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Pressure and velocity on an ogee spillway crest operating at high head ratio: Experimental measurements and validation

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ABSTRACT

This paper aims at validating pressure and velocity measurements conducted in two physical scale models of an ogee spillway crest operating at heads largely greater than the design head. The design head of the second model is 50% smaller than the one of the first model. No pier effect or air venting is considered in the study. The velocity field is measured by Bubbles Image Velocimetry. The relative pressure along the spillway crest is measured using pressure sensors. Comparison of measured velocities between both spillways indicates low scale effects, the scaled-profiles collapsing in most parts of the flow. By contrast, measurements of relative pressure along the spillway crest differ for large heads. A theoretical velocity profile based on potential flow theory and expressed in a curvilinear reference frame is fitted to the velocity measurements, considered as reference, for extrapolating the velocity at the spillway crest. Comparing the extrapolated velocity at the spillway crest and the velocity calculated from the relative pressure considering a potential flow finally emphasizes that bottom pressure amplitudes seem overestimated for the larger spillway, while an averaging effect might operate for the pressure measurements on the smaller spillway.

1. Introduction

Uncontrolled ogee spillways are commonly used as flood release structures on dams. Their shape is designed regarding a given upstream head, the design head H_d, so that a zero relative pressure is obtained all along the crest profile (Hager, 1987; USBR, 1987) when the corresponding design discharge flows over the weir.

For at least thirty years and without considering potential effects of climate change, the availability of longer statistic chronicles and the evolution of the calculus methods impose a continuous review of the safety criteria of hydraulic structures (Millet, 1988; Xlyang and Cederström, 2007). This usually results in an upward revision of the design floods for existing spillways. These spillways were indeed designed for smaller discharges/head as the ones requested by the revision, meaning some of these structures might face higher heads than the initial design head.

When considering ogee crest weirs, working with a higher head than the design one is not necessarily a drawback. The efficiency of the spillway, quantified by its discharge coefficient C_d, is indeed 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 1, the relative pressure on the crest is negative and the discharge coefficient increases. Under-designed ogee spillway crests (*i.e.* crest designed considering a design head smaller than the maximum operation head) are thus more efficient. Indeed, for a given upstream head, they enable to release 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 piers or at the end of short spillway chutes) or induces a risk of cavitation if the pressure falls locally below the water vaporization pressure (USACE, 1990). This explains why ogee spillway crests are usually designed considering a design head equal to the maximum operation head. However, if enough care is taken regarding the pressure decrease effects, smaller design heads will provide higher discharge capacities.

In the literature, few studies focused on the flow characteristics over an ogee spillway crest for heads largely greater than the design head. Among the available references, very few studies deal

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Notation

A	gradient matrix expressed in finite differences (m^{-1})
B	width of the spillway (m)
h	water depth above the spillway-crest measured at $x = x_m$ (m)
δh	uncertainty on the water depth (m)
h_{uf}	height of the upstream face of the spillway (m)
g	gravity acceleration ($m \cdot s^{-2}$)
H	head (m)
δH	uncertainty on the head (m)
H_d	design head (m)
H_{max}	design maximal head (m)
P_{rel}	relative pressure (m)
δP	uncertainty on the pressure (m)
Q	discharge at the inlet ($m^3 \cdot s^{-1}$)
δQ	uncertainty on the discharge ($L \cdot s^{-1}$)
r_0	curvature radius when $h_0 = 0$ (m)
r	curvature radius (m)
r_0	curvature radius when $h_0 = 0$ (m)
u	longitudinal component of the velocity ($m \cdot s^{-1}$)
U	discharge velocity ($m \cdot s^{-1}$)
w	vertical component of the velocity ($m \cdot s^{-1}$)
v	norm of the velocity ($m \cdot s^{-1}$)
v_0	norm of the velocity in $\eta = 0$ ($m \cdot s^{-1}$)
v_{0p}	norm of the velocity in $\eta = 0$ computed from the relative pressure measured on the spillway ($m \cdot s^{-1}$)
x	streamwise direction (m)
x_m	streamwise position of the measurement section (m)
y	spanwise direction (m)
z	vertical direction (m)
ξ	curvilinear coordinate along a streamline (m)
η	curvilinear coordinate along an isopotential line (m)
η	origin of the curvilinear coordinate along an isopotential line (m)
ϕ	potential ($m^2 \cdot s^{-1}$)
θ	local direction of the flow in the curvilinear reference frame (rad)
ρ	volume mass of water ($kg \cdot m^{-3}$)

with the flow dynamics and only the upstream head and the pressure along the weir-profile are generally measured. Rouse and Reid (1935) assessed the influence of the crest shape by comparing the discharge coefficients and the pressure distributions of three different ogee spillway profiles with those of a sharp crested weir until a head ratio, H/H_d, equal to three. Abecasis (1970) and Cassidy (1970) focused their investigations on a procedure to control the minimal pressure that occurs on an ogee spillway designed following the recommendations of USBR (1948) until a head ratio of three. Vermeyen (1991, 1992) studied, in the frame of a dam project, an ogee-spillway operation until a head ratio of five, but here again no information is available regarding the velocity distribution in the flow. After these previous studies, no more occurrences of studies dealing with ogee spillway working at high-head ratio can be found in the literature. The few studies we have found deal with other type of crests, e.g. round crest (Castro-Orgaz, 2008). The knowledge of the velocity field is yet paramount for better understanding the phenomena that drive the flow dynamics in the vicinity of the spillway and to validate the pressure measurements.

Within the framework depicted here-above, the study presented in this paper concerns the validation of velocity and pressure measurements conducted in 2 physical models with different scale factor of an ogee spillway crest operating at head ratios largely greater than one. In this study, no pier effect or air venting is considered. The experimental setup, the selected crest profile, the measurement techniques and the theoretical background are presented in Section 2. Then, the results are presented in Section 3 and compared with theory in Section 4 in order to be validated.

2. Material and method

2.1. Experimental facility

The main purpose of the project is to reproduce in a controlled environment flows over ogee spillways for heads much higher than the design head. To achieve this, high specific discharges are necessary. Due to the available discharge capacity in the laboratory and to the choice of a model 20 cm wide in order to minimize wall effects, a maximum design head of 15 cm was possible. Regarding real-life weirs, the dimensions of the present experiment roughly correspond to one tenth of prototypes.

In the present experiments, the use of a pressure chamber and of another fluid than water was not possible. Therefore, similarities in term of atmospheric pressure and surface tension could not be respected. The experimental facility was made of a large reservoir with an inner width of 0.90 m, a length of 4.00 m and a height of 3.20 m. At the extremity of the reservoir, a removable spillway with a vertical upstream face and a smooth chute was set (Fig. 1). The chute was 4.5 m long in order to avoid any backwater effects on the flow in the vicinity of the crest.

The spillway profile being the key-parameter, geometric effects had to be minimized in order to obtain results as general as possible and independent from the scale of the experiment:

- Walls in polyvinyl chloride (PVC) were added in the reservoir for reducing the flow section to the width of the spillway: $B = 0.20$ m. The flow was thus confined in a 2D-vertical slice passing by the centreline of the spillway and contraction effects affecting the nappe stability were then avoided. The deformation of the new reservoir geometry was minimized by ensuring equality between the hydrostatic pressure distributions on both sides of the walls, through holes at the bottom of the PVC plates.
- Given the maximum design head of 0.15 m and the dimensions of the experimental facility, the expected maximum head over the spillway-crest, H_{max}, was found approximately equal to 0.75 m during the design phase. The independence of the spillway performance from the height of the upstream face of the spillway, h_{uf}, was ensured by setting h_{uf} equal to $3H_{max}$ (Melsheimer and Murphy, 1970; Reese and Maynord, 1987).

The feeding of the reservoir was performed in closed-loop, with one to three regulated pumps bringing the water through one to three pipes depending on the desired discharge. The pipes were terminated by a strainer, which allowed the injection of the water over the whole water column.

2.2. Spillway profiles

Two ogee spillways were constructed for this study. Their geometry follows the standards defined in the book "Hydraulic

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