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INVESTIGATION OF VACUUM AND CAVITATION IN A SHAFT SPILLWAY WITH A POLYGONAL CROSS SECTION

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ABSTRACT

In this research paper, our study focused on the importance and reliability of the shaft spillway flow in order to avoid the presence of vacuum and the possibility of erosion by cavitation at high flow rates. The proposed characteristics of the intake funnel consist on 12-sections polygonal configuration, on which a total of 124 piezometer gauges in the scale model (including the elbow) was placed to determine the pressure distribution. The physical model in the form of a dodecagon was tested on laboratory flume at the hydroelectric power stations of the State University of Environmental Engineering in Moscow (Russia). This flume having a zero bottom slope, a width of 100 cm and a length of 950 cm is connected to a feed tank whose dimensions are 1.64 m x 2.0m.The results showed that the realization of the crest of the intake funnel in the form of a polygonal cylindrical surface reduces the maximum vacuum by two times compared to the vacuum on the crest of rectilinear weir dams, not exceeding a value of 2 m of water column which is not dangerous for the appearance of the cavitation erosion of the water receiving funnel. It also allows shaft surfaces to be formed with a one-dimensional curvature during construction without the formation of bending edges, thus facilitating flow through the shaft and the discharge gallery.

Keywords: Shaft spillways; polygonal section; receiving funnel; vacuum; erosion by cavitation.

INTRODUCTION

One of the most important issues that determine the reliability of the shaft spillway is the issue of pressure distribution on the funnel surface of a shaft spillway. This issue is especially relevant for the non-pressure mode of operation of the spillway, in which the flow in the shaft has the shape of a hollow cone. With a shaft height of 20 to 30 m, the water velocity of the flow can exceed 16 to 20 m/s. However, this issue, and that of the aeration, is the most difficult in the theory and practice of designing shaft spillways.

The presence of a high-velocity flow in a shaft spillway with a complex kinematic structure in a wide range of flow rates creates difficulties in performing theoretical calculations to determine the vacuum zones and the magnitude of the vacuum in them (Peter, 1954). Therefore, the well receiving funnel of the shaft spillway is made as a system of truncated cones mounted on top of each other. The junction lines of these cones are at the origin of the emergence of vacuum sources, leading potentially to erosion by cavitation of the concrete.

One of the design features of the shaft spillway, influencing the conditions of its operation is the curvature of the flow on its internal drain surface. In the direction of water movement, the drain surface is given a convex curvilinear outline either according to Creager coordinates, or using Wagner coordinates (Wagner, 1954; Janakiram, 1982).

The cross-section of the shaft spillway is given a concave circular-cylindrical shape, which turns the drain surface into a surface with a spatial two-dimensional curvature. At present, the art of construction is not able to perform formwork with double curvature, as a result of which the drain surface is made in the form of a system of truncated cones placed on top of each other. As a result, in the longitudinal direction the drain surface has the form of a broken line with inflection points in the sections where the cones join. As a result of the movement of water on such a surface in each section of the bend of the drain surface, the flow is separated from the surface of the shaft.

When low flow rates are released in the bend sections, there is a constant discontinuity of the flow to form separate streams, which capture a large amount of air. As a result, in the outlet conduit of the shaft spillway entraped air appear, which burst into the shaft of the spillway with the formation of water-air jets, as it happens during the operation of the shaft spillway of the Owyhee dam (USA) as shown by Fig. 1 (Moise, 1970).

Figure 1: Observed -air -blowback in shaft spillway of the Owyhee dam (USA)

On the shaft spillway of Owyhee dam at heads on the crest of water inlet funnel in the range 0.3 to 0.6 m from the shaft barrel observed air-water emissions up to 18 m at intervals of 5 minutes.

The operation of the shaft spillway with such hydraulic modes poses a safety risk to the entire structure due to the occurrence of dynamic modes and hydraulic shocks in the outlet conduit. When high flow rates are carried, the thickness of the flow inside the shaft spillway increases until the jets close and form a pressure mode of movement. In these modes, pulsation effects in the sections of the bend of the shaft surface cannot violate the continuity of the flow and the penetration of air into its lower layers, which, breaking away from the edges of the bends, form pockets in which vacuum zones are formed.

At the same time, at present there are no theoretical developments that allow calculating the value of the averaged vacuum, not to mention the parameters of its oscillations.

The identification of vacuum zones and the magnitude of the vacuum in them in each specific case was and still is carried out on hydraulic models from shaft spillways at hydroelectric facilities (Akhutin 1935, Sun 2009).

Quite a lot of attention is paid to the issue of the emergence and development of cavitation in hydraulic structures in the publicly available literature (Kavechnikov, 1985; Bredley, 1954; Camp, 1939; Skryaga, 1958; Falvey, 1990; Guryev, 2003, 2005; Binnie, 1941; Gouryev and Beglarova, 2003; Grichin, 1954; Rozanov, 1958;1995). However, these materials cover the issues of cavitation on local and distributed resistances of linear structures and slot cavitation. These works completely lack materials devoted to the study of the pressure distribution in the flow path of the shaft, which does not allow even an approximate estimate of the danger of concrete degradation under the influence of erosion.

At the same time, field studies have established the presence of cavitation erosion of concrete on the concave surface of the connecting bend in the flow path of shaft spillways, even when partial water flows are passed with strong aeration of the flow (Gouryev 2005). In this zone, the maximum value of the centrifugal pressure force of the flow is manifested and, by definition, there should be no cavitation here. In this zone, when the flow rate was 38% of the calculated one, cavitation zones with a depth of up to 0.6 meters were formed.

In hydraulic studies on physical models of shaft spillways, the nature of the pressure distribution in the flow path of the shaft was recorded, but the analysis of experimental data was completely absent.

LITERATURE REVIEW

The operation of a shaft spillway with a submerged water intake funnel is considered in most detail by S.P. Lavrentiev (1984) and Kavechnikov (1985). Lavrentiev (1984) investigated the operation of the shaft spillway on a model installation with an elliptical water intake funnel and a conical shaft.

The most detailed study of the pressure distribution in the flow path of the shaft spillway was carried out by Lavrentiev, who studied the operation of the shore-type shaft spillway in order to improve the design of the anti-rotation device. Unfortunately, Lavrentiev did not provide data on the pressure distribution in other sections where piezometers are installed, as well as on the pressure distribution in the elbow.

Under the leadership of S.M. Slissky in 1978, model hydraulic studies of the operation of the shaft spillway of the Tishrin dam on the Northern Kébir River in Syria were carried out, the results of which are presented in Rozanov (1995).

One of the issues to be studied was the pressure distribution in the connecting elbow. The special feature of the design of shaft spillway of the Tishrin dam is that the intake funnel of circular cross-section at the outlet mates with the shaft with a rectangular cross-section measuring 11.6 x 9.0 m. These studies have revealed the advantages of connecting the shaft with the outlet conduit by means of a bend with a deflector. This option was accepted for construction. Despite the availability of valuable experimental material, Rozanov, Khanov and Fedorkov (1995) limited themselves to stating the presence of pressure without analyzing the nature of its distribution.

The first shaft spillways were designed to carry the maximum flow rates under pressurized mode along the entire length of shaft, including the outlet, which was made of circular cross-section with a diameter equal to the diameter of the lower cylindrical section of the shaft and the connecting elbow (Slissky 1986).

An unfavorable circumstance associated with the use of such a connecting bend, which has the same cross-section as the end section of the shaft, and the evacuation gallery, the presence of a range of hydraulic modes in which the shaft at a higher height and the discharge tunnel operate in a free-flow mode, and the connecting bend continues to work in pressurized mode (Hager 2021, Novak 1981).

Behind the outlet section of the connecting bend, the flow is separated from the ceiling of the water conduit, which leads to an increase in its flow rate while increasing the flow rate of the connecting bend due to a decrease in pressure beyond its outlet section. This leads to the fact that the volume of water from the lower pressure head section of the shaft is sucked into the outlet tunnel, increasing its flow rate in the initial section, which inevitably leads to its overflow and the occurrence of hydraulic hammer.

Hydraulic hammer accompanied by the release of excess water and trapped air into the shaft, which was recorded during the operation of the shaft spillway of the Owahy dam in the United States.

On the other hand, according to the data of the same source (Soyuzgiprovodhoz, 1978), full-scale examinations of the state of the flow path of shaft spillways were carried out after passing the flow rates in the range from 12% to 46% of the calculated one.

The result revealed the presence of cavitation erosion of concrete at the bottom of the coupling elbows just in the zone of maximum centrifugal pressure according to research data.

The use of the deflector as a transition section between the shaft of the spillway and the coupling elbow allows minimizing the air capture by the flow during the transition mode, as it was established according to research data (Moise, 1959; Savic et al., 2013).

Summarizing the results of the data analysis of pressure on the flow-through part of the shaft spillway, it should be noted that this issue has received very little attention, and the available experimental material is analyzed from the standpoint of evaluating the occurrence of cavitation phenomena.

Moise (1970) studied the pressure distribution on a shaft spillway model. Separately, the pressure on the receiving funnel drain surface has been studied by Camp (1939); Skryaga (1958) in order to establish the advantages of the elliptical contour of the receiving funnel drain surface proposed by the author. Following these studies, graphs of the dependence of the maximum vacuum on the drain surface of the intake funnel were obtained, and are presented in figure 2 for the profiles of the funnels, sketched at the suggestion of different authors.

As can be seen from figure 2, on all the water intake funnels studied by Moise, a vacuum is noticed, despite the fact that the contour of the edge of the drain and according to Akhutin (1935) and according to Wagner (1954) are manufactured according to the shape of the surface bottom of a jet flowing freely through an annular weir with a sharp edge.

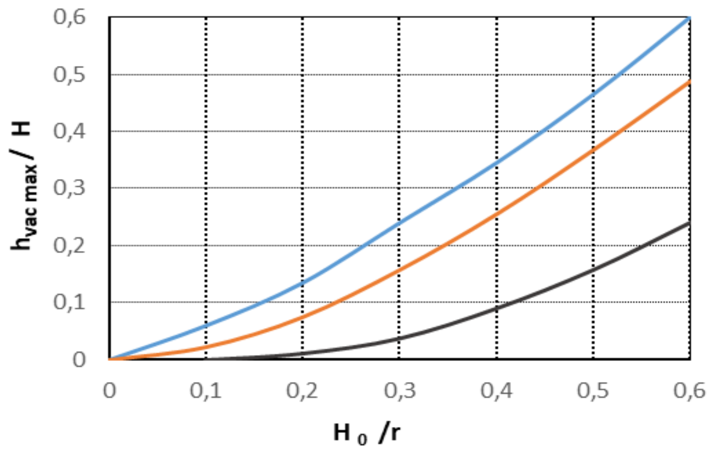

Figure 2: Relative vacuum on the drainage surface ($H_{vac.max}$ / H) = f (H/R)
by: Akhutin; Wagner ; Moise.

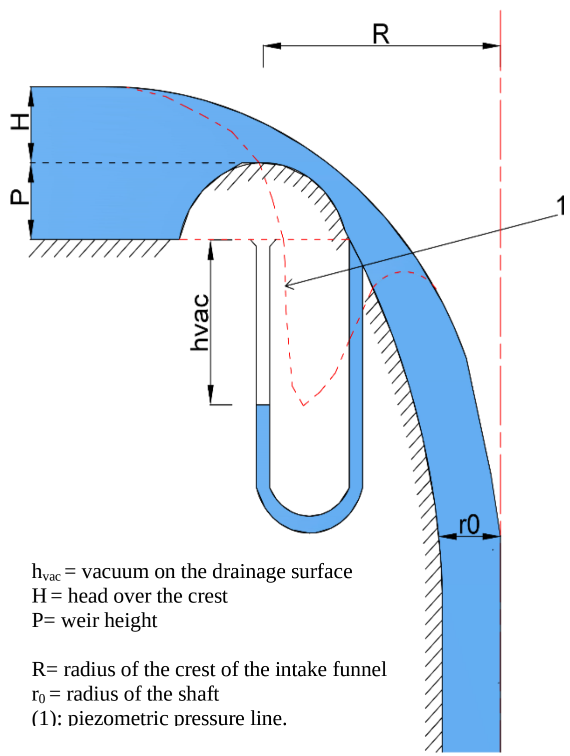

Figure 3: Definition sketch of the flow of a shaft spillway

The profile of the drain surface, produced on the recommendation of Moise, does not exclude the presence of a vacuum either, reaching 0.25 H overhead on the crest of the intake funnel.

The results of the study of the pressure distribution over the entire surface of the shaft spillway are presented by Camp (1939). This work presents the results of a study of the spillway at two levels through water intake funnel and a deep water pipe supplying water to the middle part of the shaft and noting that there is a vacuum on the convex surface of the connecting elbow during its operation in pressurized mode, but its value is insignificant.

Rozanov (1958) found that when using circular -cylinder headers on weir dams, it is possible to increase the discharge coefficient to the value m = 0.56 corresponding to a relative height (H_0/R) = 3.4, where R is the radius of the crest of the intake funnel and the relative vacuum thus reached ($h_{vac.max}$ / H) = 1,58.

Rozanov (1958) also found that the maximum vacuum pulsation in this case reached a value of 0.1 $P_{vac.st.}$ Taking these data into account, it is possible to determine the maximum value of the head H_0, at which the vacuum will not be dangerous under cavitation conditions.

$$h_{vac} = (1.1 \times 1.58 + 0.1) \times H_o = 1.838 \times H_o \tag{1}$$

The local velocity V at the surface at the top of the spillway, taking into account the pulsating component, will be:

$$V_{crest} = \sqrt{2g \times (H_o + 1.838 \times H_o)} == \sqrt{2.838 \times 2g \times H_o} \tag{2}$$

THEORETICAL CONSIDERATIONS

The shaft spillway with a polygonal cross-section was studied for a structure with a water intake funnel made in the plan in the form of a regular 12-sided polygon. The model of the spillway of the Djedra dam (in Algeria) was adopted as the base one and studied on a hydraulic model at a scale of 1:60 and made in the laboratory of hydroelectric power stations of Moscow State University of Environmental Engineering.

A definition scheme for constructing the guiding faces of an elliptical profile of the inner surface of a shaft with a water intake funnel, the head of which is made in the form of a regular polyhedron, is shown in Figure 4.

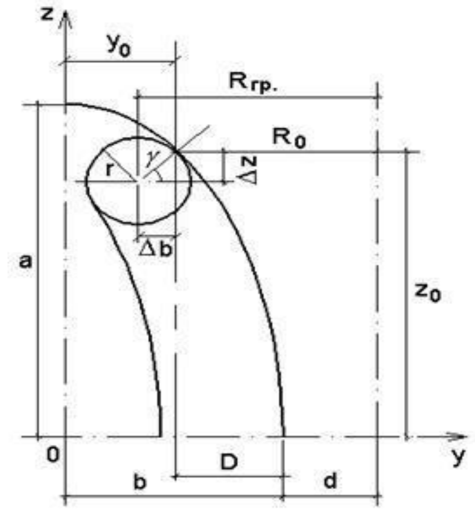

Figure 4: Diagram of construction the faces of the elliptic profile edges.

The guides of the elliptical faces of the discharge surface are described by the equation of the ellipse in analytic form:

$$\frac{a^2}{z^2} + \frac{b^2}{y^2} = 1 \tag{3}$$

After some mathematical transformations, we obtain the current coordinates of the normal line for the construction of the outer surface of the shaft:

$$\left.\begin{aligned} Y &= \frac{b}{a}\sqrt{a^2 - z^2}\left[1 - \frac{ta^2}{b\sqrt{a^4 - z^2\left(a^2 - b^2\right)}}\right] \\ Z &= z - \frac{t\,b\,z}{\sqrt{a^4 - z^2\left(a^2 - b^2\right)}} \end{aligned}\right\} \tag{4}$$

At z = 0, we obtain for the outer surface of the shaft wall: Y = b; Z = 0. At z = a, Y= 0, Z = a – t.

One of the important characteristics of a shaft spillway is its cavitation safety, which is estimated by the cavitation number σ. According to Slissky (1986) the condition for the absence of cavitation has the form:

$$\sigma = \frac{p_{abs} - p_{sat}}{V_{abs}^2 / 2g} \tag{5}$$

Where P_{abs}= The absolute pressure at the point under consideration, P_{sat} = Pressure of saturating water vapor at a temperature of 18 ° C (equal to 0.24 m), g = 9.81 m /s^2 acceleration due to gravity and V_{abs}= flow velocity in m/ s.

The pressure P_{sat} according to Slissky can be determined as follows:

$$P_{sat} = 10.33 - 0.39 - \frac{Z}{900} = 9.94 - \frac{Z}{900}. \tag{6}$$

Where Z = absolute elevation of the shaft spillway above sea.

Since the intake funnel surface has a significant curvature and slope, the pressure on it should be determined by the relationship:

$$\frac{p}{\rho g} = h \sin\beta + \frac{V_{Abs}^2 h}{g R_{cur}} \tag{7}$$

where ρ = density of water, β =the angle of inclination of the normal to the horizontal axis, V_{abs} =the flow velocity, R_{curv} = the radius of curvature of the jet in the section normal to the drain surface at the point under consideration.

The parameters included in (5) are determined as follows:

$$\sin\beta = \cos\varphi = \frac{1}{\sqrt{1 + tg^2\varphi}} = \frac{1}{\sqrt{1 + y'}} \tag{8}$$

V_{abs} depends on the shape of the velocity profile and the type of roughness protrusions. For a uniform roughness, V_{abs} = 0.4 to 0.6 of the average flow velocity V can be taken. We will assume thus:

$$V_{Abs} = 0.5V \tag{9}$$

The radius of curvature R_{curv} is determined by the following expression:

$$R = \frac{\left[1 + (y')^2\right]^{3/2}}{y''} \tag{10}$$

For an elliptical surface described by what follows:

$$\frac{a^2}{z^2} + \frac{b^2}{y^2} = 1 \tag{11}$$

We have

$$y' = -\frac{b}{a}\cdot\frac{z}{\sqrt{a^2 - z^2}} \tag{12}$$

$$y'' = -\frac{a\cdot b}{\left(a^2 - z^2\right)^{3/2}} \tag{13}$$

and the radius of curvature of the elliptical surface is then

$$R_{ellip} = -\frac{\left[a^4 - \left(a^2 - b^2\right)\cdot z^2\right]^{3/2}}{a^4\cdot b} \tag{14}$$

The radius of curvature $R_{.\,free\ srface}$ of the free surface of the flow is much larger than the radius of curvature of the elliptical surface, and therefore the determination of its mean becomes an uncertain problem. For definiteness, we can take the averaged curvature of the flow as the average value of the curvatures of the surface and bottom streams, namely:

$$\frac{1}{R_{curv}} = \left(\frac{1}{R_{free.surface}} + \frac{1}{R_{ellip}}\right)/2 \approx \frac{1}{2\cdot R_{ellip}} \tag{15}$$

Thus, expression (7) for determining the pressure of water at the point under consideration will take the form:

$$\frac{p}{\rho g} = \frac{h}{\sqrt{1+(y')^2}} + \frac{V^2 h}{8gR_{elip}} \tag{16}$$

The flow depth h is determined from continuity equation:

$$S = Q/V \tag{17}$$

The velocity *V*, taking into account the energy losses, determined according to the data of model studies, can be determined by the dependence:

$$V = 0.842\cdot\left(4 + \frac{z}{Z_0}\right)\cdot\sqrt{H + Z_o - z} \tag{18}$$

Where Z_0 = the height of the shaft from the crest to the outlet section, in which the origin of coordinates of the generating elliptical surface are located and H = head at the crest of the shaft.

EXPERIMENTAL SETUP

The test installation was placed in the organic glass pane in the laboratory of the laboratory of hydroelectric power stations of the Moscow State University of Environmental Engineering (Russia). The flume channel has a bottom with zero slope, a width of 100 cm and a length of 950 cm is joined to a feeding tank whose dimensions in plan are 1.64×2.0 m. The structure of this channel is shown in Figure 5.

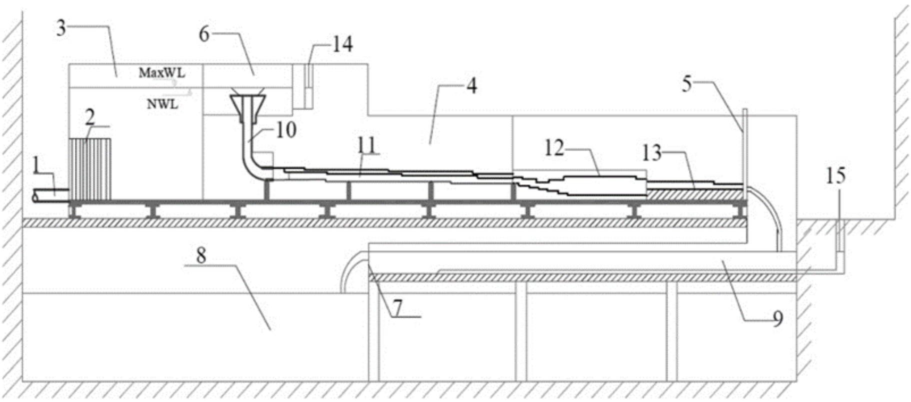

Figure 5: Experimental setup of the polygonal section model.

From a supply line **1**, the water flows into the reception tank **3** through a grid **2**. A mirror tank **4** is fixed on the reception tank, whose end is connected with a blind flap **5**, which makes it possible to adjust the water level in the tank **4**. The water then flows into the tank6, at the end of which is a triangular measurement weir **7** with a sharp edge, an angle of 90° cutouts and a threshold height *P* =280 mm. The tank **6** is installed in the tank **8** containing recycled water, located under the laboratory floor. In the initial section of the mirror chute **4**, adjacent to the receiving tank 3, was placed the modeled zone of the water zone of the upper dimension **9** adjacent to the weir well. In the simulated section of the upper dam **9**, the model comprising a water inlet funnel, the vertical well spillway **10** with the connection elbow, the horizontal tunnel **11**, and the discharge channel **12**, which are connected by a section of the bed of the channel **13**. A piezometer **14** is placed to control the installation of the upper level **3**. The height of the measurement weir **7** is determined using a piezometer **15**.

To study the distribution of the averaged hydrodynamic pressure on the drain surface of the shaft spillway, piezometers were used. The layout of piezometers in plan according to the borehole sectors is shown in Figure 6.

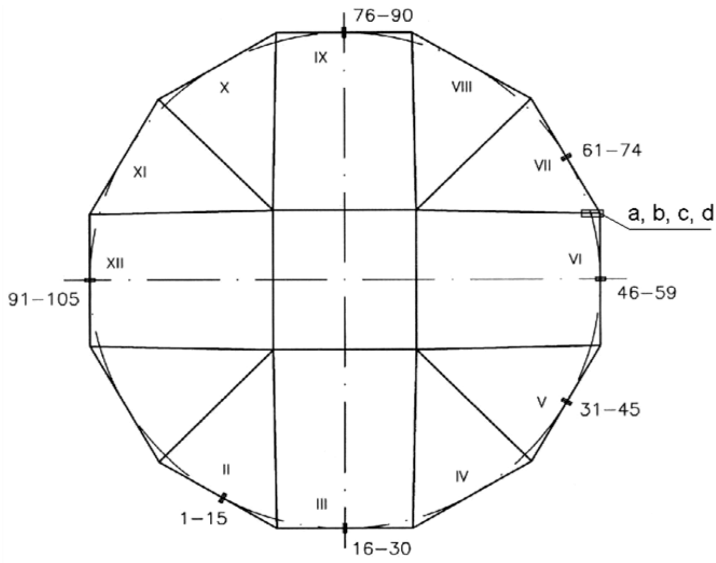

Figure 6: Layout of piezometers in plan on the drain surface of the mine:

I-XII - numbers of sectors of the drain surface;
1-105 - numbers of piezometers on the drain surface.

The distribution of flow pressures on the well surface was measured using piezometers. On 5 sectors of the drainage surface, 15 piezometers were installed, for two other sections 14 piezometers, on 5 sectors of the drainage surface, 15 piezometers were installed, for two other sections 14 piezometers, 3 others were installed in the connecting contour, 9 piezometers on the outer surface of the coupling bend and in the initial section of the tree 3.

At the junction of the 7th and 8th faces, 6 piezometers were installed. A total of 124 piezometers were installed on the shaft spillway model. The diameter of the receiving holes of the piezometers was 1 mm. The piezometers were connected to piezometric glass tubes with an internal diameter of 6 mm.

The layout of piezometers in height is shown in the longitudinal section of the shaft spillway, shown in Figure 7.

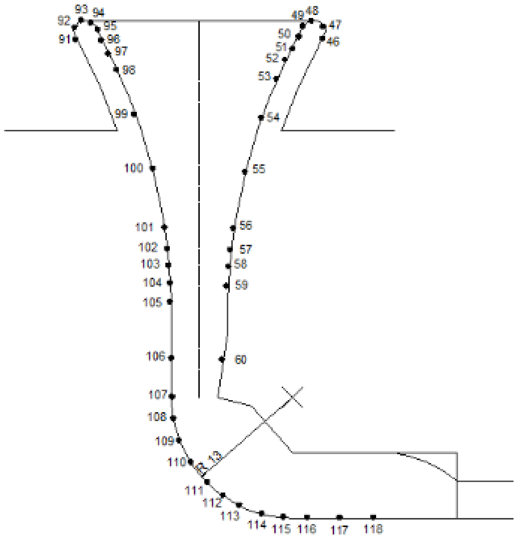

Figure 7: Layout of piezometers in the longitudinal section of the shaft.

Figure 8 shows a photo of the physical model of the intake funnel.

To create the possibility of removing pressure from the piezometers, while excluding the distortion of the hydraulic regimes by the hoses of the piezometers when water approaches the water intake funnel, its walls were made hollow, due to the implementation of the outer and inner surfaces of plexiglass 5 mm thick.

Figure 8: photo internal cavity model water inlet funnel with polyethylene hoses.

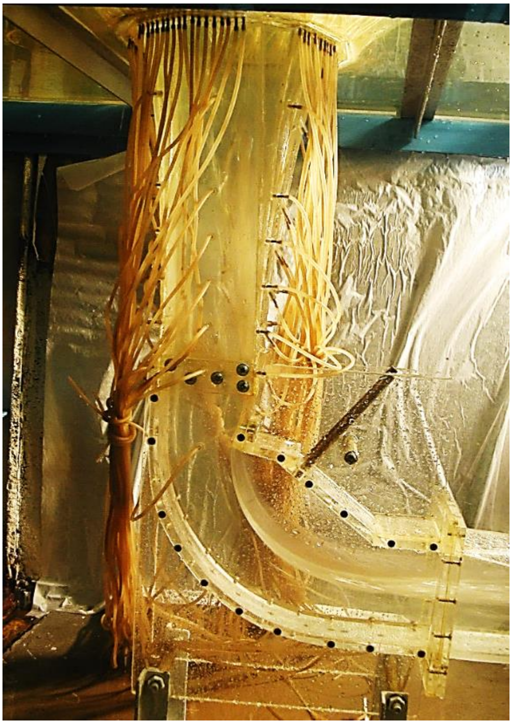

Figure 9: Photo of the model of the shaft

In the upper section of the photo in Figure 9, the outlets of the fittings of the piezometers of the intake funnel are visible. A total of 118 piezometers were installed on the model, of which 15 x 7 = 105 were installed on 7 sectors of the drain surface and 13 piezometers on the outer surface of the connecting bend.

For a detailed study of the distribution of hydrodynamic pressure at the head of the intake funnel, 4 piezometers were installed.

Hydraulic studies of the flow in the shaft spillway with a polygonal cross-section were carried out in a wide range of pressures on the ridge of the head of the intake funnel from almost zero with $H_{0.min}$ = 0.25 m to heads that create a complete submergence of the intake funnel with the pressure $H_{0.max.}$ = 7.0 m.

RESULTS AND DISCUSSION

As mentioned before, to reduce the cost of the shaft spillway of new dams and reduce the problem of cavitation, as well as overcome the difficulties during construction, a special design has been developed. It consists of replacing the circular cross-section of the shaft with a polygonal cross-section that ensures the formation of a continuous flow over the entire length of the culvert and simplifies the formwork and reinforcement work (Moise, 1970; Sun, 2009)

As an example of the distribution of hydrodynamic pressure over the height of the drain surface of the shaft, Figures 10 and 11 show pressure plots when the pressure changes on the funnel crest from H=0.87 m to H=5.86 m. For a more compact design of the graphs, the research results are presented in the coordinates (P/ρgH) = f (z), where z is the distance from the inlet section of the connecting deflector and H is the head on the crest of the shaft.

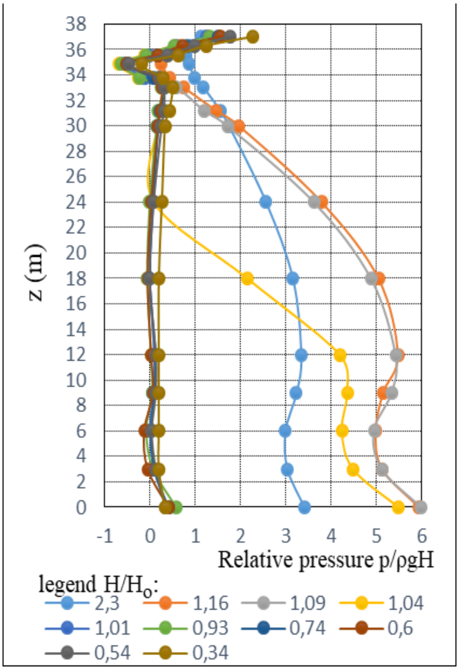

Figure 10: Distribution of hydrodynamic pressure along the height of the sector III of the shaft.

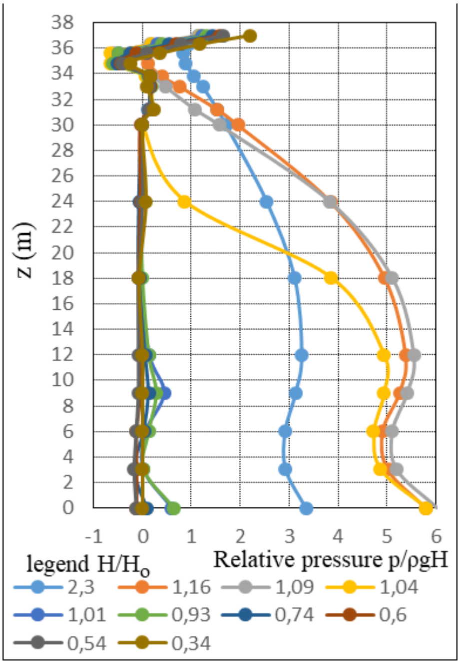

Figure 11: Distribution of hydrodynamic pressure along the height of sector IX of the shaft.

It should be noted that the first two piezometers on the top of the inlet funnel are located below its crest, and therefore, for greater clarity, the pressures of these piezometers are plotted along the z-axis extension beyond the 35.0 m mark of the funnel crest for the length of the generatrix from the crest to the location of the piezometer inlet.

As can be seen from Figures 10 and 11, in the free flow mode of operation of the shaft along the entire height of its drain surface, it is close to zero for the entire pressure range, while a vacuum of the order of 0.75 to 0.5 H is observed at the top of the funnel.

A more detailed distribution of pressure at the top of the intake funnel is shown in Figure 12 for sectors II, III, V, VI, VII and IX in the coordinates P_{min} / ρgH = f (H/r).

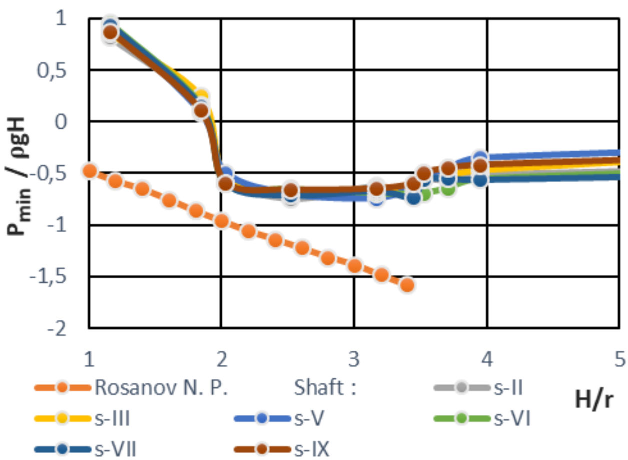

Figure 12: Detailed pressure distribution at the top of the intake funnel.

Figure 13 shows experimental data on the results of measuring the maximum vacuum at the top of the water intake funnel and compares the experimental values of the discharge coefficient of the circular cylindrical intake of the shaft spillway with similar coefficients according to the available calculated dependencies Rozanov and Rehbock.

The maximum vacuum at the intake of the shaft spillway is two times less than the maximum vacuum at the round-cylindrical form of the rectilinear spillway.

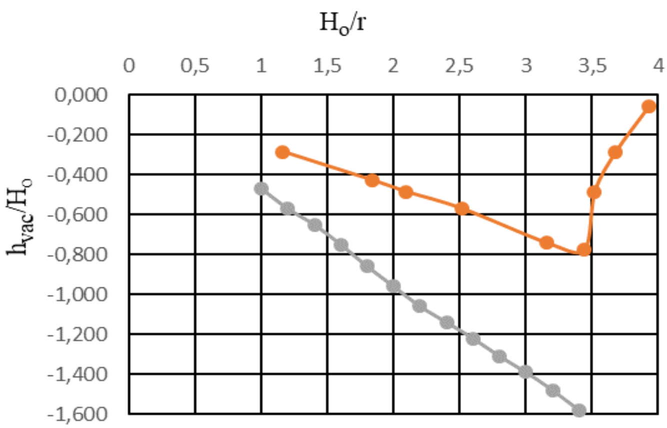

Figure 13: Comparison of the maximum vacuum at the head (h_{vac} / H_o) = f (Ho /r).

Shaft with a polygonal cross-section, experiment;

Rozanov for a rectilinear weir.

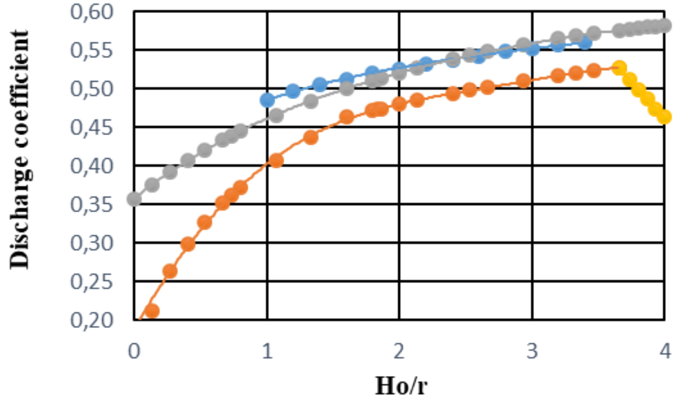

Figure 14: Comparison of the experimental data with the calculated dependence for the circular intake of the weir: ● Rozanov , ● Rehbock, ●● Authors' experiences

As can be seen from Figure 14, the maximum vacuum at the intake of spillway according to the results of studies of the Djedra dam (Algeria) reaches the value h_{vac}=0.78, with a relative head of (Ho / r) =3.4.

Using equation (7), we determine the value of the maximum pressure allowed on the round-cylinder of the shaft intake under the conditions of cavitation safety:

$$\frac{9.13+0.668H_o}{1.88\cdot H_o}=1 \tag{19}$$

Whence we obtain: $H_{o(max)}$ = 7.53 m, corresponding to the maximum pressure at which the vacuum will not yet be dangerous due to the conditions of cavitation.

According to dependence (5) in Fig. 15, graphs of pressure changes along the height of shaft are plotted on the trapezoidal and conical drain surfaces of the Djedra dam with a flow rate of 640 m^3 / s.

As can be seen from these graphs, there is a small zone with a vacuum reaching only 0.1 m water on the drain surfaces of the elliptical profile.

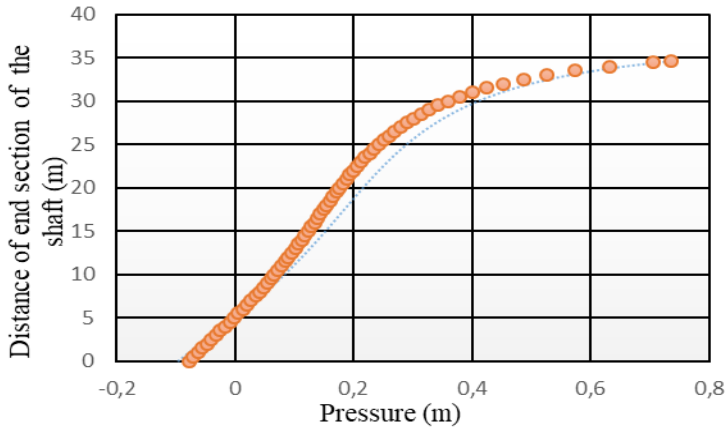

Figure 15: Pressure changes along the shaft height.

trapezoidal ; conical

Experimental pressure measurement points for the same flow rate are plotted on these graphs. As seen from Fig. 16, the calculated and experimental values agree perfectly.

Figure 16 shows graphs of the change in the cavitation coefficient for the pressures shown in Figure 15.

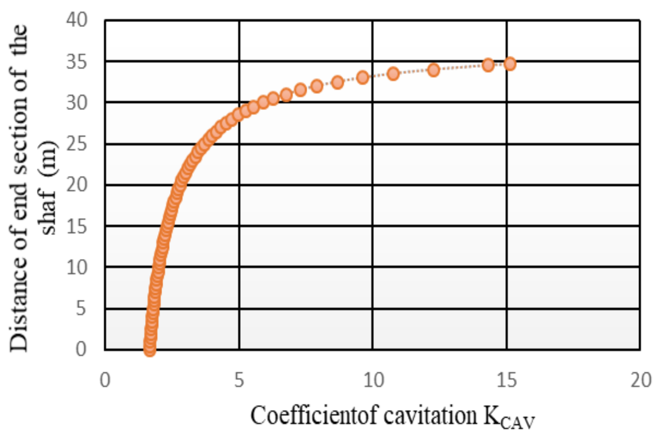

Figure 16 : Cavitation Coefficient Changes K_{cav}

Trapézoïdal ; conical

The analysis of these graphs shows, first of all, an almost complete superposition of the cavitation coefficient on the trapezoidal and conical drain surfaces, which is associated with an insignificant absolute pressure difference on them.

The criterion for assessing the risk of cavitation is the cavitation coefficient K_{cav}, which is determined as follows:

$$K_{cav} = \frac{\sigma}{\sigma_{cr}} \tag{20}$$

Where σ_{cr} is the critical number of cavitation which depends on the type and shape of the roughness of the water-flowing surface. For a uniform roughness corresponding to a concrete surface without protrusions and bends, σ_{cr} = 1, so that for the surfaces under consideration, the cavitation number is simultaneously the cavitation coefficient.

According to Moise (1959), at $K_{cav} \geq 1$, there is no cavitation, at $1 > K_{cav} \geq 0.7$, the onset of cavitation, and at $0.7 > K_{cav} > 0.2$, the stage of developed cavitation.

The actual minimum value of the number of cavitation on the drain surfaces of the elliptical profile of shaft spillways indicates a low risk of cavitation phenomena.

In addition, the minimum cavitation number for both types of overflow surfaces is within the value of 1.66.

CONCLUSION

The study of the pressure distribution in shaft spillways has shown that throughout the range of possible operating heads the vacuum is not observed. By taking into consideration the free flow mode which indicates the absence of pulsations in the latter, it can be seen that there is no danger of the appearance of cavitation phenomena.

When the flow falls on the connection elbow, there is a strong aeration of the flow which reaches 100% in the case of flow rates less than 50 m^3/s but which decreases up to 20% in the case of flow rates exceeding 640 m^3 /s.

The aeration of the shaft spillway depends mainly on the geometry of the shaft and the shape of the curvature at the transition from the shaft to the evacuation tunnel. Strong aeration of the flow excludes the risk of cavitation in the connection elbow and on the initial section of the tunnel.

Replacing the traditional circular cross section of the shaft spillway with a polygonal section allows receiving funnels with a one-dimensional curvature during construction without forming bending boards.

The research results show that the vacuum formed along the entire length of the funnel of the elliptical profile of the well is safe in terms of cavitation conditions over the full range of possible operating modes of the shaft spillway (minimum coefficient of cavitation for the overflow surface is of the order of 1.66).

In addition, the realization of this reception funnel with an elliptical generator allows all the elements of the funnel to be made without bends at a shaft height of up to 35.0 m and ensures a cavitation-free operation of the spillway.

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