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LABSKÁ – MODEL RESEARCH OF SHAFT SPILLWAY

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ABSTRACT

The article deals with the hydraulic investigation of a shaft spillway on the Labská Dam. A physical model of the right shaft spillway of the Labská Dam was built in the Hydrotechnical Laboratory and placed in the measuring flume. The hydrotechnical investigation describes the measurement of levels, discharges and pressures in the spillway and in the outlet culvert. Five types of technical options of the shaft spillway modifications were evaluated on the model. The results of the investigation include: the comparison of theoretical and measured consumption curves and comparison of pressure patterns along the whole length of the outlet culvert for all shaft spillway modifications.

KEYWORDS

physical modelling, model similarity, shaft spillway

INTRODUCTION

The shaft spillway is a suitable type of protective structure at lower design flows if it is difficult to build a crest spillway or a side spillway chute in a narrow valley with steep slopes. Its advantages are even more pronounced if it is connected to a combined structure or if the diversion tunnel is used as the spillway outlet. The shaft spillway contains an intake part, a transition part, a shaft, a knee pipe and an outlet tunnel. The intake part usually has a circular plan with a hydraulically fitting crest, designed frequently with a wide crest in the past. Deflecting baffle ribs preventing the formation of random whirlpools and stabilizing the flow are often designed on the crest and in the intake part. The curved baffle ribs create a spiral flow regime in the funnel-shaped transition part and in the shaft. The pressure distribution over the spillway casing is more uniform. The water jet is pushed to it in the upper part of the spillway so that no underpressures arise causing cavitation phenomena and vibrations. The shaft spillway flooding is a complex hydraulic process. The length of the flooded shaft section into which the water flow falling freely through the shaft passes via the transition phenomenon grows gradually with increased discharges. Both the intake and the transition part of the spillway must be designed so that they are not flooded earlier than the shaft. The hydraulic solution must include all hydraulic phenomena arising during the two-phase flow [5].

This article deals with the investigation of a shaft spillway on the Labská Dam. It is a special type of emergency spillway diverting higher discharges through a vertical shaft, followed up by a horizontal shaft connecting the reservoir storage with the space below the dam. While designing its capacity the design flow must always be diverted by means of pressureless flow. In the case that the spillway outlet shaft is flooded, its capacity is very significantly reduced [6]. In modern history, this type of emergency spillway is designed mainly in embankment dams, however, in older hydraulic structures we can also encounter it in masonry gravity dams as is the case of the Labská Dam.

VD LABSKÁ

Identification data

Dam name:	Labská
River:	Labe
HAN:	1-01-01-005
District:	Hradec Králové

Dam purpose and utilization

- Protection of the territory below the Labská Dam from the effects of floods by the transformation of flood discharges into max. harmless discharges from the reservoir of 100 $m^3.s^{-1}$ by handling water in the protective reservoir storage.

- Protection of water and water-related ecosystems associated with the Labe River below the Labská Dam by increasing discharges via water handling in the reservoir effective storage.

- Creating conditions for justified (authorized) handling of surface water in the Labe River, i.e. for using the power generation potential of surface water for the generation of electricity in small hydroelectric plants, stabilization of flows (particularly daily fluctuations) below the Labská Dam by handling water in the controlled reservoir protective and effective storage.

- Creating conditions for general water handling in the Labská Dam, i.e. for sport, recreation, navigation and fishing.

- Creating conditions for potential holding white water boat races in the Labe River channel below the Labská Dam by handling water in the controlled reservoir protective and effective storage and by increasing wave discharges below the Labská Dam.

Basic technical specifications of the dam

Dam type:	gravity, masonry, curved plan
Dam crest elevation:	694.16 m. s. l.
Dam crest length:	153.50 m
Dam crest width:	6.15 m
Max. dam crest height above terrain:	41.50 m
Dam category:	II

The Labská Dam has 5 bottom outlets (1 situated in the dam body, 4 in diversion tunnels). Their sections are DN 1000 mm.

Protection against the dam overtopping is secured by 2 emergency spillways. The frontal spillway has a total of 4 openings with a clear width at the overflow crest level of 9.90 m each. The total clear width of the spillways is, therefore, 39.6 m. The spillway crest has an elevation of 691.26 m. s. l. The second, shaft type spillway is situated on the left bank. The crest (overflow crest) of the shaft spillway also has an elevation of 69l.26 m. s. l. The inside diameter of the spillway body at the overflow crest level is 11.50 m, the outside diameter of the spillway body being 14.40 m. The shaft spillway crest houses a 1.92 m high debris rack wall with a service bridge accessible from the bank.

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The circular vertical outlet shaft starts at an elevation of 688.66 m. s. l. being 5000 mm in diameter. The shaft inlet is circular-shaped. The intake shaft part, including the rounded part, is 4 m in length (or height). From the end of the casing, the shaft passes via a circular knee pipe (the circle radius in the shaft axis being 18.83 m) into a horizontal shaft and its diameter continuously increases up to 7.00 m. The outlet shaft then opens into the diversion tunnel. The shaft spillway capacity is 79.37 $m^3.s^{-1}$.

Fig. 1 - Shaft spillway in the Labská Dam

A small hydroelectric plant is situated below the dam. Two turbines are mounted in the hydroelectric plant. The first is a Kaplan type, the second a Bánki type turbine. The Kaplan turbine has an output of 525 kW, with an absorption capacity of 2.4 $m^3.s^{-1}$. The Bánki turbine has an output of 75 kW and an absorption capacity of 0.6 $m^3.s^{-1}$.

The elevation of the permanent storage is at a level of 678.66 m. s. l. The maximum effective storage of the reservoir is 0.756 mil. m^3, and the maximum effective storage water level at an elevation of 684.62 m. s. l. The controlled protective storage has a capacity of up to 1.309 mil. m^3. The capacity of the uncontrolled protective storage is 0.254 mil. m^3. When it is full, the water level in the reservoir is at an elevation of 692.36 m. s. l. [1], [4].

Hydrological data

m - daily discharges (Q_m) [$m^3.s^{-1}$]

m	30	60	90	120	150	180	210	240	270	300	330	355	364
Q_m	4,71	3,32	2,61	2,14	1,80	1,53	1,31	1,11	0,942	0,781	0,623	0,467	0,375

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N - year discharges (Q_N) [$m^3.s^{-1}$]

N	1	2	5	10	20	50	100
Q_N	37,5	53,2	77,1	97,1	119	150	175

RESEARCH METHODOLOGY

The research included the assembly of a physical model of the Labská Dam shaft spillway in the Water Management Laboratory of the Faculty of Civil Engineering, CTU in Prague. The objective was to identify the hydraulic behaviour of the spillway at various discharges and for various technical modifications, including the water flow in the spillway vicinity [7]. The measured values provided the patterns of water levels, which were compared against calculations, and the pressure conditions in the outlet shaft.

MODEL CONDITIONS

In a Froude type similarity model, the dynamic similarity conditions of hydrodynamic phenomena are governed exclusively by gravity forces. Apart from gravity forces, however, the investigated flow may also be affected by other forces – viscous fluid frictional resistance, capillary forces, volume forces, etc. According to Froude formulae, a specific hydrodynamic phenomenon can only be investigated if the effects of the above forces are negligible compared to gravity forces. Limit conditions delimit the domains and scales in which a hydrodynamic phenomenon can be modelled. Kinematically similar phenomena affected exclusively by the gravity force are dynamically similar if the same Froude numbers are found in mutually corresponding cross-sections.

While modelling flow phenomena within the Froude similarity domain, surface water pressure may apply. Surface pressure does not apply if the overflow height on the model h ≥20 mm. If h ≤ 20 mm, due to capillary forces, the overflow jet shape nearly passes into a straight line. The surface flow velocity on object models should be u ≥ 230 mm.s^{-1}, so that capillary forces do not prevent the formation of surface waves due to gravity forces. While modelling according to the Froude similarity, the clear width of a spillway opening on the model must be b_0 ≥ 60 mm. The intake opening must be a ≥ 60 mm so that the outlet phenomenon and the outlet jet shape are not unfavourably affected by the roughness of the bottom and walls due to the surface stress effect. The water flow depth on the model must be h ≥ 15 mm – this is particularly significant for river models. The same flow regime must be preserved on the model as that on a real structure. In modelling open channels according to the Froude similarity, subcritical flow for which Fr < 1 is critical and for which Fr = 1, or supercritical flow with Fr > 1 may be encountered. This may be ensured mainly by a suitable choice of the model scale and also by securing a reduced roughness of wetted surfaces.

Based on the geometrical similarity, the scale of M_l lengths is determined. Then, it applies for the velocity scale that $M_v = M_l^{1/2}$, for the discharge scale that $M_Q = M_l^{5/2}$ and for the time scale that $M_t = M_l^{1/2}$.

The scale of the Labská Dam was identified on the basis of model similarity limit conditions, possibilities of the laboratory, structural possibilities and conditions for the research relevance. The selected scale was M_l = 1:34, the velocity scale M_v = 1:5.8, the discharge scale M_Q = 1:6740.6 and the time scale M_t = 1:5.8.

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The entire model's length L = 4 m, height H = 1 m and width B = 1 m. Water was fed to the shaft spillway model of the Labská Dam by the laboratory distribution pipes, the discharge was measured by means of a magnetic inductive flow meter, water was stilled in a stilling basin. Water from the model was discharged via a collecting tank to underground spaces of the Water Management Laboratory where the central water collection unit is installed.

Fig. 2 - Model prepared for placement in the measuring flume

ALTERNATIVE SOLUTIONS

The model investigation was divided into 5 alternative versions according to the technical modifications of the intake vicinity, but also the overflow crest itself. In all versions, ten design discharges corresponding to m-day discharges m_{30} and N-year discharges Q_1, Q_2, Q_5, Q_{10}, Q_{20}, Q_{50}, Q_{100}, $Q_{1\,000}$, $Q_{10\,000}$ were measured.

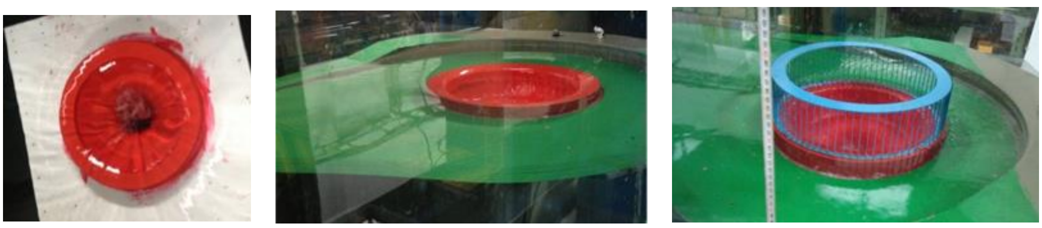
Version 1 – this version was only calculated for the spillway itself without terrain and without the debris rack.

Version2 – in this version, the model is complemented with “terrain”, which further specifies the water flow into the spillway without a potential effect of vertical flow.

Version3 – the model was complemented with a debris rack, this simulates the current state at the Labská Dam.

Version 4 – this version was complemented with four left-side flow baffles placed at the intake to the model shaft.

Version 5– this version was complemented with four right-side flow baffles placed at the intake to the model shaft.



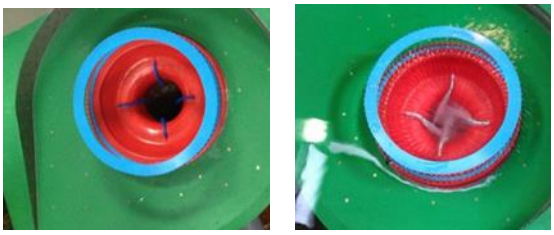


Fig. 3 - Versions 1, 2, 3, 4 and 5 (from top left)

MEASUREMENT EVALUATION

Consumption curves

One of the tasks of the model-based laboratory investigation was to compare the consumption curves obtained by measurement on the model with the consumption curves obtained by classic calculations [3].

The equation used for the overflow calculation was:

$$Q = m \cdot b \cdot \sqrt{2 \cdot g} \cdot h_0^{3/2}$$

where *m* is the overflow coefficient derived on the basis of the overflowing jet to the overflow crest width ratio,

b is the overflow crest length [m],

g is acceleration due to gravity [m.s^{-2}],

h_0 is the overflow jet height [m].

Comparing the reached results a relatively high agreement of the calculations with the model in places of low discharges was identified. Nearly identical values were reached for the majority of versions at lower discharges.

Figure 4 presents an example of consumption curves. The chart for Version 3 clearly shows a marked deflection of the model curve at higher discharges. This is caused by continuous flooding of the outlet shaft thus decreasing its capacity. At lower discharges, however, we may state that the accuracy of the calculated values compared to the values measured on the model is satisfactory.

The most significant difference between the measured and calculated values was evident in Versions1 and 2. In these versions, this is most likely thanks to the terrain and the debris rack, which limits the vertical flow effect, and the water flow capacity through the debris rack is further reduced - calculations cannot take account of these influences.

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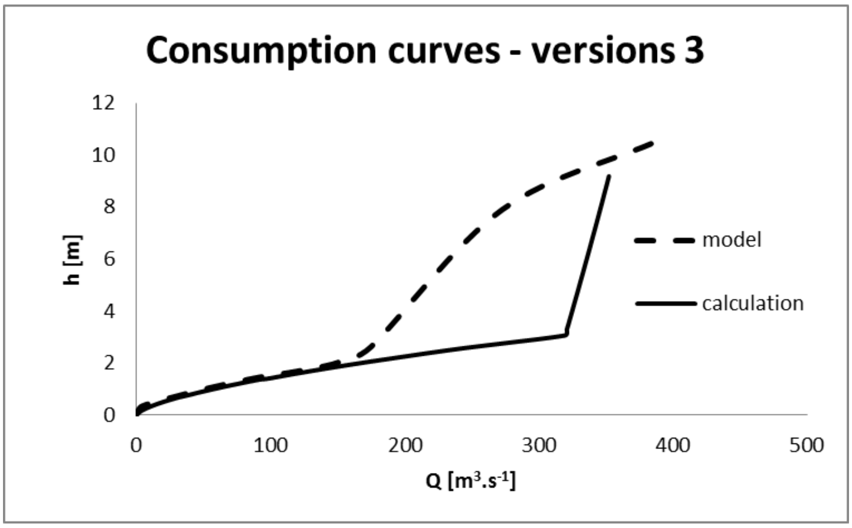

Fig. 4 - Consumption curve – Version 3

Capacity of spillways

Design discharges causing the outlet shaft flooding were identified for all alternative versions. The flooding pattern for all versions corresponded nearly perfectly to the criteria specified by Bollrich (1965). He claims that the overflow over a shaft spillway is free for $h/R < 0.45$. For $h/R > 0.60$, the inlet section gets flooded. For the h/R ratio between 0.45 and 0.60, the transition state applies [2].

In the transition to the flooded inlet, irregular pulsations manifested by the jet pull-down into the outlet shaft followed by a massive water jetting back into the reservoir could be monitored. This state was evident in all four versions; in Version 2 this state came earliest, while in Version 1, on the contrary, it came last.

Pressure conditions in the outlet shaft

Relative real-time hydrodynamic pressures were measured for all versions and design discharges. 12 piezometric sensors, connected to pressure sensors with 1 Hz sampling, were used for the measurement, and, besides, pressure sensors with 1 kHz sampling were used for the Q_{50} discharge.

The sensors were distributed at three height levels, four sensors at each of them, mounted perpendicularly to the outlet shaft. The distance between individual sensors at one level was the same. The mounting diagram of sensors is displayed in Figure 5. The samplings from the pressure sensors were evaluated and compared for individual versions in length and time units and frequencies on the model.

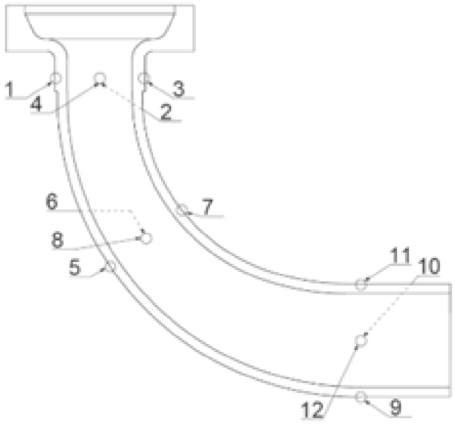

Fig. 5: Diagram of pressure sensor distribution

The obtained values evidently show very significant differences in pressures depending on the sensor position and the discharge. The greatest range in pressures was always reached at discharges causing flooding. The place most loaded by pressure was localised in the domain of bottom sensors placed in front of the outlet tunnel. These were sensors 9, 10, 11 and 12. The least loaded place, on the contrary, is the upper level of the sensors, mainly sensors 2 and 3 and, in the middle level, sensor 5. The charts also allow identifying individual phases of water suction and re-jetting from the outlet shaft. The greatest range of the acting pressures was measured for Version 5, i.e. the version using right-side flow baffles. In this case, there was a local increase in pressure against the version without their use.

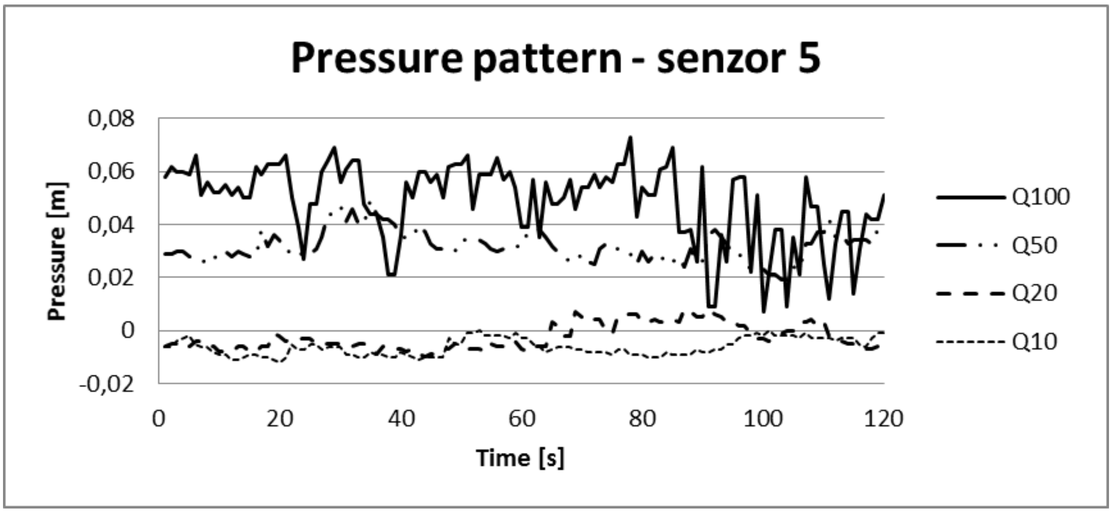

Fig. 6 - Pressure pattern - sensor 5 - Version 3

Interesting information was also provided by the mutual linking of the results of individual interrelated sensors. As an example, there is a chart describing the pressure pattern in sensors 1, 5 and 9, i.e. sensors placed at the bottom part of the outlet shaft. These values correspond to the average value, occurring during the total measured time for a respective discharge and sensor. Figure 7 clearly shows that underpressures arise in the inlet part at all discharges, followed by a nearly pressureless flow in the bend and by very significant pressures in front of the horizontal outlet shaft. Thus, the entire outlet system is considerably loaded.

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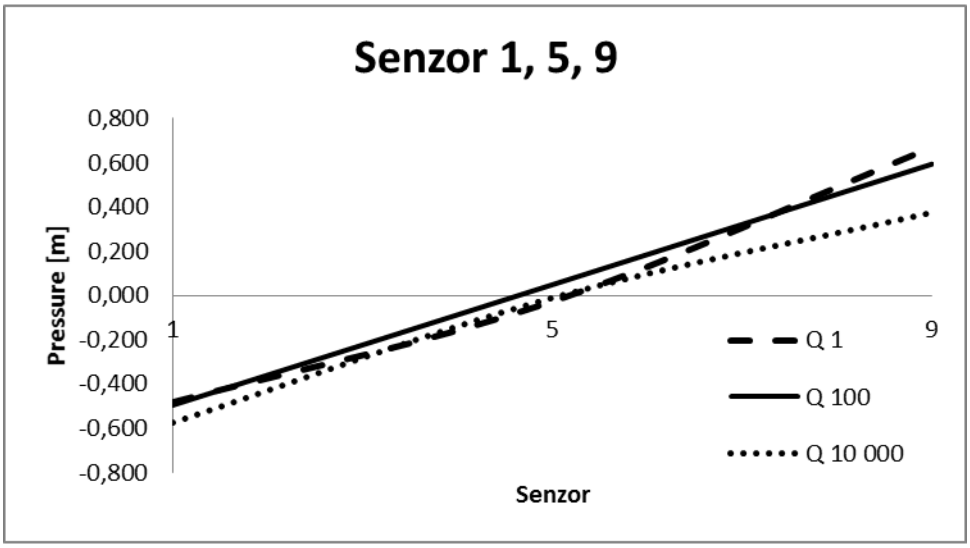

Fig. 7 - Pressure pattern - sensors 1, 5, 9 - Version 3

Frequency in the outlet shaft

For Version 3 (current state), the pressure pattern was measured by means of a pressure sensor with a fast sampling frequency. Evaluating this measurement, the pulsation frequency in the outlet tunnel was monitored by pressure sampling with a time step of 2 ms. The measurement was performed under the same conditions as that of relative pressures. The Q_{50} discharge, when the shaft spillway is flooded, was selected. Figure 8 displays the frequency analysis of the measurement in the outlet shaft. It is evident that these pressure pulsations do not show a significantly dominant oscillation frequency, which corresponds to pulsations in all measured pressure samplings. It follows from this that the pressure pulsations do not propagate as far as the outlet tunnel. The purpose of the measurement was to assess and avoid the propagation of pressure pulsations to the outlet tunnel by subsequent modifications.

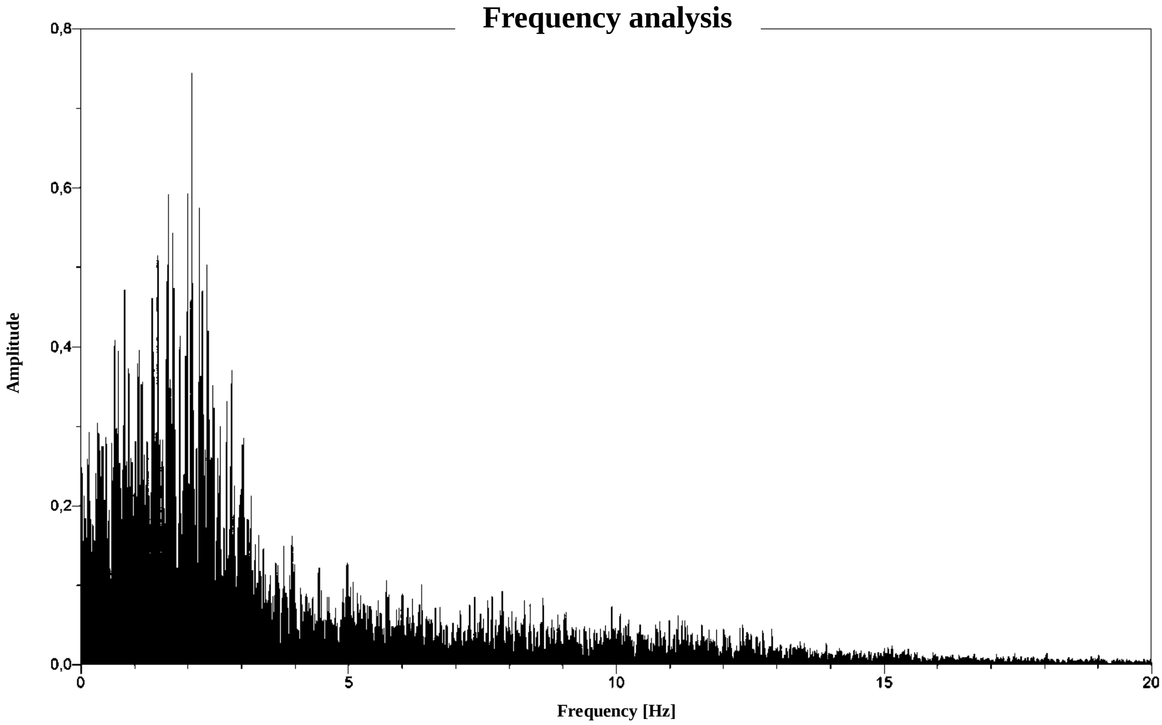

Fig. 8 - Pressure pattern – sensor 5, Version 3, Q50

CONCLUSION

The investigation of the shaft spillway in the Labská Dam included the assembly of a model at a 1:34 scale. The objective was to analyse the spillway behaviour and capacity with different technical modifications, compare the reached values with the results obtained by an analytical method and assess and specify in more detail the pressure conditions in the outlet shaft.

Consumption curves were used to identify the agreement of the capacity reached on the model and the calculation. The curves confirmed the relatively corresponding results, but also pointed out some facts relevant for the resulting spillway capacity (real terrain shape, curvature of flow lines by the supporting wall, non-uniform distribution of the inflow into the shaft spillway, debris rack position, baffle elements). Among them, the effect of the baffling elements at the start of the shaft is of most relevance. It was identified on the model that the left-side curvature had a minimum effect on reducing the capacity of the emergency spillway compared to the right-side one.

Thanks to the piezometric sensors installed, detailed data on the pressure patterns in the outlet shaft were obtained. The most loaded places were localised; it is, above all, the end of the outlet shaft before it is widened. The places least loaded by pressures, on the contrary, were detected behind the inlet part into the emergency spillway shaft. In total, the outlet shaft is exposed to the greatest pressures in the case that flow baffles are used, when the values measured in some places were up to twice higher than without them. This higher pressure contributes to the total pressure stability and there is a lower probability of the occurrence of pressure pulsations and undesirable underpressures. While comparing the pressure pulsations for Version 3 and 4, better results were reached for Version 4 using left-side baffles.

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