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HYDRAULIC AND STRUCTURAL ANALYSIS OF FLAP GATES

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Abstract: *Undesirable vibrations of either structural or technological parts of gated weirs are often observed during the service life of these hydraulic structures. Such vibrations cause inconvenience to the environment due to the induced excessive noise as well as shift the design point of view to fatigue capacity of the appropriate parts. Nowadays, flap gate present the most frequently designed type of gate for weirs in river engineering. Despite their many advantages, such as uniform load of the foundation structure, good regulation of water level, favourable hydraulic properties, when lowered, and most importantly good price to gated head ratio, they suffer from vibration issues. The paper presents results and comparison of in-situ measurements, laboratory experiments and numerical modelling.*

Keywords: ***flap gates, vibrations, in-situ measurements***

1. Introduction

The necessity of detailed study of potential vibrations of flap gates and their foundation structure results from operational and service life reasons as well as from hygienic standards setting safety limits for noise and vibrations. Although no dam or spillway failures have been reported in Czech Republic in recent years, several gates, some of them are brand new, are experiencing undesirable vibrations. Due to the complexity of the phenomenon, is it extremely difficult to completely eliminate the possibility of vibration affecting the construction during the design stage (ICOLD, 1996) and therefore evaluation of the possible impact based on the measured data must take place. Theoretical part of the paper focuses on the discharge over the edge of the gate.

The experimental part presents methods and procedures used for measurement and evaluation of selected variables on both laboratory model and in-situ. Forces in operating rods under steady conditions and accelerations and deformations of the gate are also presented. An example of the visible effects of the vibrations, which were captured using video camera and digital camera, is presented in the final part of the paper.

Measured data were used for calibration of numerical models created in ANSYS Workbench environment, while using ANSYS CFX code for modelling of flow and ANSYS Mechanical code for structural analysis. After calibration, the results from numerical models could provide for detailed assessment of the impact of vibration on the whole construction and its surroundings.

2. Discharge over the edge of the gate - theory

The phenomenon of water flowing over an obstruction or construction called spillway is generally regarded as overfall. The relative elevation of the highest point of the spillway structure presents an important variable. In case of raised flap get the highest point is the edge of the gate. However, when completely lowered the highest point of the spillway construction should not be the edge of the gate. It should be pointed out that vibrations generally take place when the gate is raised.

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Flow over spillway results in changes in pressure and flow velocity. Upstream and downstream water surface level difference affected mainly by the height of the raised gate is of importance.

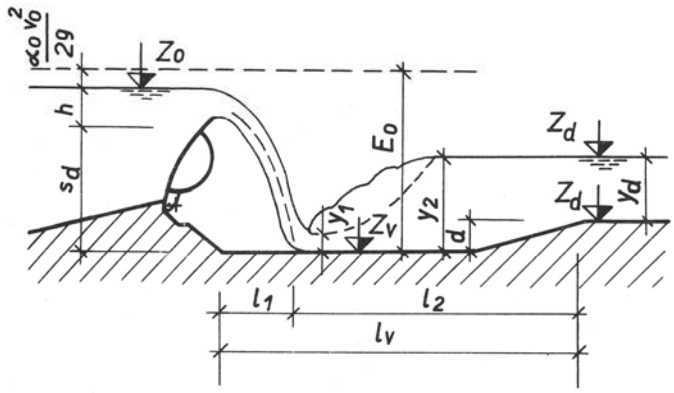

Fig. 1: Calculation scheme – free overfall

Bazin`s equation can be used for calculation of spillway discharge under the conditions of steady flow which is not influenced by the tailwater level (e.g. Kolář et al, 1983; Gabriel et al, 1989)

$$Q = m b_0 \sqrt{2g}\, h^{3/2} \tag{1}$$

Where Q stands for spillway discharge [$m^3.s^{-1}$], m for coefficient of discharge [-], b_0 for effective width of spillway [m], g for gravitational acceleration = 9,81 $m.s^{-2}$ and h for head [m].

3. Physical modelling

Physical model can faithfully represent the hydraulic structure, under certain conditions, and thus provide answers related to numerous hydraulic, static and dynamic conditions. To ensure that results obtained from hydraulic research can be safely used in the analysis of real structure, it is necessary to follow restrictions based on the type of the problem. In this case Froud`s Law of Comparison was used. Several similar models, which complement and extend each other's range of interest, have to be built, so that obtained results can be generalized. The models should cover whole range of possible topologies, hydraulic conditions and loading cases.

During the physical modelling all sorts of variables are measured and logged. For example, both static and dynamic action of water on the foundation structure, on the flap gate structure, on the operating rod and their response and also hydraulic conditions in front and behind the gate. Typically, water pressure, force in operating rod and water levels are measured for selected flows or discharge rates. Thomson's spillway was used to measure flow rate, pressure probes to gather pressure distribution along the spillway, cylindrical gauges to measure deformations of the flap gate and position of the water surface, force transducers to gain the force in time distribution in the operating rods and accelerometers.

3.1. Physical model of the weir structure in Strakonice town

The weir structure on river Otava in Strakonice town consists of two 20 m long and 1,3 m high steel hollow flap gates, central pillar and a foundation structure. Both flap gates are single side operated using lifting pin-rods placed in the side pillars. They can be either operated automatically, the machine rooms are inside the side pillars, or manually. According to handling regulations it is possible to change the position of the gate in 100 mm high steps and keep the weir headwater level at 388,50 m ASL till the flow in the river exceeds 110 $m^3.s^{-1}$. In case of Strakonice weir structure it is however unnecessary keep the headwater on the level mentioned above as there are no intake or discharge structures present which would require such operation. Therefore the flap gates in this particular weir are either fully lifted or fully folded and the procedure take place when the river flow is close to 100 $m^3.s^{-1}$.

The laboratory research was focused on evaluation of the overall performance of the weir structure, sport channel combined with brush fish pass (according to proposed design), stilling basin and a part of the river channel below the weir structure for discharges up to 100 $m^3.s^{-1}$.

The hydraulic conditions and the capacity of the spillway were evaluated for completely lifted gate and also for several intermediate positions. The comparison of measured capacity curves, see Fig. 2, allowed for evaluation of the effects of energy dispersion blocks placed inside the stilling basin, which would influence hydraulic conditions mainly during higher flows, and also allowed for correction of coefficients of discharge used for the calculated capacity curves.

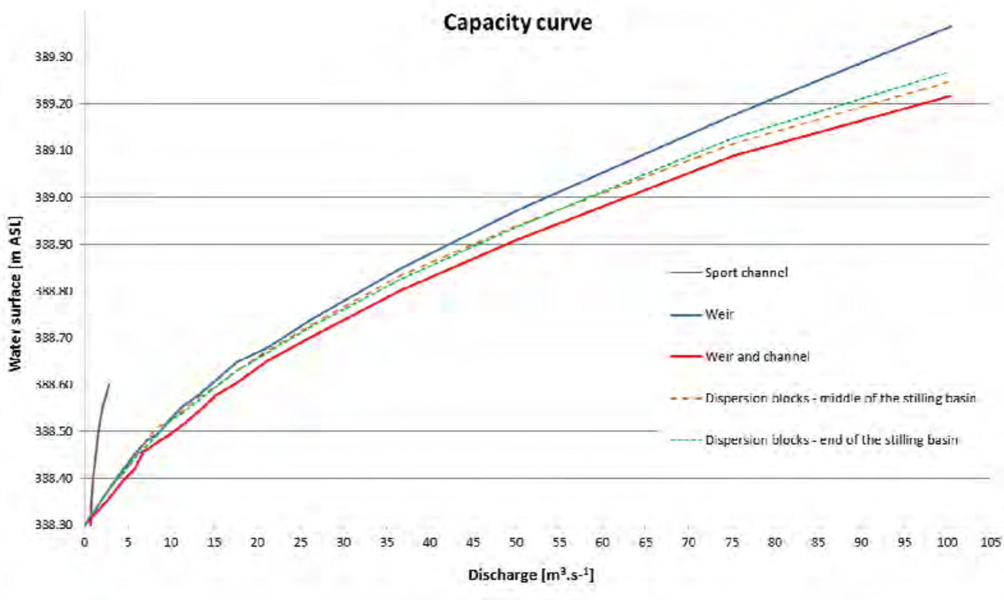

Fig. 2: Capacity curves for different model setups

The forces in lifting pin-rods due to the static loading for completely lifted gate were measured with force transducers and averaged as the process is not completely steady. In order to improve the accuracy of the results, two models of the same flap gate were constructed. First one having dimensions scaled 1:14 included the whole length of the gate while the second, more detailed, segmented model had dimensions scaled 1:7 but included only a part of the gate. Following figure presents how the level of details of the edge of the gate and baffle blocks on the edge, that also work as a siphon, influence the outcome.

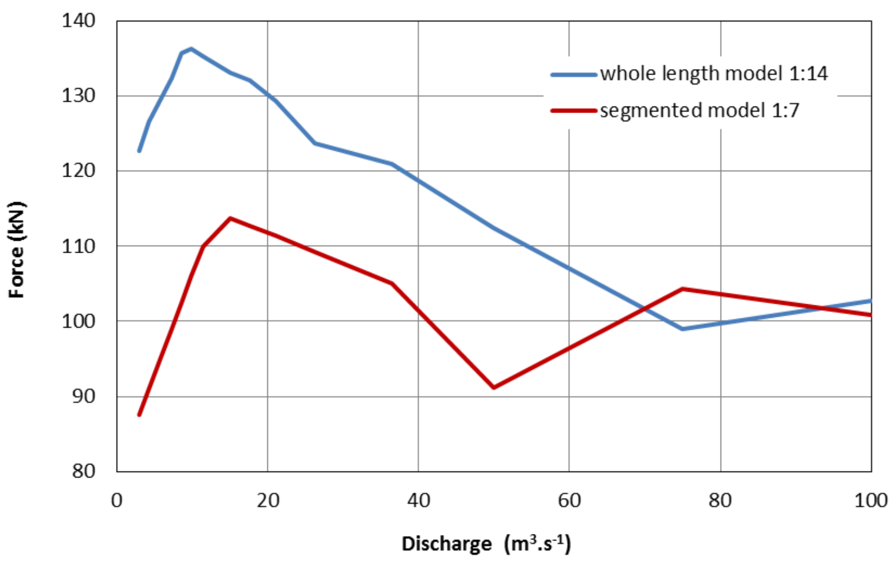

Fig. 3: Average forces in lifting pin-rod

The influence of insufficient aeration on the downstream face of the gate on the capacity curve was evaluated on the segmented model. Figure 4 presents results for two extreme cases. In first case the air pressure is safely achieved along the whole downstream face of the gate. In second extreme case no aeration pipeline is provided and the downstream face is underpressurised leading to increased capacity of the spillway. The relative increase in capacity due to negative pressure was less than 5%.

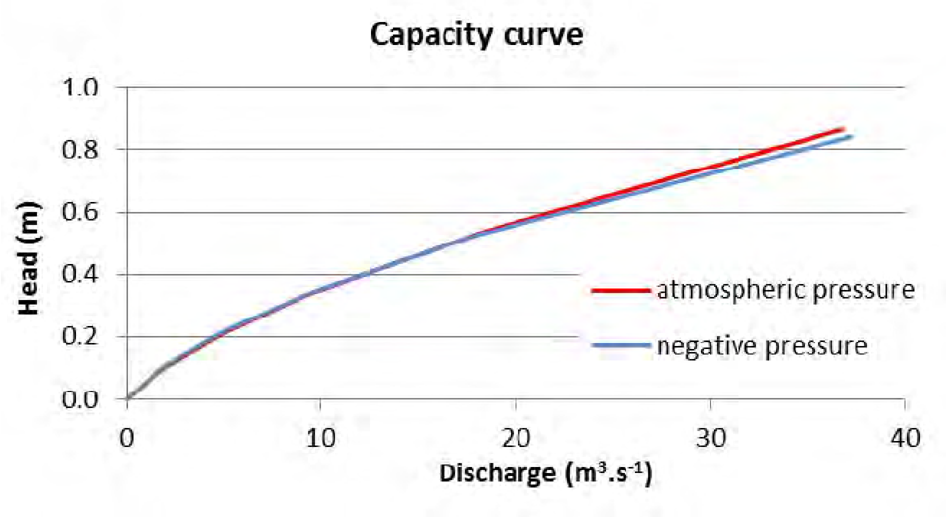

Fig. 4: Capacity curve of the segmented model for different aeration conditions

The accelerations in all three dimensions were measured for different positions of the gate and varying discharge on the 1:7 segmented model. Vibrations measured by triaxial accelerometers were evaluated with the help of FFT. The first eigenfrequency of the laboratory model calculated with help of numerical model built in ANSYS Workbench was 50 Hz. Comparing the measured and calculated shapes and frequencies we confirmed that the construction (model) oscillates in frequencies which are equal to eigenfrequencies. The excitation force, however, is necessary to harmonize on different frequency due to the effect of two fluids with very different properties being in contact with the structure. The last mentioned statement still awaits verification.

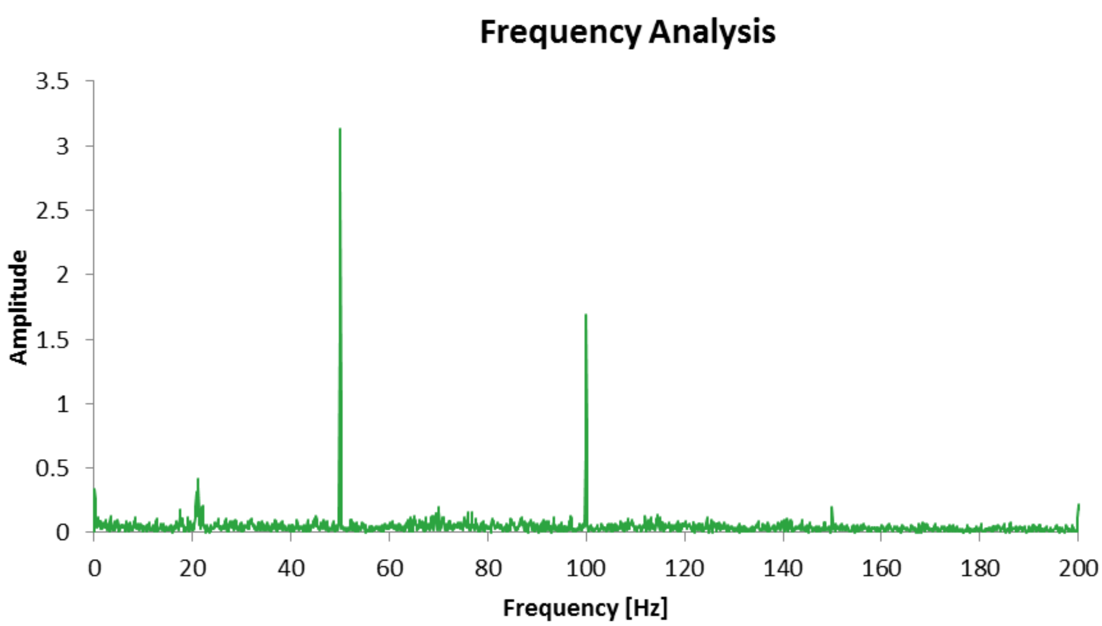

Fig. 5: FFT analysis of vibrations measured for gate folded to 40° overflown by 16,9 mm of water

4. Numerical modelling

Assuming properly calibrated model Computational Fluid Dynamics provides results which are generally on the same level of accuracy as those obtained from the physical model. The advantage of numerical model is however in observation of details which are difficult to study on laboratory models due to its size or limited accessibility. Dynamic part of horizontal load is typically caused by wave action on both upstream and downstream face. The hydraulic jump and its unsteadiness can also prove to be the cause of excessive dynamic load. Significant portion of total dynamic load in horizontal and vertical direction during the free overfall, i.e. without the influence from flow in the stilling basin or channel downstream, is caused by the oscillation of the overfalling nappe which frequency corresponds with the eigenfrequency of the construction.

For flap gate with operating rods on both sides it technically possible to obtain following eigenshapes. First there is an oscillation of the whole flap gate upstream and downstream with highest amplitudes of deflection in the central part and small deformations in the operating rods as shown in Fig. 6.

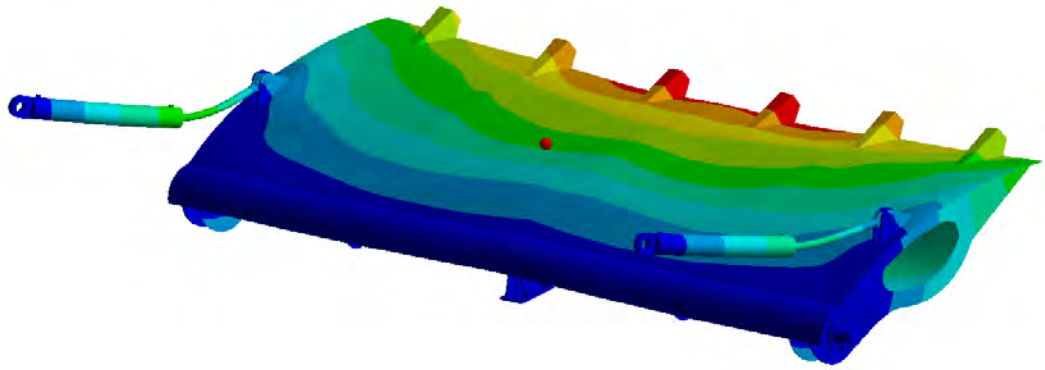

Fig. 6: First eigenshape for flap gate with operating arms on both sides – oscillation is parallel with the direction of flow (displacements are colored)

Second possible shape assumes oscillation perpendicular to the direction of flow which bends the gate to the shape of letter S, see Fig. 7. Without the damping effect of water, i.e. assuming only single fluid (air) in the surroundings, the calculated frequency belonging to this shape equals 32 Hz. The damping effect of water would most likely decrease the frequency by half which will then be close to in-situ measured value at hydraulic structure Doksany.

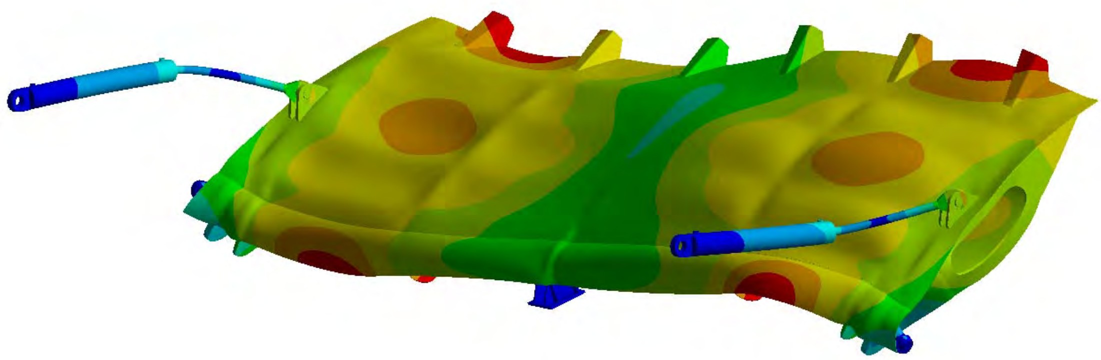

Fig. 7: Second eigenshape for flap gate with operating arms on both sides – S shape

The second shape also corresponds to the in-situ measured deflections which are highest near the outer buffer blocks. In the middle of the gate the fluctuations of deflections are negligible which corresponds to pressure fluctuations in headwater being close to zero in the middle.

5. In-situ measurement

The experiments on real construction were focused on mechanical vibration of the steel gate under selected flow conditions and assessment of the impact of measured vibrations on the reliability and service life of the structure. At first it was necessary to confirm repeatability of the experiments for selected thickness of overfalling nappe. Second the range of frequencies which can be expected was estimated and measuring device selected. As the vibrations induced audible noise low frequencies were assumed and MEMS accelerometers connected to data logger were selected for measurement.

5.1. Hydraulic Structure Ceske Vrbne

The experiments took place on the left flap gate which was mounted two years ago as a replacement for the original hydrostatic pressure operated gate. The selected hydraulic conditions prescribed the head, which was small when compared to the height of the gate, and the accelerometers were placed on the buffer blocks. As the vibrations induce excessive noise an electret microphone that has a frequency response covering essentially the range of the human ear was positioned near the edge of the gate.

The resulting FFT for acceleration in three directions related to the structure and acoustic pressure can be observed in Fig. 8. The highest acceleration is observed in the direction perpendicular to the construction and parallel with the flow direction. Double integration leads to displacement fluctuations which does not exceed ± 0,2 mm. Dominating oscillating frequency for acceleration and acoustic pressure under described conditions is around 26 Hz.

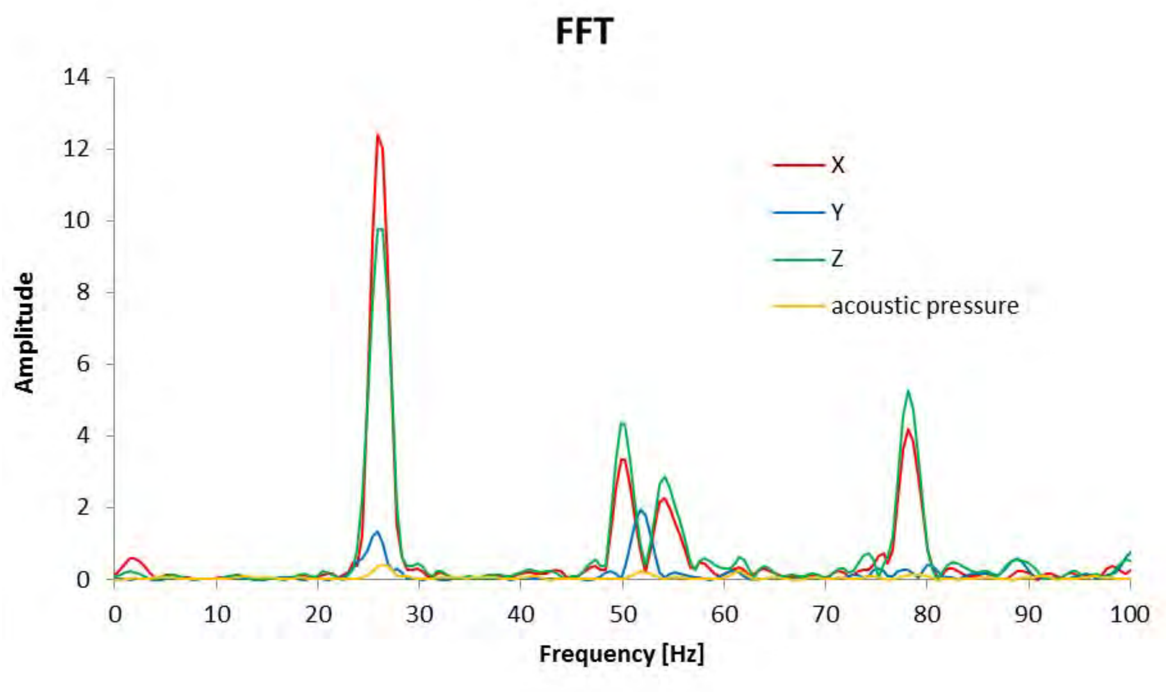

Fig. 8: FFT analysis of acceleration and acoustic pressure

5.2. Hydraulic Structure Doksany

The experiments took place on the right flap gate which was mounted approximately one year ago as a replacement for the original roller drum gate. Although the gate vibrates only under specific hydraulic conditions, the excessive noise trespasses limits set by hygienic standards and strong vibrations can also be observed on the adjacent structures (abutments, stilling basin, foundation structure, etc.). The strongest vibration are observed when the head is between 6 and 10 cm and the visible manifestation of the vibrations is clear form oscillation of the overflowing nappe in Fig. 9

Fig. 9: Oscillation of the overflowing nappe

The highest accelerations are observed in the direction perpendicular to the theoretical axis of the construction and parallel with the flow direction, see Fig. 10. Double integration leads to displacement fluctuations which does not exceed ± 0,15 mm and dominating oscillating frequency for acceleration and acoustic pressure under described conditions is around 16,6 Hz.

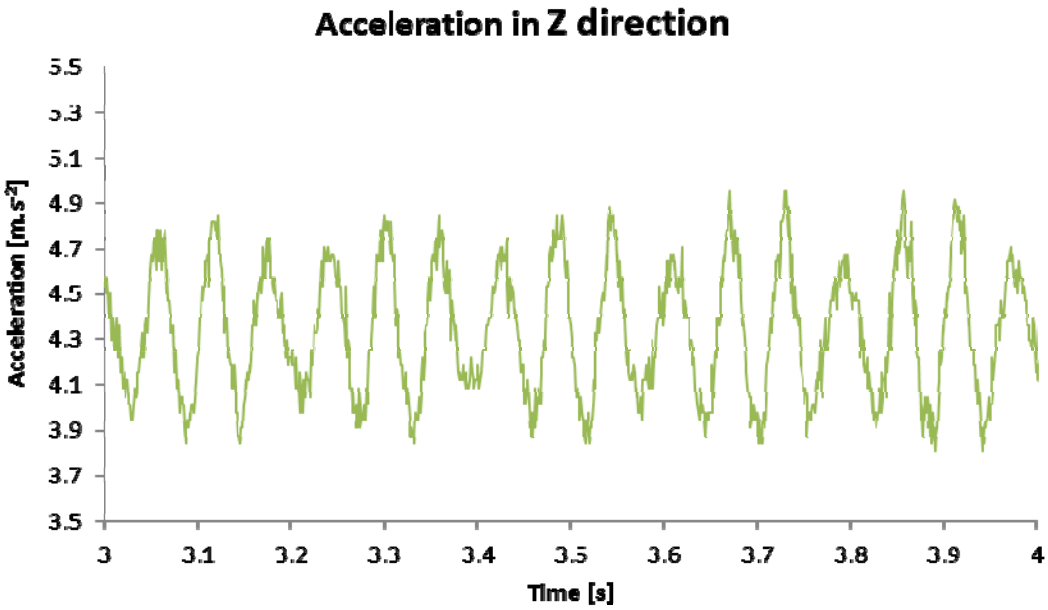

Fig. 10: Measured acceleration normal to the axis of the gate

The pressure sensor with integrated AD converter measuring relative pressure joint with logging unit and USB interface was used in order to evaluate the propagation of the vibrations to reservoir. The sensor was placed in a modified protection plastic tube and the readings were verified via independent submerged pressure sensors. The sensor was submerged and pulled out at constant rate 0,5 m/s. Figure 11 shows the measured pressures and their oscillations for different depths.

The obtained values confirmed that vibrations from the gate which propagate into the reservoir are measurable and as the subsequent FFT analysis provided similar frequencies with dominating number

16,6 Hz it was concluded that pressure sensors can be used to verify data gained from different approaches.

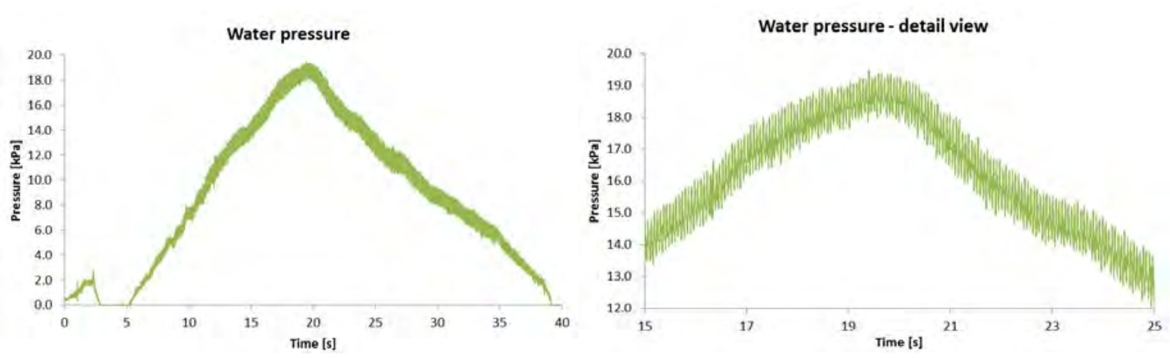

Fig. 11: Pressure fluctuation in water in the weir reservoir

6. Conclusions

The paper presents several selected results gained during the research focused on the vibration of flap gates including in-situ measurements, laboratory experiments and numerical modeling. It was shown that applying all three approaches results in robust analysis which allows for solid assessment and practical recommendations for mitigation or elimination of the undesirable vibrations.

Reliability analysis and impact on service life assessment cannot be done without numerical model, as neither in-situ measurement nor laboratory model can provide sufficient information about the stress state in the whole gate body, joints and operating rods.

Laboratory model on the other hand allows for design recommendations related to the shape of the edge or position of the baffle blocks which would eliminate the vibrations without affecting the hydraulic characteristics of the spillway in undesirable way. The laboratory model can also serve other purposes such as confirmation of the effect of aeration or forces in lifting rods in different positions of the gate.

In-situ measurements serve for the calibration purpose in case of numerical models and verification in case of laboratory model. It provides for correct selection of the eigenshape and assessment of the impact of vibration to the adjacent areas in terms of excessive noise and vibration pollution.

Apart from design recommendations to adjustments on the real construction it is also usually possible to avoid the impact of vibrations by restricting the time of action in the handling manuals to the flap gate. Although such approach does eliminate the cause of vibrations it presents the least demanding and in Czech Republic the most often used way to minimize the negative impact of undesirable vibrations.

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