# Cavitation risk estimation at orifice spillway based on UVP and dynamic pressure measurements

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Orifice spillways might be affected by cavitation if the profile of the inlet structure includes a relevant curvature. At one of the world's largest dams, such damages were observed on the profiled slab. To limit their progression, an adapted operation regime of the gates had to be defined using physical model tests. The risk estimation was based on dynamic pressure and velocity measurements, indicating that a maximum gate opening ratio of 0.8 should be respected until the damage is repaired and the profile re-shaped. Beside this, the data set allowed to compare the flow characteristics at the profile surface in terms of turbulence intensity and dominant frequencies. The Ultrasonic Velocity Profiler (UVP) provides comparable characteristic values as the dynamic pressure transmitter (DPS).

**Keywords:** Cavitation, pressure, spillway, turbulence, velocity

## 1 INTRODUCTION

Fast flows in contact with concrete structures are known to potentially generate cavitation damages, in particular if the related bottom pressure is low. Several spillways and chutes evacuating severe floods from reservoirs, thus avoiding dam overtopping and the related failure, suffered from these damages. However, cavitation erosion on such structures may be suppressed if applying chute aerators [1, 2], so that their safe operation under extreme conditions is possible.

A different spillway type may also be prone to cavitation, even if this is less obvious. Orifice spillways intend to remove the water from the concrete surface by generating free jets, thus avoiding cavitation and other unwanted phenomena. However, the inlet structure of these orifices might be a sensitive element, even if the flow velocities and pressures are a priori below a critical range. The cavitation potential of these inlets results from the curvature of the inlet profile inducing a curvature of the streamlines, increasing local velocity and decreasing pressure. Furthermore, the flow may separate from the surface and generate a local back flow zone.

## 2 CAVITATION ANALYSIS

### *2.1 Situation*

Severe cavitation damages on an orifice spillway inlet profile were observed at one of the world largest dams. The dam owner paid particular attention to that damage, as a proper operation of the gates is necessary to guarantee a safe reservoir management. Physical model tests were therefore conducted to assess the cavitation potential for different gate opening ratios (equivalent to discharges), based on which the dam owner defined an adequate operation regime as a first step. Rehabilitation and an adaption of the concrete profile will follow in a second step.

The cavitation potential depending on the operation mode was estimated in a physical model on the base of dynamic pressure measurements and on velocity sampling. The latter indicates a flow separation zone for maximum gate opening. Combined with the analysis of the dynamic pressure measurements, a comprehensive description of the flow processes was possible.

A model including all orifices was built (Fig. 1) with a geometrical scale factor of 65 and considering the hydraulic similitude according to the Froude number. The maximum spillway discharge of 9'000 $m^3/s$ in prototype corresponds to 264 l/s in the model. The model tests were conducted with a constant reservoir water level. The cavitation potential was estimated for various operational scenarios (Table 1).

Figure 1: Physical model of orifice spillway seen from reservoir, considered gate is second from right

Two sensors were installed (Fig. 2):

- A piezoresistive dynamic pressure transmitter DPS (Series 23, www.keller-druck.com) of pinhole type with an acquisition range between +/–0.1 bar, an acquisition frequency of 1 kHz and an acquisition time of 65 s. The pressures were measured at a defined "measurement point" MP on the slab of a particular orifice, where severe cavitation damages occurred in prototype. The latter is located in the transverse center of the orifice. The tap hole connecting the transmitter with the surface was drilled 3 mm below the abrupt profile edge (model dimensions). The measurement cavity was de-aerated to avoid resonance phenomena.

- An UVP transducer (TX1-13-16, www.met-flow.com) with an emitting frequency of 1 MHz, an active diameter of 20 mm (instead of 13 mm) and an acquisition time of 10 s. The measurement beam was horizontal ($x$=0 m at MP) and pointing to the tap opening of the pressure transmitter. The transducer was located 0.24 m away from MP to avoid an effect of the UVP on the flow, corresponding to 15.6 m in prototype. Only the 7.0 m closest to MP were considered in the data analysis. The values were furthermore corrected with the angle of the profile, which is approximately 25° relative to the horizontal at MP. Positive velocities represent a flow direction from left to right in Fig. 2, and negative values indicate a flow from right to left.

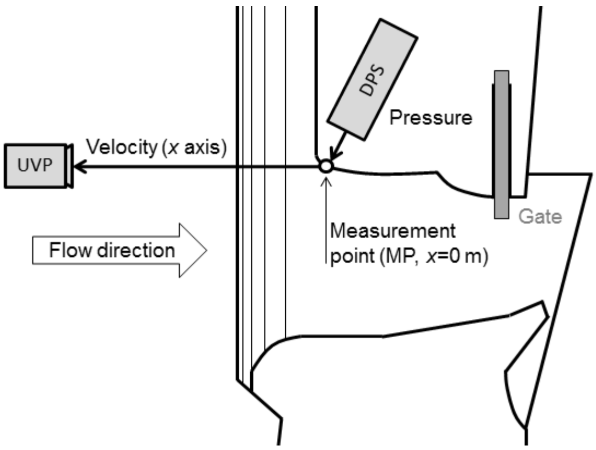


Figure 2: Section of dam with orifice spillway and measurement equipment

Table 1: Test scenarios

| Scenario | Opening ratio of considered gate | Opening ratio of neighbor gates |
|---|---|---|
| A1 | 0.2 (20 %) | 0.0 |
| A2 | 0.4 (40 %) | 0.0 |
| A3 | 0.6 (60 %) | 0.0 |
| A4 | 0.8 (80 %) | 0.0 |
| A5 | 1.0 (100 %) | 0.0 |
| B1 | 0.2 | 1.0 |
| B2 | 0.4 | 1.0 |
| B3 | 0.6 | 1.0 |
| B4 | 0.8 | 1.0 |
| B5 | 1.0 | 1.0 |

## *2.2 Velocity measurements*

Figure 3 shows the up-scaled horizontal velocity profiles, with $x$=0 m at MP and $x$>0 m at increasing distances from the latter (Fig. 2).

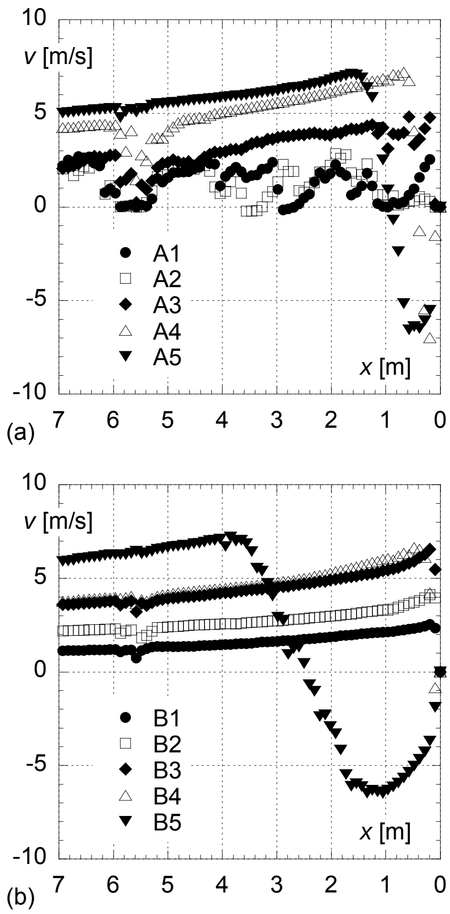


Figure 3: Average flow velocities $v$ ($x$=0 m at MP of Fig. 2, prototype values) for scenarios (a) A and (b) B

The following observations were made:

- The velocities increase towards the profile if approaching MP. This is due to streamline curvature, induced by the rounded inlet profile. This increase of velocity is linked to a drop in pressure, both supporting the occurrence of cavitation.
- The profiles indicate a discontinuity between $x$=5 to 6 m. The latter is caused by an inlet vortex as observed in prototype. There, the horizontal velocity component decreases, whereas the rotational component (not detected by UVP) increases.
- The velocities generally increase with increasing opening ratio, as the related discharges also increase.
- Small discharges (small opening ratios) show an unstructured flow characteristics if the neighbor gates are closed (A1, A2), whereas larger gate openings generate higher velocities and more

homogenous flow fields.

- Negative velocities occur for maximum gate opening ratios, indicating a flow separation zone with back flow close to the profile. The main flow is thus unable to follow the profile shape, indicating a too pronounced curvature. The back flow zones are related to cavitation formation, as the shear zone between the two flow cells is highly turbulent with pronounced pressure peaks. The thickness of the separation zone increases with the discharge.

### *2.3 Pressure measurements*

Figure 4 shows the up-scaled pressure heads at MP. For small gate opening ratios, the average values are close to the hydrostatic head of 17.8 m water column (WC). With increasing gate opening ratio, the pressure heads decrease. For maximum gate opening ratios of 1.0, distinctively negative pressures are detected. Cavitation onset is observed in prototypes for pressures around –7 to –10 m WC [3] (grey area in Fig. 4), i.e. at opening ratios of 1.0 for the present case. Note that pressures below these values will not occur in prototype, as the water changes its phase to vapor.

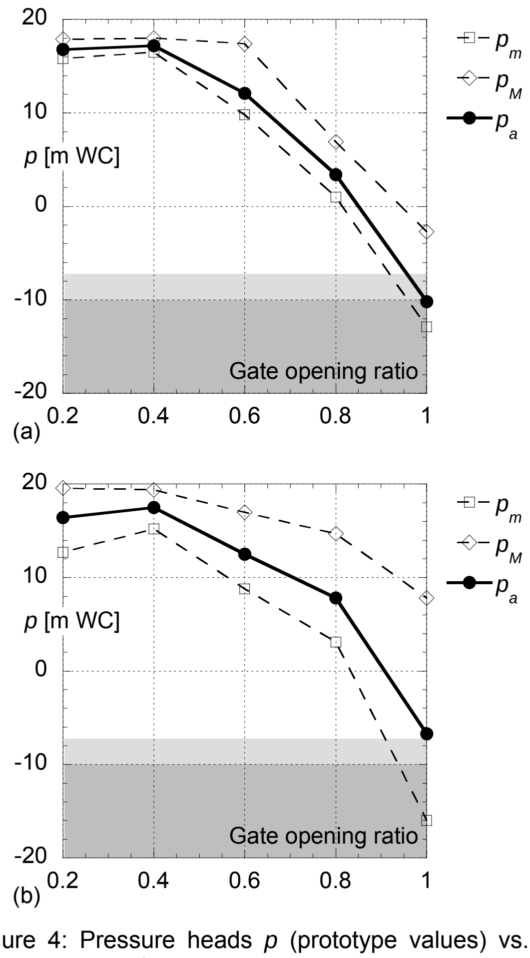


Figure 4: Pressure heads $p$ (prototype values) vs. gate opening ratios for scenarios (a) A and (b) B, with $m$= minimum, $M$= maximum, $a$= average, in grey: cavitation zone below vapor pressure

### *2.4 Interpretation*

Model tests clearly support observations on prototype: Under full operation, the investigated orifice represents a significant risk for cavitation damages. The results of the interpretation concerning the two scenarios A and B are similar for high discharges. The velocity measurements indicate that a separation zone with back flow emerges for gate opening ratios of 0.8 to 1.0. The pressure measurements show that the values drop below vapor pressure for the maximum gate opening ratio. The following applies:

- The herein derived results are only valid for a smooth inlet ceiling profile. Cavitation is more likely for a rough and already damaged surface than for a smooth one.
- The results were derived based on the analysis and interpretation of measurements at one single point MP in a scaled model. They have thus a qualitative character, but are nevertheless revealing a significant cavitation risk.

## 3. COMPARISON UVP WITH DPS

### *3.1 Turbulence intensity*

Regarding cavitation, the flow turbulence is relevant because it also indicates the occurrence of minimum pressures. For measured time series, the turbulence intensity is defined as [4]

$$T_u = \frac{RMS}{\bar{x}} \qquad (1)$$

with *RMS* as root mean square of a time series and $\bar{x}$ as mean value. Figure 5 shows $T_u$ for both acquisition systems (UVP and DPS) and for both scenarios. The $T_u$ values of the DPS are located on the profile surface at $x$=0 mm (MP), and those of the UVP at $x$>0 mm.

The $T_u$ values of the DPS measured on the profile surface are between 1.0 and 1.2 for all scenarios. Those from UVP are derived in the flow at different locations $x$ near the profile. The UVP measurement closest to the surface at $x$=0.61 mm indicates a $T_u$ which is one order higher than that from DPS, both located in the turbulent boundary layer (TBL). For large distances of around $x \geq 9.49$ mm the UVP values are around $T_u$=0.1 to 0.5, as probably located in potential flow. Between these extremes, the $T_u$ of the UVP are close to those of the DPS. Removing the outlier at A2 ($T_u$=62 at $x$=2.09 mm) in the UVP data set and averaging all scenarios between 2.09 mm$\leq x \leq$3.57 mm results in $T_u$=1.14, and averaging all scenarios in the UVP data set between 2.09 mm$\leq x \leq$5.05 mm results in $T_u$=0.90. These averages are close to the mean of all DPS measurements with $T_u$=1.03. The flow turbulence near a surface is thus correctly represented by UVP if considering the DPS data as reference and if taking into account the zone between 2 mm and some 4 to 5 mm away from the rigid surface. Besides that, the general trend with increasing $T_u$ towards the surface, i.e. in the TBL, is confirmed.

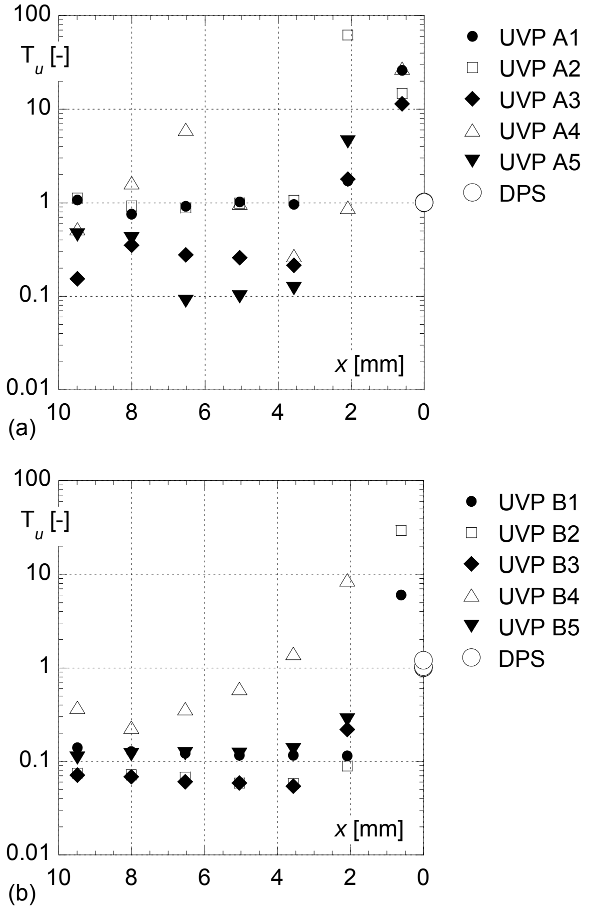


Figure 5: Comparison of $T_u$ derived from UVP and DPS for scenarios (a) A and (b) B ($x$=0 mm at MP of Fig. 2, model values)

### *3.2 Power spectra*

The power spectral densities based on the Welch periodogram are shown in Fig. 6, including A5 and B5 and comparing the DPS and the UVP data ($x$=3.57 mm for A5, at $x$=2.09 mm for B5). The unit of the ordinate is Bar$^2$/Hz for pressures, and (m/s)$^2$/Hz for velocities. The curves of the velocity were smoothened by a symmetrical moving average over five values.

For A5, no dominant frequency occurs for both sensors, whereas B5 indicates a peak at around 2 to 3 Hz in both curves. The general trend seems similar for both instrumentations.

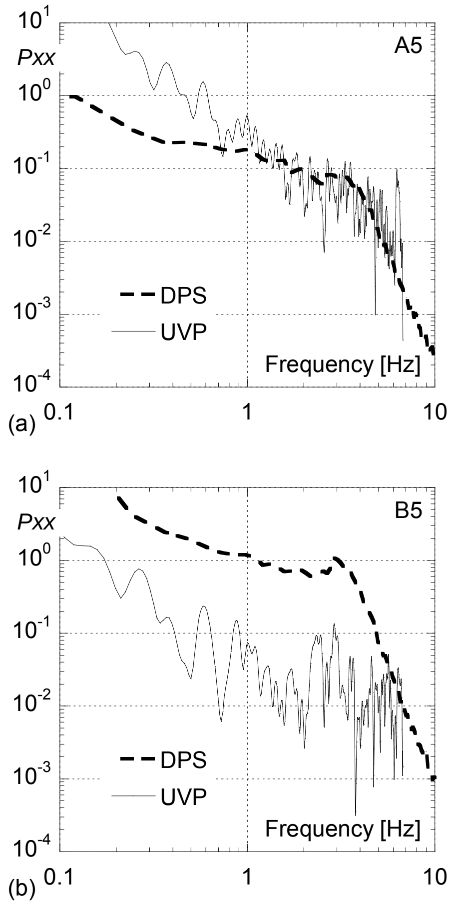


Figure 6: Power spectra derived from UVP and DPS for scenarios (a) A5 and (b) B5

## 4. CONCLUSIONS

Dynamic pressure measurements are essential for cavitation prediction. Velocity sampling supports the analysis of the flow field. Basically, DPS and UVP provide comparable turbulence characteristics and dominant frequencies. Beside a sufficient acquisition period, the distance to the rigid surface was found as essential parameter for UVP turbulence estimation.

## REFERENCES


[1] Pfister M, Hager WH: Chute aerators I: Air transport characteristics, J Hydraulic Eng, 136(6), 352-359 (2010).

[2] Pfister M, Hager WH: Chute aerators II: Hydraulic design, J Hydraulic Eng, 136(6), 360-367 (2010).

[3] Vischer D, Hager WH: Dam Hydraulics, John Wiley & Sons, Chichester (1998).

[4] Ervine DA, Falvey HT, Withers W: Pressure fluctuations on plunge pool floors, J Hydraulic Res, 35(2), 257-279 (1997).