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Experimental Study of Ogee Crested Weir Operation Above the Design Head and Influence of the Upstream Quadrant Geometry

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Abstract: *The effect on the flow characteristics of the upstream quadrant shape of four ogee spillways is investigated at high head operation by means of experimental modelling. Each spillway is designed following the latest recommendations of the U.S. Army Corps of Engineers. The upstream and downstream quadrants of the reference spillway have the same design head. The absence of scale-effects is verified with a second reference spillway designed with a smaller head. The last spillway has an upstream quadrant with a design head respectively larger and smaller than the one of the downstream quadrant. The discharge coefficient is evaluated until head ratios of five for each case and until seven for the smaller model. The discharge coefficient continuously increases until a head ratio of 5.5 and then drops due to a flow separation at the spillway crest. The spillway efficiency (discharge coefficient) reduces with an oversized upstream quadrant while an undersized quadrant has no effect, but it does affect the measured relative pressure and thus the risk of cavitation.*

Keywords: *Spillway, free surface weir, experimental modelling, discharge coefficient, quadrant geometry, cavitation risk.*

1. Introduction

Uncontrolled ogee-crested spillways are common flood release structures equipping dams. Their shape is designed regarding a given upstream head, the design head H_d, in order to get a zero-relative pressure all along the crest profile (Hager 1987; USBR 1987). In these conditions, the flow over the ogee crest is the same as the free jet observed over a sharp crested weir.

The efficiency of the spillway, quantified by its discharge coefficient C_d, is directly related to the pressure on the crest. For real upstream heads, H, smaller than the design head (head ratio $H/H_d<1$), the relative pressure on the crest is positive and the discharge coefficient decreases in comparison to its value for the design head. For head ratio higher than one, the relative pressure on the crest is negative and the discharge coefficient increases. Under designed ogee spillway crest (spillway designed considering a design head smaller than the maximum operation head) is thus more efficient from a discharge capacity point of view. Indeed, for a given upstream head, it enables the release of a higher discharge than a spillway designed with a higher design head. However, negative relative pressure on the crest opens the door to flow detachment in case of connection of the lower part of the nappe with the atmosphere (for instance close to piles or at the end of short spillway chutes) or induces a risk of cavitation if the pressure falls locally below the water vaporization pressure. This explains why ogee spillway crests are usually designed considering a design head equal to the maximum operation head.

In the literature, few studies focused on the characteristics of the flow over an ogee spillway crest for heads largely greater than the design head. Rouse and Reid (1935) studied the influence of the shape of the crest by comparing the discharge coefficients and the pressure distributions of three different ogee spillway crests with those of a sharp crested weir until head ratio equal to three. In the sequel, Cassidy (1970) and Abecasis (1970) focused their investigations on a procedure to control until a head ratio of three the minimal pressure that occurs on an ogee spillway designed following the recommendations of USBR (1948). Vermeyen (1992) in the frame of a project had to study an ogee-spillway working under head ratio of five (Vermeyen, 1991). More recently, Castro-Orgaz (2008) proposed an approximate curvilinear flow model and applied it to a spillway profile tested experimentally by Hager (1991) with head ratio up to two.

It should be noted that in the previous studies when conclusions exist they differ from an author to another because of the various crest configurations that were studied. According to Cassidy (1970), for an ogee spillway designed following the recommendation of USBR (1948), a flow separation at the spillway crest occurs at head ratio of three.

On the other hand, Vermeyen (1992) pointed out that under ideal entrance (i.e. no contraction of the flow when approaching the spillway) the head ratio can reach five on a spillway designed using recommendation of USBR (1987); but under this flow condition, the nappe is very unstable and 'nappe separation can occur from very small surface disturbances' (Vermeyen, 1992: 1).

Besides, if in the field the downstream quadrants of the spillways generally follow the same standards, multiple geometries exist for the upstream quadrant. This large variability of shapes for ogee-crest spillways was rarely considered in the literature (Melsheimer and Murphy, 1970, Reese and Maynord, 1987) or was not completely analyzed (Rouse and Reid, 1935). Even if Melsheimer and Murphy (1970) and Rouse and Reid (1935) found that the curvature immediately upstream from the crest axis determines in large part the efficiency of the spillway and the minimum pressure on the structure, the incidence of the shape of the upstream quadrant cannot be plainly distinguished from the one of the downstream quadrant.

The objectives of the research depicted in this paper are twofold: considering the most commonly used profile of ogee spillway, 1) investigate the flow characteristics over the spillway crest operating with head ratio largely greater than one and 2) analyze the influence on these flow characteristics of the geometry of the upstream quadrant. The analysis has been mainly performed by means of scale physical modelling. In this study, no piles effect or air entrance is considered. The experimental setup and selected crest profiles are presented in section 2. Then, the results are presented in section 3 and discussed in section 4 in particular regarding discharge capacity and pressure distribution on the crest.

2. Experimental Setup

2.1. Ogee Spillway Profiles

In this study, the authors used as a reference the geometry of ogee spillway defined in the book *Hydraulic Design Criteria* (USACE, 1987), i.e. the so-called "Waterways Experiment Station (WES) Geometry", also reported in USBR (1987). The design head of the reference spillway W1 is set to 0.15 m with a slope for the chute equal to 51°. The upstream quadrant is designed with three arcs of circle (see the coordinate in Table 1) and the downstream quadrant follows a power-law equation (Eq. (1)):

$$x^{1.85} = -2H_d^{0.85}z \tag{1}$$

where in the Cartesian coordinate system, x, y and z are the streamwise, spanwise and vertical directions, respectively; $(x, y, z) = (0, 0, 0)$ at the crest. The z-axis is directed in the upward direction.

Table 1. Coordinates for upstream quadrant (USACE, 1987).

x/H_d	z/H_d*	x/H_d	z/H_d*
0.0000	0.0000	-0.2200	-0.0553
-0.0500	-0.0025	-0.2400	-0.0714
-0.1000	-0.0101	-0.2600	-0.0926
-0.1500	-0.0230	-0.2760	-0.1153
-0.1750	-0.0316	-0.2780	-0.1190
-0.2000	-0.0430	-0.2800	-0.1241
		-0.2818	-0.1360

* *The z-axis is oriented in the upward direction.*

Three additional crest profiles which were designed following the WES standards were also studied. They have the same downstream quadrant as W1 and the slope of the chute is also equal to 51° for each case. Their characteristics are summarized together with those of W1 in Table 2 and they are represented in Figure 1.

The geometry of W2 is identical to the reference case W1 but with a smaller design head of 10 cm which allowed the authors to reach higher heads for the same discharges. This difference in scale was also used to identify the presence of scale-effects (Peltier et al., in press). The geometry of W3 and W4 envelop the shape of sixteen existing spillways exploited by the French company of electricity EDF (Figure 1). These spillways were not designed following the WES standards exactly, but it appears that the design head of their downstream quadrant, at least close to the crest, can be approximated by the WES standards (Figure 1). The design head of the downstream quadrant, $H_{d\text{-}down}$, for W3 and W4 is the same as for W1, but the design head of the upstream quadrant, $H_{d\text{-}up}$, is different (Table 2). It is equal to $2.5H_d$ and $0.7\ H_d$ for W3 and W4, respectively. These values have been chosen to circumscribe the real upstream quadrant profiles.

Table 2. Characteristics of the crest profiles geometry and of the $Q(H)$ relationship for each spillway.

	$H_{d\text{-}up}$ (m)	$H_{d\text{-}down}$ (m)	S_c (°)	H_d (m)	$Q\times10^{-3}$ ($m^3.s^{-1}$)	H (m)	H/H_d
W1	0.150	0.150	51	0.150	5.5 – 359.4	0.056 – 0.790	0.37 – 5.26
W2	0.100	0.100	51	0.100	3.0 – 296.7	0.043 – 0.739	0.43 – 7.39
W3	0.375	0.150	51	0.150	3.6 – 358.2	0.045 – 0.779	0.30 – 5.19
W4	0.105	0.150	51	0.150	2.8 – 352.5	0.044 – 0.749	0.29 – 4.99

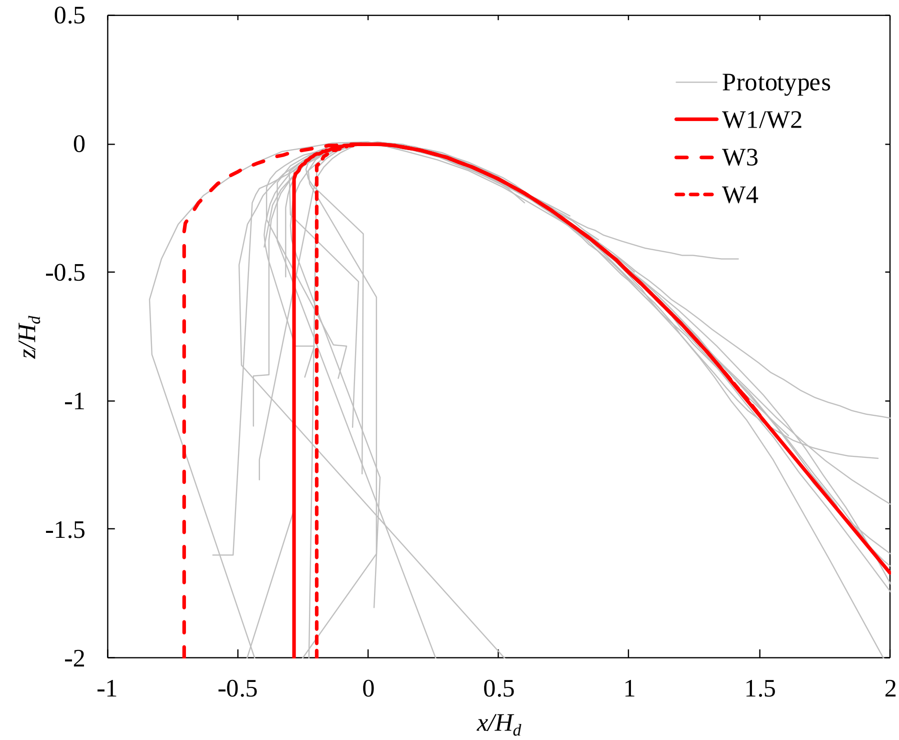

Figure 1. Shape and normalised dimensions of the ogee crests tested in this study.

2.2. Experimental Facility

The experimental facility used in this study is detailed by Peltier et al. (in press). It is made of a 20 cm wide ogee crest section embedded in a large reservoir with an inner width of 0.90 m, a length of 4.00 m and a height of 3.20 m. The upstream face of the spillway is vertical with a height h_{uf} of more than 3 H_{max} to get a discharge coefficient independent from the approach flow depth (Melsheimer and Murphy, 1970, Reese and Maynord, 1987). A smooth chute 4.5 m long is added downstream (Figure 2). Walls are in polyvinyl chloride (PVC) or Plexiglas. The flow is thus confined in a 2D-vertical slice passing by the centerline of the spillway and contraction effects affecting the nappe stability are avoided (Vermeyen, 1992). Water alimentation is a closed loop with one to three regulated pumps pushing the water through one to three pipes and strainers along the whole water column.

2.3. Instrumentation

The upstream head is the main parameter of the study. The measurement cross-section was positioned at a distance from the spillway-crest equal to at least twice the maximal head over the spillway, i.e. x_m = 1.5 m. At this distance, the feeding pipes and the spillway have low influences on the velocity profile in the reservoir, which is therefore quasi-uniform on the vertical. Under such flow conditions, the head is easily evaluated by measuring the water depth h relative to the crest of the spillway and by adding a term of kinetic energy calculated with a uniform velocity equal to the ratio of the discharge Q to the area of the measurement cross-section (Eq. (2)–B is the weir width).

$$H = h + \frac{Q^2}{2gB^2\left(h + h_{uf}\right)^2} \tag{2}$$

The discharge was measured with an electromagnetic flowmeter (Siemens, Magflow) mounted on each pipe. The uncertainty on the discharge δQ was equal to 0.7 L.s^{-1} with one pump, to 0.98 L.s^{-1} with two pumps, and to 1.11 L.s^{-1} with three pumps. The water depth was measured at a distance x_m from the weir crest using an ultrasonic probe (Microsonic, PICO+100). The precision on the measurement δh was estimated to ±1 mm.

Eighteen relative pressure transducers (KELLER, PR23Y) with a measuring range from -5 m to 2 m were distributed along the centerline of the spillway. They gave 1 kHz measurements of the relative pressure P through holes of 2 mm diameter perpendicular to the weir surface. The uncertainty of the pressure measurement was found equal to ±20 mm.

Uncertainties were estimated for every measured variable (h, Q, P) and propagated to the head and to the discharge coefficient following Equations (3) and (4).

$$\delta H = \sqrt{\left|\frac{\partial H}{\partial h}\right|^2 \left(\delta h\right)^2 + \left|\frac{\partial H}{\partial Q}\right|^2 \left(\delta Q\right)^2} \tag{3}$$

$$\delta C_d = \sqrt{\left|\frac{\partial C_d}{\partial H}\right|^2 \left(\delta H\right)^2 + \left|\frac{\partial C_d}{\partial Q}\right|^2 \left(\delta Q\right)^2} \tag{4}$$

with C_d computed as

$$C_d = \frac{Q}{B\sqrt{2gH^3}} \tag{5}$$

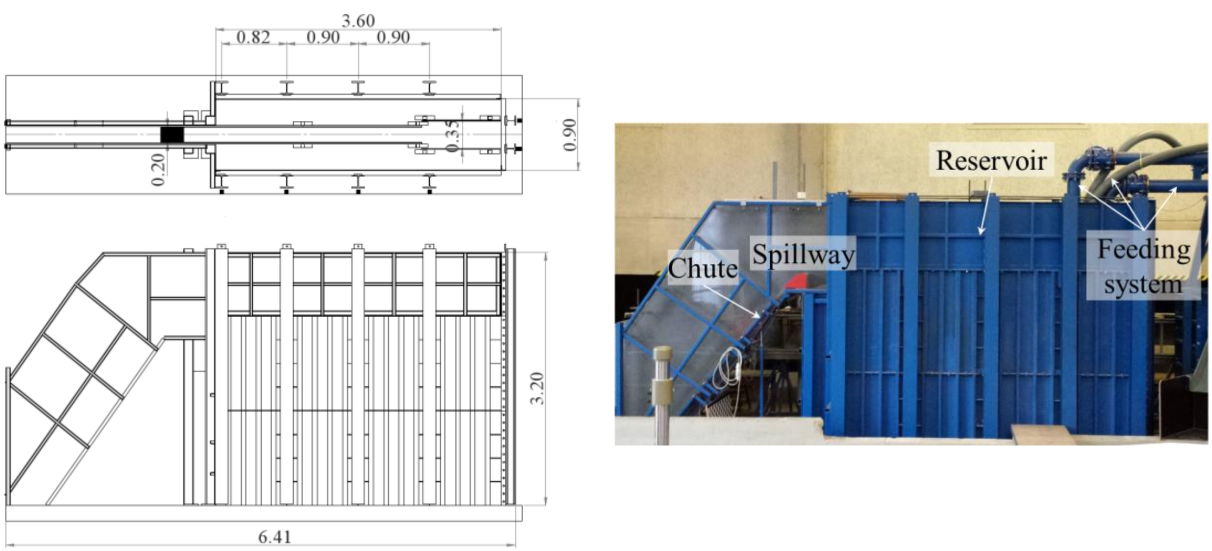

Figure 2. Photograph, plan, and section views of the experimental facility. Dimensions are in meters. From Peltier et al. (in press).

3. Results

3.1. Discharge Coefficient

Between 86 and 131 measurements of Q and H were acquired with each model. The measurements were performed following several sequences of ascending/descending discharges in order to highlight hysteresis effects and to vary the water feeding configurations of the experiment (number of pumps and pipes). The characteristics of each experiment in term of discharge, head, and head ratio are summarized in Table 2.

For each spillway, the discharge coefficients are plotted relative to the head ratio in Figure 3. For W1 and W3, an ellipse locates a zone of large uncertainties (Figure 3a and Figure 3c) which are due to the passage of air bubble on the free surface during the measurements of the water depth. Nevertheless, each plot reveals that the discharge coefficient monotonously increases with the head. Moreover, W1, W2, and W4 follow an empirical law of the type of Equation (6) (USACE, 1987):

$$C_d = 0.501\left(\frac{H}{H_d}\right)^{0.12} \tag{6}$$

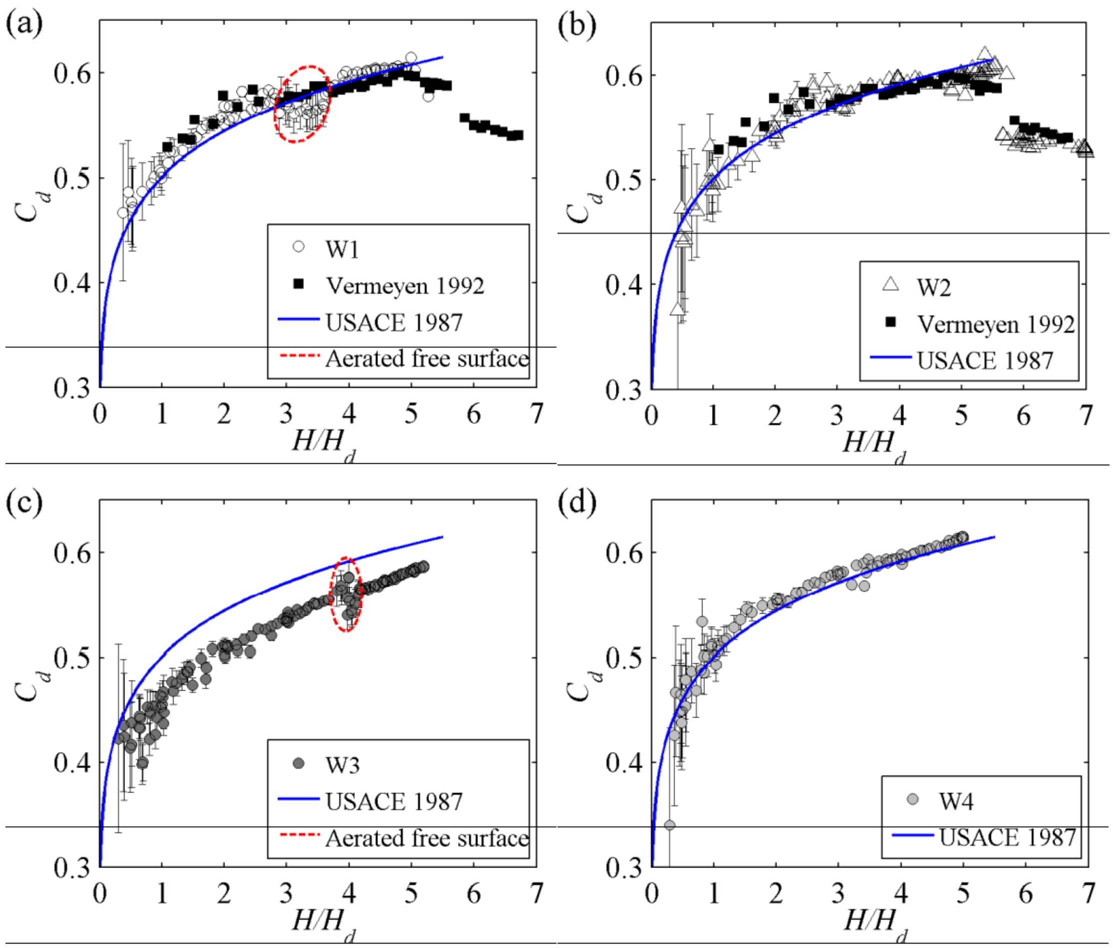

Figure 3. Discharge coefficients of the present experiments plotted together with past experiments and Eq. (5).

3.2. Relative Pressure Along the Spillway

The relative pressure measured along the spillway centreline is plotted in Figure 4. It is normalised by the design head of the downstream quadrant. While for the unit head ratio, the relative pressure along the spillway is close to zero (to the uncertainty) as expected; for higher head ratios, the relative pressure strongly decreases with increasing head ratio.

In all cases, the minimum pressure is measured upstream from the crest and the pressure then quickly increases for reaching zero downstream from x = 1.5$H_{d\text{-}down}$, except for W3 whose shape is closer to a broad-crested spillway. The position of the minimum pressure belongs to [-0.25$H_{d\text{-}up}$ – -0.23 $H_{d\text{-}up}$] which is consistent with the literature from Melsheimer and Murphy (1970) and Vermeyen(1992).

When considering the head ratios for which a drop in the discharge coefficient was observed (W2 at H/H_d = 6 and 7, Figure 4b), results indicate that the minimum pressure is less negative than for H/H_d = 5, but the negative pressure is observed on a longer distance downstream. This behaviour must be related to a nappe detachment occurring at the crest for H/H_d > 5.5 (Figure 5). Given the pressure and velocity conditions at the crest, the flow curvature is no more able to follow up the spillway shape downstream. The flow, therefore, separates from the spillway downstream from the crest which decreases the discharge coefficient (Figure 3b) but makes the pressure field along the crest downstream from the separation point more uniform.

In Figure 4a and in Figure 4b, the relative pressure is represented for W1 and W2, respectively. Similar behaviours are observed until H/H_d = 3, but for greater head ratio, pressures measured on W1 are systematically smaller (increased peak). This could indicate a scale-effect, but it is improbable as no difference is observed on the discharge coefficient (shown in Figure 3 above). A more relevant explanation (Peltier et al., in press) could be that the surface of pressure measurements is relatively larger for W2 than for W1 (dimensions of W2 are smaller than dimensions of W1, but the pressure sensors are the same) while it is clear that the minimal pressure occurs on a limited length.

Considering now the amplitudes of relative pressures on W3 (Figure 4c), they are much smaller than those of W1. This is due to the 'broad' shape of the upstream quadrant, which induces smaller vertical velocities and therefore less negative relative pressures. Notice that from x = 0.4H_d both distributions are equivalent. The opposite observations can be made when comparing W1 and W4 in Figure 4d. The sharp aspect of the upstream quadrant is responsible for systematic more intensely negative pressure at a given head ratio. Nevertheless, from the crest, the distributions for both W1 and W4 coincide.

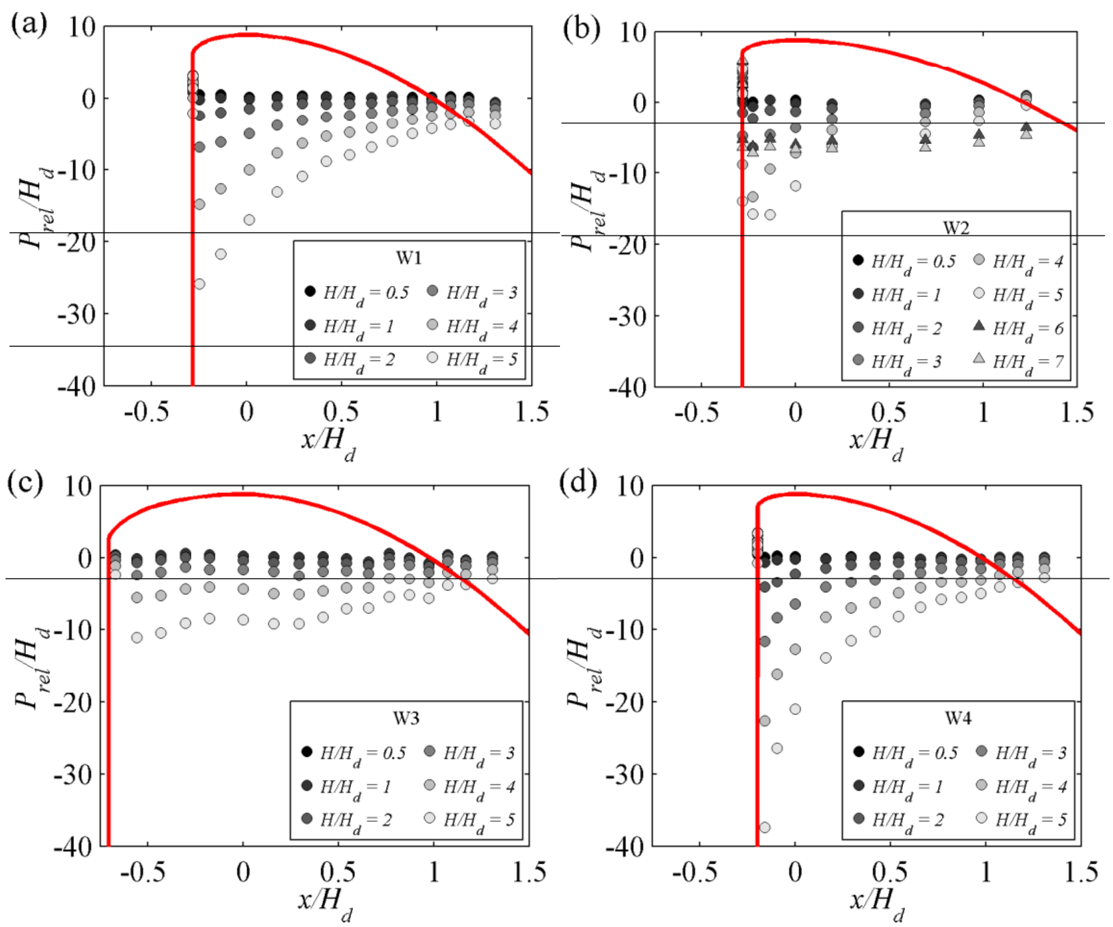

Figure 4. Relative pressure on the four tested spillways for various H/H_d.

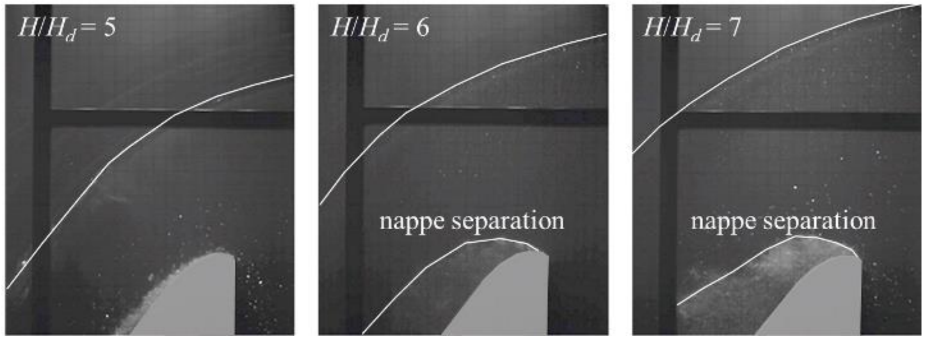

Figure 5. Separation of the lower nappe over an ogee spillway. Flow-case W2.

4. Discussion

4.1. Discharge Coefficient

For W1 and W2, the measurements of Vermeyen (1992) were added in Figure 3a and Figure 3b. The three distributions are in good agreement which indicates no significant scale-effects regarding the discharge coefficient for head ratio until five. Beyond the head ratio of five, the maximal head for W1 prevents reaching the drop in discharge coefficient observed for W2 and data of Vermeyen (1992). Nonetheless, the distributions for W2 and data of Vermeyen (1992) are close which tends to prove there are few scale-effects here too: the design head of Vermeyen experiments being equal to 0.038 m (Vermeyen, 1991, 1992). These results also emphasize the continuous increase of the discharge coefficient until a head ratio of 5.5 and a maximum value of C_d approximately equal to 0.6. Beyond this point, a sudden drop is observed and the discharge coefficient then slightly decreases with increasing head ratio until seven. Its value is, however, still 10% higher than the one at the design head.

Considering W3 (Figure 3c), the discharge coefficient at a given head ratio is smaller than for W1 and W2. In contrast, the evolution of the discharge coefficient for W4 (Figure 3d) is similar to the one for W1. This confirms that the shape of the upstream quadrant can have an incidence on the discharge coefficient (Melsheimer and Murphy, 1970). When the design head of the upstream quadrant is higher than the one of the downstream quadrant, the discharge coefficient is reduced. The opposite situation has little effect on the discharge coefficient.

These tendencies were highlighted using an extrapolation of the empirical law proposed by USACE (1987) in Figure 3. This relationship was established for head ratios smaller than one and for an ogee spillway designed following the WES standards. As displayed in Figure 3, the extrapolation of this law for head ratios greater than one and the discharge coefficients of the measurements are in good agreement for W1, W2 and W4, which would indicate that Equation (6) can be extrapolated beyond $H/H_d = 1$. Obviously, as soon as the nappe separates, this equation is no longer valid. In Table 3, the statistics of the distribution of the relative differences RD between the measured discharge coefficients and the empirical discharge coefficients are given for H/H_d in [1 – 5.5]. The analysis of the mean and of the percentiles indicates that the distribution of RD is almost centred on 0% for W1 and W2, which confirms that Equation (6) can be extrapolated beyond $H/H_d = 1$ when using the WES standards for designing an ogee spillway. When using different design heads for the upstream and the downstream quadrant, RD emphasizes that the empirical law overestimates by 6% the discharge coefficients for W3 and underestimates it by 1% for W4.

Finally, as for W1 and W2, no flow detachment is observed for W3 and W4 for head ratio smaller than 5-5.5 which is consistent with the literature in the case of similar experimental setup (Vermeyen, 1992).

Table 3. Relative differences RD between the measured discharge coefficients and the discharge coefficients computed with Equation (5) for each tested spillway and H/H_d in [1 – 5.5].

	mean	σ[%]	Ple_{25} [%]	Ple_{50} [%]	Ple_{75} [%]
W1	0.47	1.93	-0.38	0.45	1.49
W2	-0.06	1.94	-1.58	-0.52	1.15
W3	-5.99	1.86	-6.74	-5.71	-4.78
W4	1.03	0.91	0.61	1.11	1.53

4.2. Minimum Pressure

The previous results indicate an influence of the upstream quadrant on the spillway efficiency. While a too broad upstream quadrant (W3) decreases the crest efficiency whatever the head ratio, because of an increased pressure field along the crest, a sharp upstream quadrant maximizes the discharge coefficient up to $H/H_d = 5.5$. Nevertheless, a too sharp crest impacts the relative pressure distribution along the crest and, in particular, increases the amplitude of the local negative peak. This strong decrease in pressure can be responsible for cavitation and nappe instabilities.

The evolution of the measured minimum pressure Δp_{min} is represented in Figure 6a. Considering the data without flow detachment for W1 and W2, it appears that the relationship (Eq. (7)) proposed by Schirmer and Diersch (1976) (cited by Hager and Schleiss, 2009) underestimates the minimum pressure for head ratio greater than three.

$$\frac{\Delta p_{\min}}{H} = 1 - \frac{H}{H_d} \tag{7}$$

Based on the results for W1 and W2 (Figure 6a), which are representative of the standard WES geometry, the following relationship (Eq. (8)) is found more appropriate:

$$\frac{\Delta p_{\min}}{H} = 1.25\left(1 - \frac{H}{H_d}\right) \tag{8}$$

Notice that the difference between Eq. (7) and Eq. (8) could be greater since it is not certain that the minimums of pressure measured in this study are the absolute minimums. The difference is even greater when looking at the minimum pressure for spillway with undersized upstream quadrant (W4). As shown in (Figure 6b), the minimum pressures are much lower for W4 which implies that the coefficient of 1.25 in Equation (8) is too small in the case of smaller upstream quadrant.

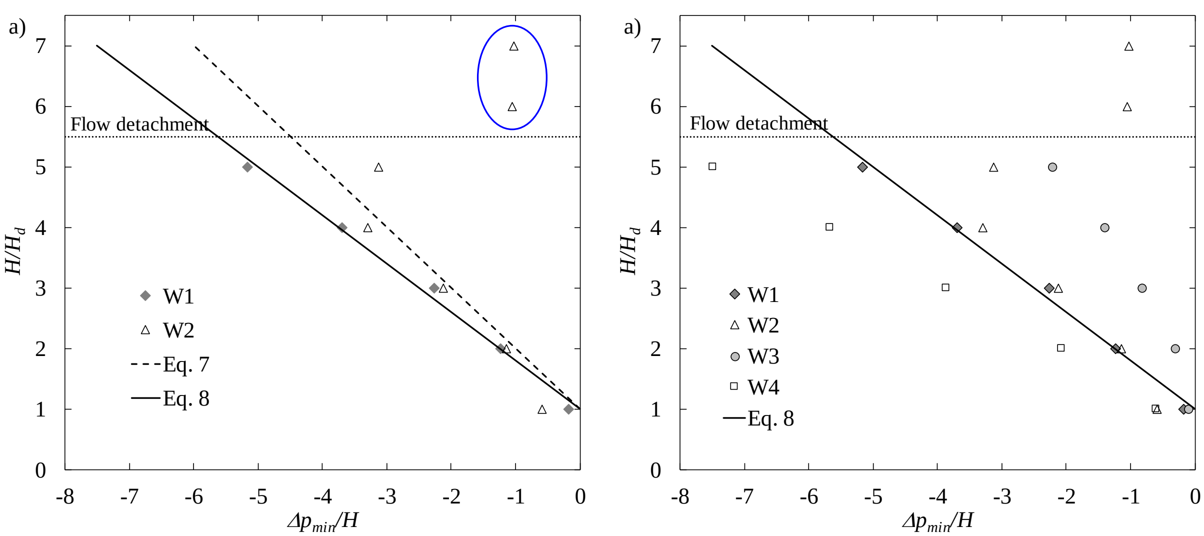

Figure 6. Evolution of the normalised pressure as a function of the head ratio, (a) for W1 and W2; (b) for all flow-cases.

These considerations on the prediction of the minimum pressure are useful for evaluating the risk of cavitation, especially when transposing results from model to prototype. According to Hager and Schleiss (2009), the cavitation relative pressure is close to -7.6 m for smooth spillways. Replacing Δp_{min} by this value in Eq. (7) and Eq. (8) gives an estimation of the limit of appearance of cavitation. In Figure 7, these curves are plotted together with the curve proposed by Abecasis (1970) which accounts for fluctuation of pressure on the spillway. This formulation is more restrictive than Eq. (8) for low heads and less restrictive for high heads. It results that with the classical criterion of the literature, cavitation should be observed as soon as the head ratio exceeds two for a spillway working under moderate head ($H < 5$ m). On the other hand, with the present results, higher head ratios seem acceptable.

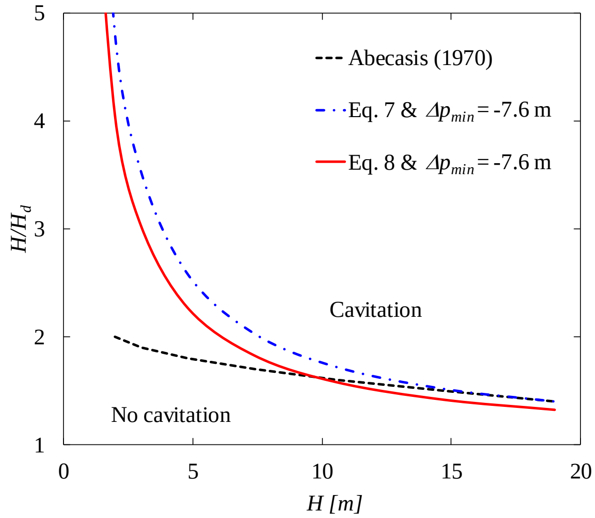

Figure 7. Maximum head before cavitation.

5. Conclusion

Four ogee spillways have been investigated for high head operation on an experimental model. The purpose of this study was to understand how the discharge coefficient is affected by the shape of the upstream quadrant when operating at heads largely greater than the design head.

The spillways were designed according to the recommendations of USACE (1987): WES standard geometry. The two first spillways followed the WES standards (W1 and W2) exactly, but the design heads were different. For the two other spillways, the design head of the upstream quadrant was taken differently from the downstream quadrant one. The upstream design head of W3 was greater than the design head of the downstream quadrant while for W4, the upstream design head was smaller.

All spillways were tested until high head ratios: five for W1, W3 and W4, and seven for W2. Except for the minimal pressure of W2, no relevant scale-effects were found in experiments which confirm the general validity of the study.

Results first indicate that the discharge coefficient continuously rises until a head ratio of 5.5 for each spillway. This evolution can be approximated by a power-law relationship as proposed by USACE (1987). For head ratios greater than 5.5, the discharge coefficient suddenly decreases due to a flow separation at the spillway crest.

The results also emphasize a net influence of the upstream quadrant on the efficiency of the spillway. When the design head of the upstream quadrant is greater than the design head of the downstream quadrant, the broader aspect of the spillway induces a significant decrease in the discharge coefficient. By contrast, a sharper upstream quadrant has little effect on the discharge coefficient but on the pressure distribution along the crest. In all cases, a minimum relative pressure appears at the beginning of the upstream quadrant followed by a continuous increase in pressure downstream. The latter remains negative or close to zero relatively to the atmospheric pressure until a distance equal to 1.5 H_d downstream of the crest. The relative pressure drop decreases with the oversizing of the upstream quadrant and increases with its undersizing.

When considering the minimum pressure measured on the spillway, it is found to be less significant than proposed in the literature. This suggests that the classical criterion from the literature to avoid cavitation risk is maybe too restrictive.

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