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Hysteresis, Non-Linearity and Instabilities on Circular Crested Weir

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ABSTRACT

Waters flowing over rounded weirs experience a rapidly accelerated flow region near the crest. The head-discharge relationship of a half-round crested weir was tested physically over two orders of magnitudes. With increasing discharge, the nappe was initially attached to the weir's downstream wall, until some nappe detachment occurred. With a further increase in flow rate, the detached nappe re-attached at large flow rates. The transitions, i.e., both nappe detachment and re-attachment, were characterised by large instabilities, change in flow properties, and sometimes loud noise, and the processes were subject to some hysteresis. In the current study, detailed hydrodynamic measurements were conducted the same facility, with a focus on the instabilities and hysteresis process. The findings may be used to estimate accurately the hydrodynamic efforts and unsteady loads on half-round circular crested weirs.

INTRODUCTION

Circular-crested spillway designs were developed during the 19th century to improve the discharge capacity for a given head above crest of thick-crested weirs, including broad-crested weirs, prior to the introduction of the ogee profile (Creager 1917, Wegmann 1922). The simple shape is commonly used for lateral spillways (Fig. 1). Figure 1 presents the half-round circular crest along the lateral spillway of Chèze dam (France). Waters flowing over rounded weirs experience a rapidly accelerated flow region near the crest where the pressure is not hydrostatic, owing to the streamline curvature (Fawer 1937, Vo 1992). The head-discharge relationship of circular-crested weir was tested physically under carefully controlled flow conditions for a range of weir design with a small to large radius of curvature (e.g. Rehbock 1929, Ramamurthy and Vo 1993, Chanson and Montes 1998). Most physical studies investigated non-ventilated un-detached nappe overflows, although a recent work highlighted nappe deflection for a range of relatively large discharges (Chanson 2020).

With un-ventilated circular-crested weirs, the overflow may be attached to or detached from the downstream wall (Fig. 2), depending upon the flow rates. The transitions, i.e., both nappe detachment and re-attachment, are characterised by large instabilities, including changes in upstream and downstream flow properties, and sometimes loud noise (Chanson 2020). In the present study, detailed hydrodynamic measurements were conducted with a specific focus on the instabilities and hysteresis process of nappe attachment/detachment. The works aim to gain new information, to estimate ultimately the hydrodynamic efforts and unsteady loads on half-round circular crested weirs.

Figure 1. Circular-crested weir application: half-round crest along the lateral spillway of Chèze dam (France) on 11 June 2022.

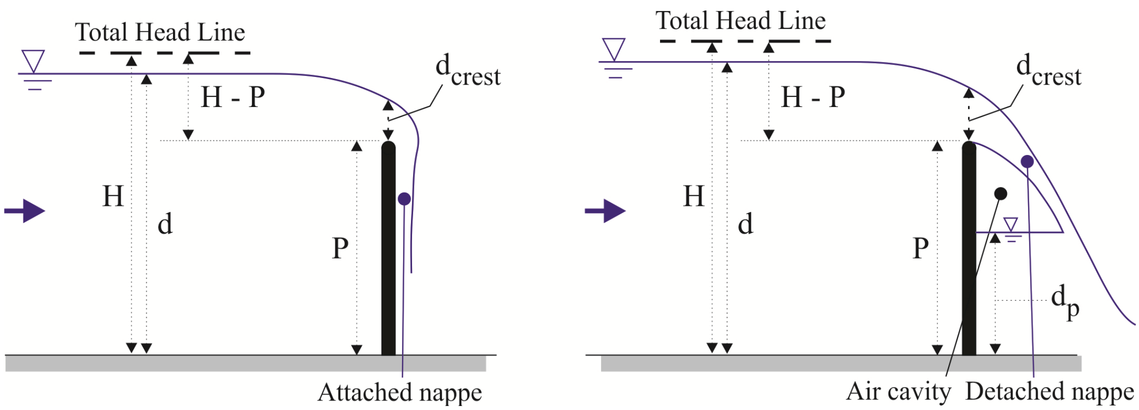


Figure 2. Definition sketch of half-round circular-crested weir overflow with attached and detached nappe.

EXPERIMENTAL FACILITY AND INSTRUMENTATION

The experiments were conducted in the Hydraulics Laboratory at the University of Queensland. A 3.0 m long 0.4 m-wide horizontal flume was used (Fig. 3). The channel bed was in PVC and the sidewalls were made of glass. The water was supplied by a constant head reticulation system, feeding a 0.75 m×0.90 m×1.0 m intake channel equipped with baffles, and delivering water to the test section through a 0.54 m long three-dimensional convergent. The arrangement delivered a constant flow rate with smooth inflow conditions to the flume's upstream end. A free overfall ended the test section.

The discharge was measured with a 90° V-notch weir, calibrated independently with flow rates up to 0.12 m^3/s (Chanson and Wang 2013). The water depths were measured with rail-mounted pointer gauge as well as through the glass sidewalls. Further observations were taken with a digital camera Sony™ DSC-RX100VA recording movies at 25 fps and 100 fps, and a dSLR camera Pentax™ K-3.

The circular-crested weir was a half-round circular profile (radius: r = 10.0 mm) installed 1.34 m downstream of the flume's upstream end. The weir was 0.020 m thick and 0.250 m high following the design of Tullis et al. (2019). The entire weir was machined out of PVC with an accuracy of ±0.2 mm. For all the experiments, the nappe was un-ventilated.

Figure 3. Circular-crested weir overflow for $Q = 0.01705\ m^3/s$ and $d_1 = 0.321$ m (with detached nappe). Flow direction from left to right.

BASIC FLOW PATTERNS

With increasing discharges, three basic flow patterns were observed for different ranges of flow rates. At low flow rates for $d_c/P < 0.214$, the nappe was attached, with $d_c = (q^2/g)^{1/3}$, P the weir height, q the unit discharge and g the gravity acceleration (Fig. 2). The overflow nappe sticked to the downstream wall of the weir. For $0.214 < d_c/P < 0.293$, the nappe detached from the weir and an air cavity formed, as illustrated in Figure 3. At large flow rates for $d_c/P > 0.293$, the overflow re-attached to the weir wall. As previously reported (Chanson 2020), some hysteresis was observed, with some differences in change in flow regime depending upon the experimental procedure: i.e., with increasing flow rate, or decreasing flow rate.

Quantitative observations were conducted across a wide range of flow conditions, i.e. $0.55\times10^{-3}\ m^3/s < Q < 37.5\times10^{-3}\ m^3/s$, with both increasing and decreasing discharges. The upstream and downstream water depth data sets are reported in Figures 4A and 4B respectively, showing a quasi-monotonic increase in water depths with increasing flow rates. On each graph, the mean changes in flow patterns are reported in thick solid vertical lines. At the crest of the circular weir, the water depth d_{crest} differed from d_c because of the non-hydrostatic pressure and non-uniform velocity fields (Fawer 1937, Chanson 2006). Let us remember that the expression $(q^2/g)^{1/3}$ is the critical depth only for hydrostatic pressures and uniform velocity distribution in a horizontal channel (Bakhmeteff 1932, Chanson 2004). The observations of water depth d_{crest} at the crest are reported in Figure 4C, showing ratios d_{crest}/d_c less than unity, except for one data point at a very low flow rate. In Figure 4C, r is the radius of curvature of the weir crest. Further, the results (Fig. 4C) showed some hysteresis, although neither headwater and tailwater depth data sets (Figs. 4A & 4B) suggested much hysteresis.

At a weir crest, the relationship between unit discharge q and upstream head above crest (H-P) is usually expressed as in a modified form of the Bernoulli principle:

$$(1) \qquad q = C_D \times \sqrt{g} \times \left(\frac{2}{3} \times (H - P) \right)^{3/2}$$

with H the upstream specific energy, and C_D a dimensionless discharge coefficient. C_D is typically larger than unity for a circular crested weir. Present data are presented in Figure 4D. Beyond some marked hysteresis, the discharge coefficient data showed some significant scatter, consistent with the results reported by Tullis et al. (2019) and Chanson (2020). It is believed that some scatter was directly caused by non-linear instabilities observed during long-duration experiments (see below),

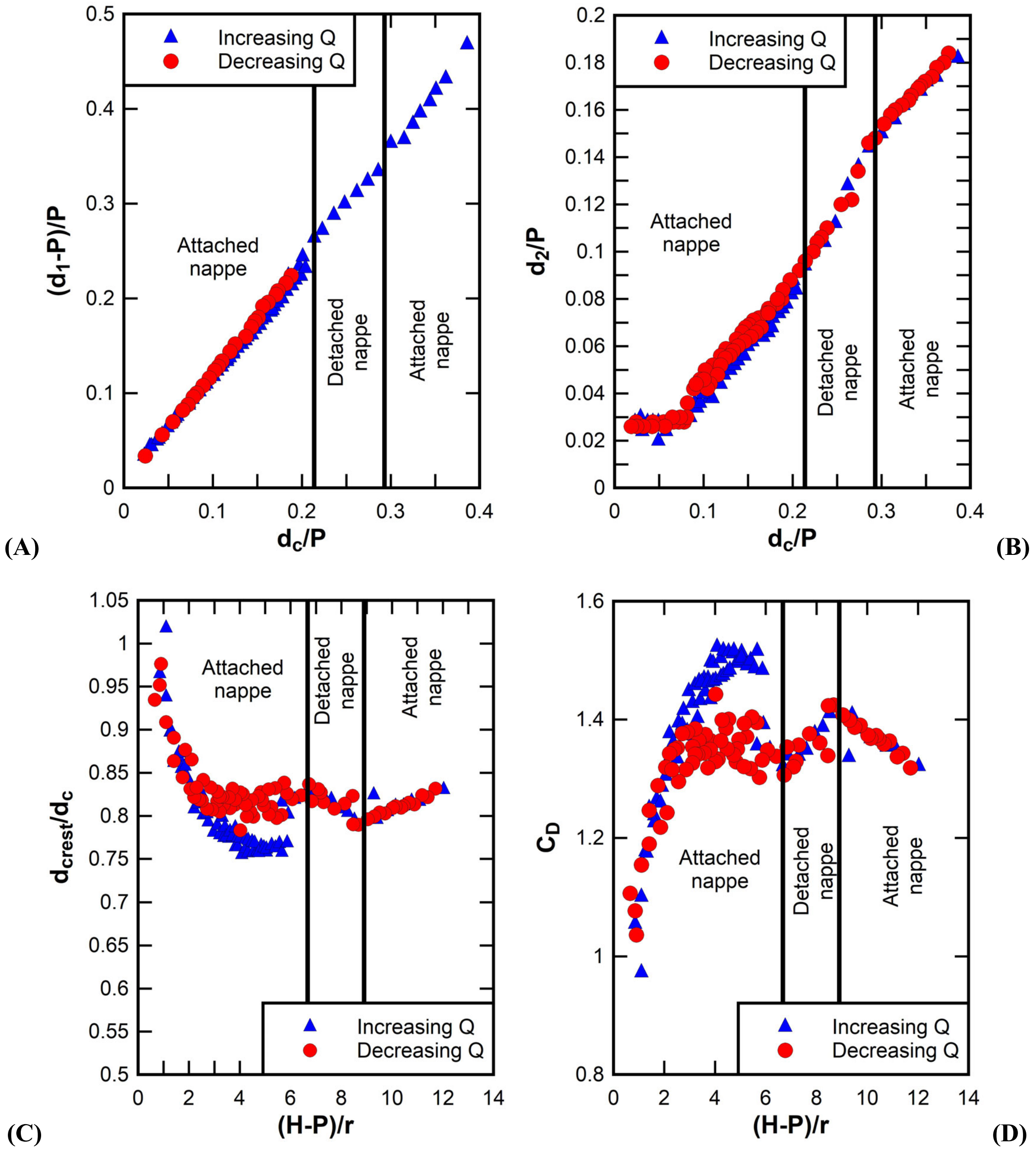


Figure 4. Circular-crested weir overflow characteristics. (A) Upstream water depth d_1. (B) Downstream water depth d_2. (C) Water depth d_{crest} at crest. (D) Dimensionless discharge coefficient C_D.

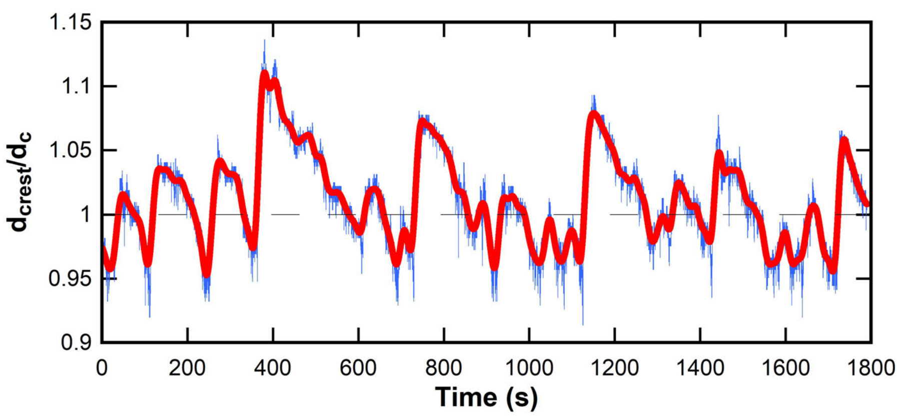
NON-LINEARITY

In Figure 4, the "mean" conditions for the changes between attached and detached nappes were presented with a thick vertical line. In practice, both changes in flow patterns took place over a relatively broader range of flow rates. Herein, long duration experiments were conducted for flow conditions close to the transitions between flow patterns. For each experiment, the flow conditions were set for 30 minutes minimum, prior to the start of any observations. From then, the observations were undertakes for a minimum of 30 minutes and typically repeated over several hours, while the flow rate remains unchanged, as checked regularly, e.g. every ten minutes.

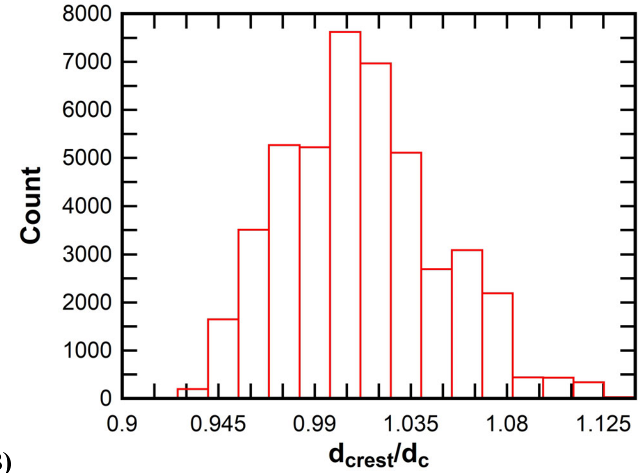
During these long observation series, some non-linear behaviour was observed, with some cyclic pattern between nappe re-attachment and nappe detachment. In several cases, the cyclic behaviour took place between detached nappe with a large air cavity and partially-attached nappe with a very small air cavity. A key feature of the non-linear behaviour was the marked change in streamline curvature at the weir crest over time. With an attached nappe, the streamline curvature was strong at the weir crest, with a radius of curvature slightly larger than the crest radius. In turn, the upstream water depth was relatively smaller and the discharge coefficient was larger, in line with the application of irrotational flow theory (Vallentine 1969, Chanson 2014). For the same flow rate, a detached nappe induced flatter streamlines at the weir crest, and in turn a larger upstream depth and lesser discharge coefficient.

Typical long-duration records of the water depth at the weir crest are shown in Figure 5. Figure 5A presents a 30-minute long time-series, with the instantaneous time series in thin blue line and the smoothed trendline in thick red line. The data indicated fast fluctuations super-imposed on slower fluctuations. Figure 5B shows the corresponding skewed histogram of water depth data d_{crest}. For the same flow conditions, Figure 6 indicates the time series of cavity dimensions. Figure 6A presents the air cavity height (d_p-P), with d_p the vertical depth of the pool of water beneath the nappe, and Figure 6B shows the air cavity surface area, viewed through the glass sidewall. For this data set - Figures 5 and 6 correspond to same flow conditions, ten large excursions in air cavity sizes were seen for the 30-minute long record. Typically, the air cavity filling was a relatively slow process, spanning over several minutes. In contrast, the cavity opening was a very rapid transient. The initial stage of the air cavity formation was very rapid, lasting less than one second and could sometimes be violent and accompanied by a loud noise which could be heard from quite far away - e.g. the other end of the hydraulics laboratory. This initial transient was followed by a period of slower cavity expansion, spanning from a couple to a dozen of seconds.

Altogether, the results (Fig. 6) illustrated the cyclic pattern between a detached napped and a partially-attached nappe with a very small air cavity. Further, the comparison between Figures 5A and 6 demonstrated a positive correlation between air cavity size and water depth at the crest.

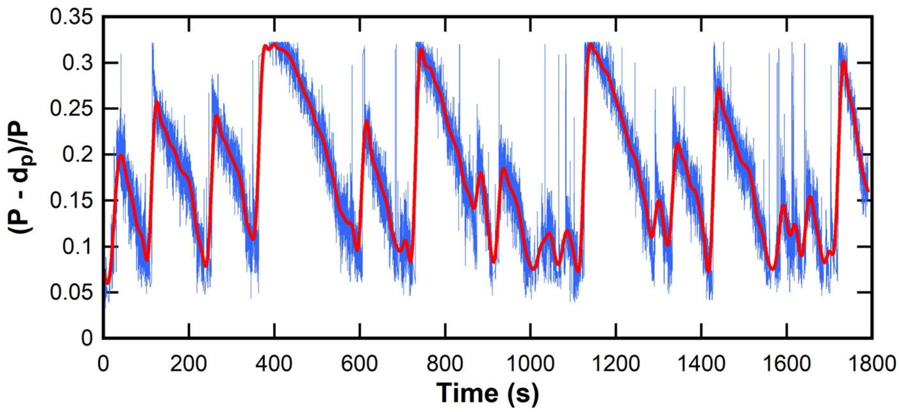


(A)

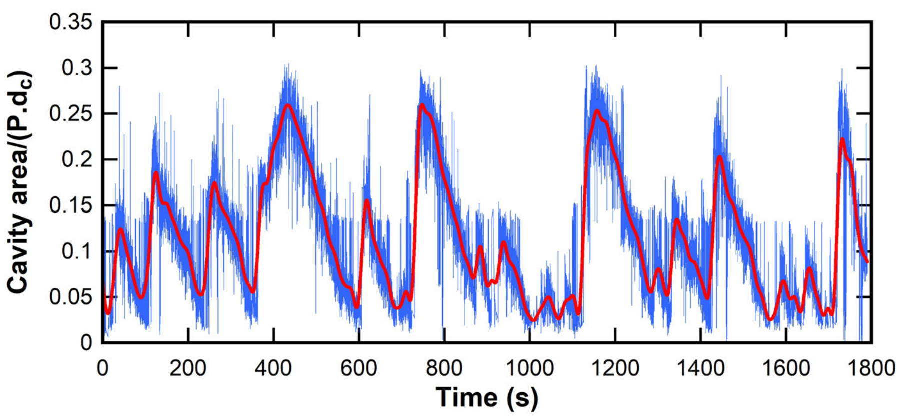


(B)

Figure 5. Fluctuations of water depth d_{crest} at crest during the circular-crested weir overflow for d_1-P = 0.085 m, d_c/P = 0.28. (A) Time variation of dimensionless water depth d_{crest}/d_c at crest (25 fps movie). (B) Histogram of dimensionless water depth d_{crest}/d_c at crest distribution.



(A)



(B)

Figure 6. Fluctuations of cavity water depth d_p and air cavity size during the circular-crested weir overflow for d_1-P = 0.085 m, d_c/P = 0.28. (A) Time variation of air cavity height (P-d_p) (25 fps movie). (B) Time variation of air cavity size (25 fps movie).

DISCUSSION

The present results demonstrated the existence of transient motion over un-ventilated half-round circular weir. The nappe detachment and attachment were associated with intense transient pressure loads on the weir and loud noises. The physical processes may induced vibrations to the weir wall and it might even impact onto the structure stability of thin-walled weir structures, during high-intensity transients. In addition, the attachment and detachment were linked to changes in upstream water level, for a given constant discharge, that might induce sloshing and seiching in the upstream reservoir. In parallel, the changes between nappe flow patterns (attached / detached) would cause sudden changes in instantaneous outflow discharges, which would be associated with surges travelling downstream.

Altogether, the hydrodynamic instabilities would interact air cavity oscillations, which could be enhanced by resonance effects (Rockwell and Naudasher 1978). Typically identified as un-desirable and potentially hazardous, some most recognisable features of these interactions include the horizontal banding on the nappe, the low frequency acoustic energy resulting in low rumble noise that can be heard, and un-necessary vibrations to the weir itslef.

CONCLUSION

An un-ventilated half-round circular weir was tested physically across a relatively large range of flow conditions. Three basic flow patterns were observed, with attached, detached and attached nappe with increasing flow rates. The establishment of the flow patterns was characterised by some hysteresis and different results depending on whether the flow rate was increased or decreased during the experiment. Despite a very careful experimental procedure, the results in terms of dimensionless coefficient showed large data scatter, consistent with prior relevant studies (Tullis et al. 2019, Chanson 2020). It is believed that the scatter was caused by the development of non-linear instabilities, observed in the current study.

For the flow conditions close to the transition between flow patterns, large hydrodynamic instabilities were observed, including some cyclic patterns linked to the absence of nappe ventilation. Long-duration experiments were undertaken to document carefully and under controlled conditions the cyclic behaviour. The results showed that the cycle's "mean period" could be more than 10 minutes long, with direct adverse implications on physical modelling only conducted over short periods. Further, the qualitative and quantitative observations indicated that the air cavity filling was a slow process lasting several minutes, when the cavity formation was a very rapid transient, sometimes violent with loud noise.

Overall, the present work illustrated some complicated physical modelling characterised by transient flow patterns spanning over relatively long durations. The findings reinforced the importance of the quality of experimental setup and expertise of the individual experimentalists. The present example highlights some major limitations of numerical modelling, including CFD modelling, which would not detect any such transient processes with commercial softwares on desktop workstations.

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BIOGRAPHY

Hubert Chanson is Professor of Civil Engineering at the University of Queensland, where he has been since 1990, having previously enjoyed an industrial career for six years. His main field of expertise is environmental fluid mechanics and hydraulic engineering, both in terms of theoretical fundamentals, physical and numerical modelling. He leads a group of 5-10 researchers, largely targeting flows around hydraulic structures, two-phase (gas-liquid and solid-liquid) free-surface flows, turbulence in steady and unsteady open channel flows, using computation, lab-scale experiments, field work and analysis. He has published over 1,250 peer reviewed publications including two dozen of books. He serves on the editorial boards of International Journal of Multiphase Flow, Flow Measurement and Instrumentation, and Environmental Fluid Mechanics, the latter of which he is currently a senior Editor. His Youtube channel is: {https://www.youtube.com/channel/UCm-

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