = 0.097$,

ξ_{wl} – loss coefficient at inlet, $\xi_{wl} = 0.10$,

ξ_{zg} – loss coefficient at gate from headwater, depending on gate opening degree, for fully opened gate it is $\xi_{zg} = 0.10$,

ξ_{zd} – loss coefficient at gate from tailwater, depending on gate opening degree, for fully opened gate $\xi_{zd} = 0.10$ is assumed,

ξ_k – loss coefficient due to direction change (90º bend), $\xi_k = 0.51$ is assumed.

The results of calculations show a significant departure from currently valid discharge curves (original design), particularly in the case of small openings of the gate at the mouth of the conduit. This results from the fact that local losses in the case of small opening are significant, influencing essentially the value of discharge coefficient. Verified results of calculation in a graphical relation of water level elevation and gate opening degree from tailwater, are shown in Fig. 6. For fully opened gate at mouth of conduit and for water level in reservoir at 352.0 m a.s.l., capacity for this device equals 8.125 $m^3\ s^{-1}$. Simultaneously, in Fig. 7 a comparison of currently valid discharge with verified one is shown, for fully opened gate and water level at 352.0 m a.s.l.

The moment the four conduits of intermediate outlets start working under conditions of damming up level at 350.0 m a.s.l. (spillway crest elevation) and the gates are fully opened, the outflow equals 85 $m^3\ s^{-1}$, which means that outflow from bottom outlets still remains not submerged. Just when spillway openings start operating, downstream water level gradually rises. This causes a change of outflow character from not submerged to submerged one, which is equivalent to a change of hydraulic conditions of bottom outlets operating. It should be calculated from [5]

$$H \geq \Sigma\, h_{str} \tag{2}$$

where:

H – head, calculated as a difference between water level elevation in reservoir and tailwater level,

h_{str} – sum of local and length losses, calculated for the above case.

From the above condition after transformation a flow velocity is determined; velocity is smaller if tailwater level is higher. Subsequently a discharge is calculated.

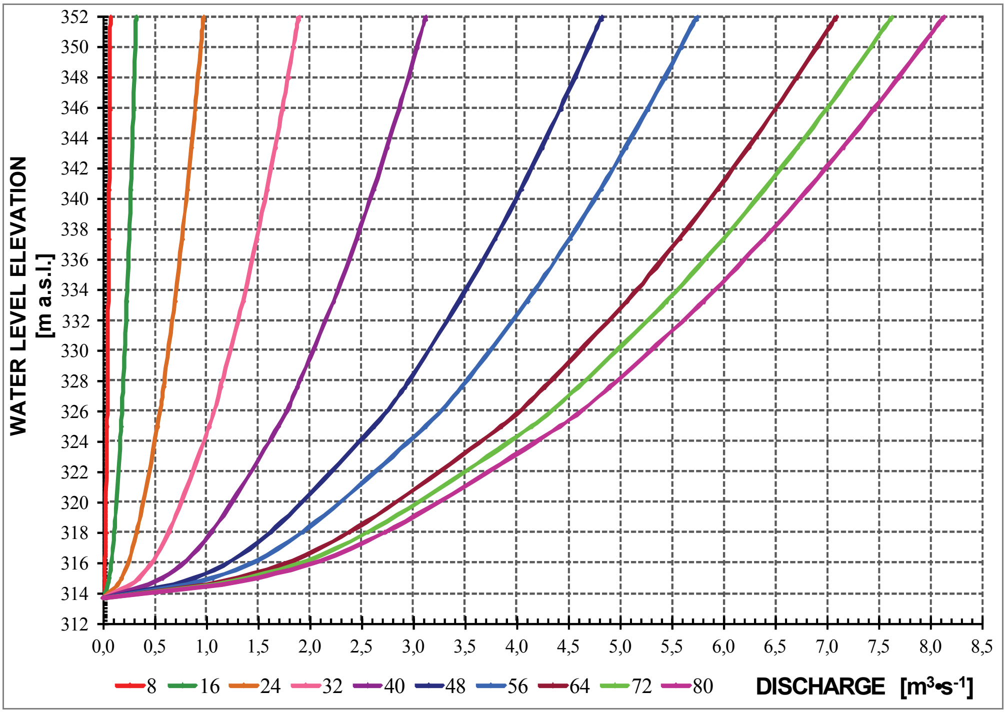

Fig. 6. Verified capacity of the bottom outlet of the Lubachów storage reservoir for specified valve opening in cm

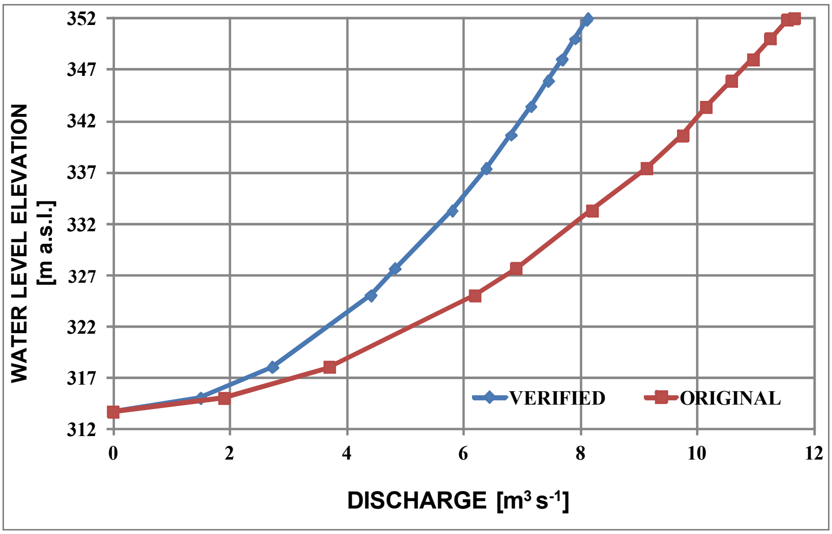

Fig. 7. Comparison of original and verified capacity of bottom outlet

6.2. INTERMEDIATE OUTLETS

The capacity of intermediate outlets depends on water level in reservoir, and the height of opening of gates on each conduit. Their cross-sections change along their lengths; at an inlet of each conduit is rectangular with 1.0 m width and 1.60 m height, topped with slight arch finial. Along the conduit length its height gradually decreases, which is important because of the need to maintain continuous flow in the conduit in such way that at its mouth the cross-section area is about 1.0 m^2. Hence, discharge of individual conduit was calculated, assuming a changeable inlet cross-section area, depending on gate opening degree, assuming variable value of discharge coefficient, which for 0.20 m opening height is equal to 0.600 and 0.700 for fully opened gate at inlet of intermediate conduit. The following equation was applied [5]–[9]

$$Q = C\,B\,a\,\sqrt{2\,g\,H} \tag{3}$$

where:

Q – discharge; m^3 s^{-1},
C – discharge coefficient,
B – opening width; B = 1.0 m,
a – height of gate opening,
H – height of damming up, measured in relation to inlet crest.

Determination of the moment the cross-section changes from an inlet to an outlet was of major importance and at the same time the most difficult task in the analysis. This problem was solved analyzing a path of free water jet from an orifice, treating it as sharp edge. Results were compared with existing conduit cross-section contour on the premises of Lubachów dam body. The moment of change occurs in a situation when water jet touches the upper edge of the cross-section so that it is completely filled with water.

Water jet outflowing freely from an orifice draws a path (Fig. 8), which can be described by coordinates x (distance) and y (height) [5]. Neglecting an air resistance it can be written

$$x = \upsilon_r\,t \qquad y = \frac{g\,t^2}{2} \tag{4}$$

where:

υ_r – real velocity of outflowing water from an orifice,
t – time when free water jet will reach position x, y,
g – gravitational acceleration.

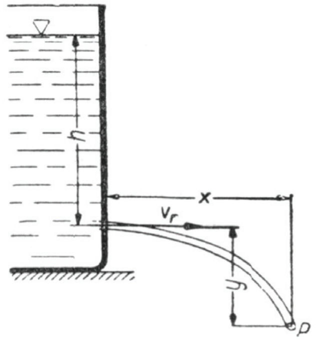

Fig. 8. Path of free water outflow from an orifice

Eliminating from above equations time *t*, we obtain

$$x^2 = \frac{2\,\upsilon_r^2}{g}\,y \tag{5}$$

in which

$$\upsilon_r = \varphi\,\sqrt{2\,g\,h} \tag{6}$$

where:

h – position of orifice axis in relation to water level in reservoir,

φ – velocity coefficient, for sharp edge orifice φ = 0.97–0.98.

Analyzing a curvilinear contour of the flowing surface of intermediate outlet, it was found to overlap the path of water jet from the completely opened orifice. Hence, it was necessary to determine a moment of change of a free flow (resulting from gate opening) into operation of completely filled intermediate outlet. It was important also to determine if this moment has place when a gate is partly opened and at what opening degree or when a gate is completely opened. At last it was determined that this moment has place when a gate is 50% opened.

As regards the aeration problem, it was finally eliminated because its entertainment is impossible when the cross-section of intermediate outlet is totally filled. This phenomenon may occur when the inflow of air is possible from the mouth side to its interior. Because this phenomenon occurs only in the case of very small discharges, it was excluded from further considerations.

Different issue is an impact of water flux flowing on downstream wall of dam, especially under conditions of water damming up in reservoir which reaches dam crest and the necessity of maximum release of water under certain conditions. Unfortunately, this problem cannot be solved analytically, but only by investigation on a physical model in big scale due to the possible aeration of water jets flowing from spillway openings. Verified capacity of intermediate outlet conduits for varied water levels in reservoir and assumed degree of gate opening is shown in Fig. 9.

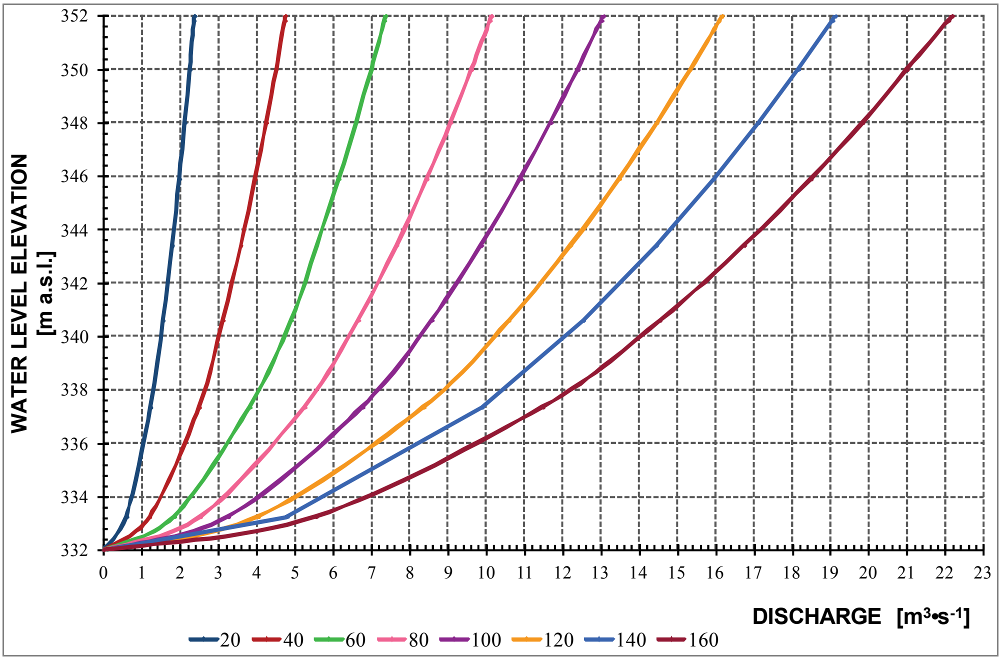

Fig. 9. Verified capacity of intermediate outlet of the Lubachów storage reservoir

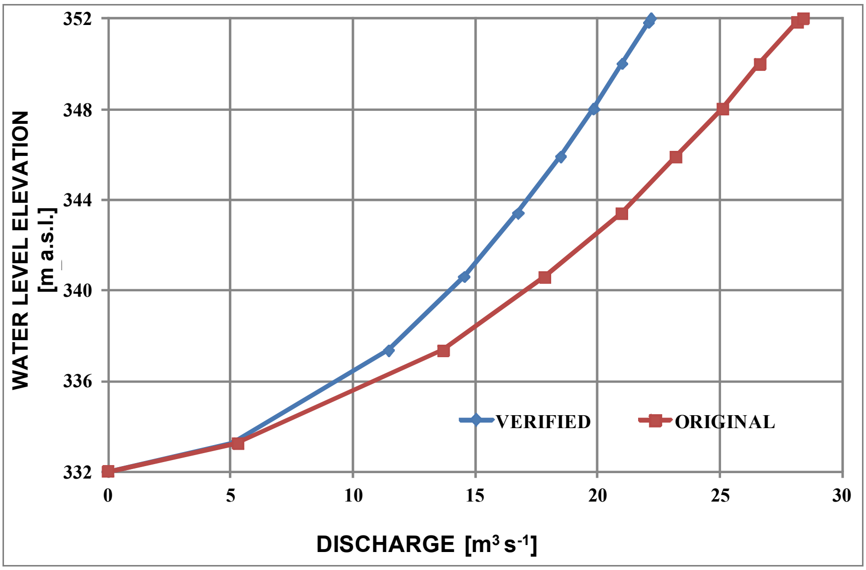

Fig. 10. Comparison of original and verified intermediate outlet capacity

The results of calculations significantly differ from design discharge curves. From the curve for fully opened gate at the mouth and assuming the lack of damping an outflow from intermediate outlet by spillway water jet, the capacity of this device at water level in reservoir at 352.0 m a.s.l. equals 22.150 $m^3\ s^{-1}$. In Fig. 10, a comparison of currently valid capacity with verified one, for fully opened gate and at water level in reservoir at 352.0 m a.s.l. is shown.

6.3. FRONT SPILLWAY

Analyzing the capacity of front spillway openings, it has been noticed that flow characteristic was determined for not submerged rectangular weir. In reality, depending on water level in reservoir, three flow conditions occur, differing from each other. Taking into account the geometry of opening, as given in Figs. 2 and 3, the following types of flow can be distinguished, depending on the thickness of water layer that overflows the weir [5], [6], [9]:

– $0 < H \le 30$ cm, free flow for rectangular cross-section with a straight insert on its crest,

– $30 < H \le 130$ cm, free flow through spillway with a straight insert on its crest but under conditions of changeable width, narrowing with height,

– $130 < H \le 200$ cm, water outflow from not submerged orifice.

An interesting proposal was given by Rędowicz [2]. He based his theoretical calculations of flow through a spillway opening on a method available in professional literature [5]. According to this method the cross-sectional area of an opening is divided into stripes of infinitesimal thickness *dz*, within which flow velocity can be assumed to be constant. Taking the position of a chosen strip in relation to water level in reservoir as *z*, then flow velocity within such strip can be calculated as

$$\upsilon = \sqrt{2\,g\,z} \tag{7}$$

For discharge calculation through cross-sectional area equal to

$$dA = y(z)\,dz \tag{8}$$

first a specific discharge should be determined from

$$dQ = \sqrt{2\,g\,z}\;y(z)\,dz \tag{9}$$

and next, after integration in limits from H_1 to H_2, a total discharge through the cross-section of spillway opening equals

$$Q = \mu\sqrt{2g}\int_{H_1}^{H_2} y(z)\,z^{1/2}\,dz \tag{10}$$

To solve the above equation it is necessary to know function $y(z)$. In the case of the spillway base, the solution could be expressed as follows

$$Q = \frac{2}{3}\mu b \sqrt{2g}\,(H_2^{3/2} - H_1^{3/2})\,. \tag{11}$$

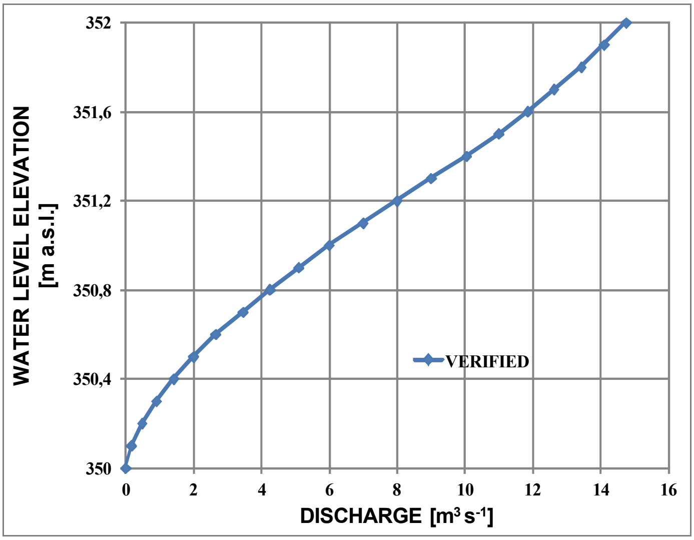

Fig. 11. Verified capacity of spillway of the Lubachów storage reservoir

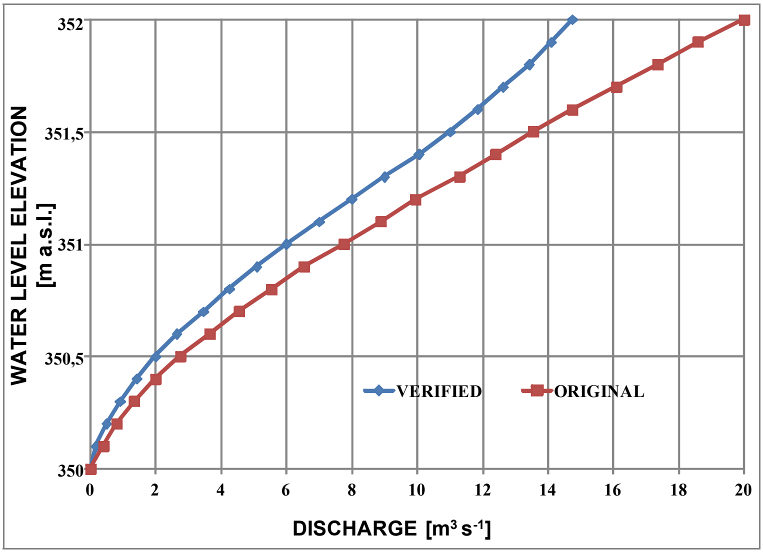

Fig. 12. Comparison of original and verified spillway capacity

Because an equation describing a curvature of spillway opening vault is not known, hence Rędowicz [2] proposed a division of integrated area into seven areas close to rectangle, and next an integration of each area within some adequate limits. Obtained in that way verified capacities of spillway openings for different water levels in reservoir are presented in Fig. 11. Simultaneously, in Fig. 12, a comparison of the designed capacity with verified one is shown, at water level in reservoir at 352.0 m a.s.l.

7. COMPARATIVE ANALYSIS

In the table below, authors compare results obtained from calculations with original data determined by German designers. For comparison the capacities at damming up water in reservoir at 352.0 m a.s.l. were taken.

No.	Type of outlet device	Discharge Q [m^3 s^{-1}]		Differences	
		according to archival discharge curves	calculated by the authors	ΔQ [m^3 s^{-1}]	%
1	Bottom outlets 2 × 800 mm	23.300	16.250	7.05	43.38
2	Intermediate outlets 4 openings	113.60	88.74	24.86	28.01
3	Front spillway 10 openings	200.0	147.50	52.50	35.59
4	Hydro power plant	4.60	4.60	–	–
Total		341.50	257.09	84.84	32.83

From the results of analytical calculations the capacity of existing outlet installations is clearly seen to be overestimated nearly 30% in relation to their actual capacity. This is mainly due to the fact of the hydraulic characteristics of intermediate outflows and front spillway being incorrectly assumed with respect to real conditions of their functioning.

8. SUMMARY

The authors carried out analytical calculations to determine a capacity of outlet devices of the Lubachów reservoir, particularly of those elements that facilitate the effective manoeuvres of water outflow, including prereleases. Based on the above, they tried to get an answer to the question of how far computational discharges can safely pass through the existing outlet devices. Unfortunately, the capacity of these devices was proved to be significantly overestimated, which created a crucial threat of water flowing over the dam crest of Lubachów reservoir. Hence, in further investigations the authors made an estimation of transformations of freshet waves and conditions of their passage through reservoir.

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