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Non-linearities at Circular Weirs under Environmental Flow Conditions

Hubert Chanson [1]

[1] The University of Queensland, School of Civil Engineering, Brisbane QLD4072, Australia
* Email: h.chanson@uq.edu.au

Abstract

At a control structure for free-surface flows, the shape of the passage controls the discharge capacity. The circular weir design has been known for its relatively large discharge capacity, its simplicity of design and construction, and the ease of passing floating debris. Recent studies reported a number of large experimental discrepancies ine absence of nappe ventilation, with hysteresis as well as some cyclic behaviour between attached and detached nappe, for a constant discharge. This study provides a detailed characterisation of the transient flow properties above an un-ventilated circular weir, including flow instabilities, hysteresis and non-linearities. The markedly different flow patterns were investigated physically, showing periods up to more than 10 minutes, for some flow conditions. The occurrence of such instabilities implied direct adverse effects on physical and numerical modelling, despite the apparent simplicity of the geometry.

1. Introduction

Many civil, environmental and coastal engineering engineers need to solve real-life problems associated with fascinating, sometimes challenging, fluid flow motion (Castro-Orgaz and Hager 2017). While modern developments in aerospace, aeronautics and hydrodynamics have shown the necessity of investigating fluid motion on a purely physical basis, water engineers too often treat the flow of water from a more or less empirical perspective (Rouse 1932, Montes 1998). During the past decades, computational fluid dynamics (CFD) tools, using RANS and LES models, gained acceptance to resolve numerically complex hydraulic flows (Rodi et al. 2013, Leng et al. 2018). Yet, the numerical solutions rely upon physical laboratory experimentation for their validation because "*Nature is the final jury*" (Roache 1998).

The half-round circular weir is a seminal crest design, that had been extensively studied for the last three decades (Ramamurthy and Vo 1993, Chanson and Montes 1998) (Fig. 1). The circular weir presents a simple geometry which is more stable than the sharp-crested weir for small to medium water discharges and has a greater volumetric capacity than the broad-crested weir and the ogee crest for a given upstream energy. Above the circular profile, the water experiences a rapidly accelerating fluid flow region near the crest, characterised by a strong streamline curvature (Fawer 1937, Castro-Orgaz and Chanson 2014). Two recent physical studies developed a number of large discrepancies associated with the hysteresis above circular weirs in absence of ventilation (Tullis et al. 2019, Chanson 2020). The results challenge the 'traditional' validation approach of CFD models.

Using the Bernoulli principle and the law of momentum to the general case of two-dimensional flow motion, their application to weir discharge is illustrated by the physical investigations conducted of a half-round circular weir profile. Despite the simplicity of the crest profile, the physical observations demonstrate that an absence of ventilation leads to non-linearity, transients and instability that are discussed in length.

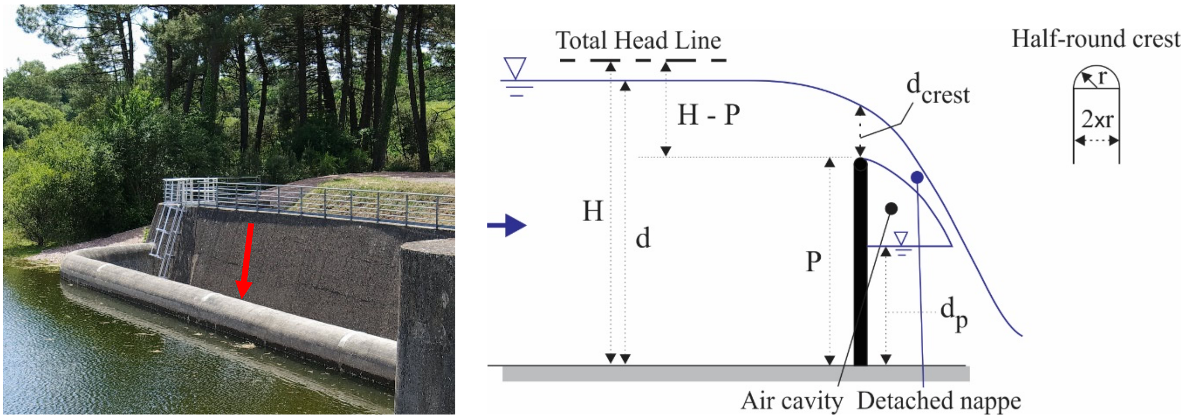

Figure 1. Half-round circular rested weir - Left: circular crest of lateral dam spillway (red arrow). Right: Schematic of detached nappe above circular weir.

2. Physical Modelling

New experiments were conducted in the AEB Hydraulics Laboratory at the University of Queensland, Brisbane (Australia). A horizontal, 12 m long and 0.5 m wide flume was used. The channel bed was in PVC and the sidewalls were in glass. The water was supplied by an upstream intake equipped with baffles, flow straighteners, and a smooth three-dimensional convergent. The water discharge provided to the intake was supplied by a water reticulation system equipped with a constant-head reservoir. The combination of a constant head water system and intake structure ensured a constant discharge with very-smooth inflow conditions to the upstream end of the flume, over long periods of time. A free overfall ended the flume.

The circular weir had a half-round circular profile (Fig. 2). The weir was 0.3125 m high with a 0.0125 m radius of curvature. It was machined out of PVC and the downstream face was covered by thin marine plywood to achieve a weir thickness equal to twice the radius of curvature. For all the experiments, the nappe was un-ventilated. The weir was installed perpendicular to the flow direction, sealed with silicone on the sides and bottom, while two buttresses were installed on the downstream side to support the pressure force acting on the weir.

The water discharge was measured by an orifice meter installed in the reticulation system pipeline. The orifice was built based upon British Standards (1943), and the error of the flow rate was less than 2%. The water depths were measured with rail-mounted pointer gauges as well as using graduated rulers through the glass sidewalls. Further observations were taken with an Apple™ iPhone XI, and a dSLR camera Pentax™ K-3iii. The dSLR camera was equipped with professional-grade prime lenses, which produced images with negligible degree of barrel distortion.

The experiments were conducted for flow rates between 0.0036 m^3/s to 0.060 m^3/s, corresponding to Reynolds numbers between 2.9×10^4 to 4.7×10^5. For each observation, three minutes of flow establishment were observed followed by three minutes (minimum) of recording. In case of instabilities, or when the flow was not established after three minutes, longer recording periods of up to 60 minutes were undertaken. Further, experimental observations were conducted with increasing and decreasing discharges to document the hysteresis phenomena.

3. Basic Flow Features

With the un-ventilated weir crest, three type of overflow patterns were observed. At low discharges, the nappe attached to the crest and a strong streamline curvature was observed (Fig. 2 left). For a range of intermediate flow rates, the nappe was detached and a well-defined air cavity formed beneath the lower nappe (Fig. 2 Middle). For large flow rates, the nappe re-attached and the air cavity disappeared, although some flow separation and recirculation was visualised beneath the overflow nappe (Fig. 2 Right). As previously reported (Chanson 2020), some experimental hysteresis was seen, with some different flow conditions for the changes in nappe flow regime between experiments conducted with either increasing or decreasing discharges. Herein, a detached nappe was seen for $5.9 < (q^2/(g\times r^3))^{1/3} < 7.4$ during increasing discharge experiments, with q the unit discharge, g the gravity acceleration and r the radius of curvature of the crest. With decreasing discharge experiments, a detached nappe was observed for 1.7 to 5.9 < $(q^2/(g\times r^3))^{1/3}$ < 7.0.

The change in overflow patterns was characterised by flow instabilities and often cyclic patterns, from fully-detached to completely re-attached nappe (6.2 < $(q^2/(g\times r^3))^{1/3}$ < 7.0), or from fully-detached to partially-detached nappe with small air cavity (3.0 < $(q^2/(g\times r^3))^{1/3}$ < 6.8), with some overlap depending upon the initial experimental setup. The periods of cyclic flow pattern were mostly between 3 minutes and 10 minutes, but some wider range of periods, from 1 minute to more than 12 minutes could be observed.

Practically, the repetitions of nappe detachment/attachment would generate large transient pressure loads on the weir wall and often great noises. The process could induce vibrations and fatigue to the structure, possibly impacting the structural stability of thin-walled weir structures, during high-intensity events.

Figure 2. Basic flow patterns above a half-round circular weir. From left to right: attached nappe with strong streamline curvature, detached nappe with air cavity beneath, re-attached nappe with flow separation and recirculation underneath.

4. Flow Characteristics

Quantitative observations were carefully documented for the full range of flow rates. Both increasing and decreasing discharge experiments were undertaken. Typical results are presented in Figure 3 in terms of the water depth at the crest d_{crest} and the dimensionless discharge coefficient defined as:

$$C_D = \frac{q}{\sqrt{g\times\left(\frac{2}{3}\times(H_1-P)\right)^3}}, \qquad (1)$$

with H_1 the upstream total head and P the weir height (Fig. 1). C_D characterises the hydrodynamic efficiency of the weir crest design. Figure 3 includes both steady flow conditions and instantaneous data during cyclic flow patterns, the latter being documented with dSLR photography at relatively high shutter speed.

Considering a steady irrotational flow above the circular weir, the velocity field and water surface may be derived analytically and graphically (Rouse 1932, Dressler 1978), Indeed, the detailed experimental measurements of Vo (1992) (also Ramamurthy and Vo (1993)) demonstrated that the boundary layer thickness at the weir crest was very small and its effects were negligible in first approximation. At the weir crest, the application of the Bernoulli equation along the free-surface gives an expression between the upstream total head H_1, the water depth at the crest d_{crest} and the maximum velocity V_{max} above the crest

$$H_1 - P = d_{crest} + \frac{V_{max}^2}{2\times g}\times\frac{1}{\left(1+\frac{d_{crest}}{r}\right)^2}, \qquad (2)$$

The present data showed that the water depth at the crest was typically smaller than the water depth above a broad-crested weir, i.e. $(q^2/g)^{1/3}$ (Fig. 3 Left). Importantly. the results showed some major hysteresis and scatter, directly linked to the absence of ventilation and associated instabilities including cyclic flow patterns, which would not be predicted by steady irrotational flow considerations.

The discharge coefficient C_D was basically greater than one, in line with earlier data sets (Sarginson 1972, Vo 1992). The present data highlighted (a) a significant scatter, consistent with the data reported by Tullis et al. (2019) and Chanson (2020) with half-round circular weirs, and (b) a marked hysteresis. Neither two-dimensional theoretical and computational approaches could model the hysteresis process.

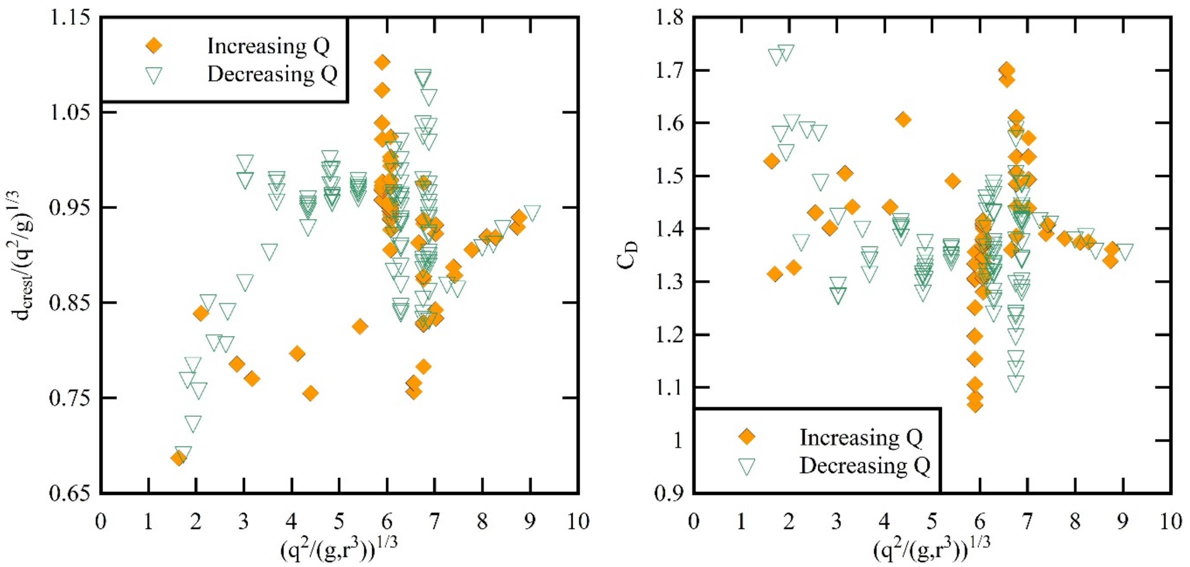

Figure 3. Dimensionless water depth at crest and discharge coefficient above a half-round circular weir as function of dimensionless discharge. The data include instantaneous observations during cyclic nappe behaviour.

For a steady two-dimensional irrotational flow above a circular-crested weir, the application of the Navier-Stokes equations and Bernoulli principle may be developed within the framework of Dressler's (1978) theory. Integrating the velocity and pressure distributions across the water column, and setting the atmospheric pressure boundary condition at the free-surface ($d = d_{crest}$), this yields an analytical relationship between the discharge coefficient C_D and water depth at the crest d_{crest}:

$$\frac{3}{2} \times \frac{d_c}{d_{crest}} \times C_D = 1 + \frac{1}{2} \times \left(\frac{d_c}{d_{crest}}\right)^3 + \frac{\left(\frac{d_{crest}}{r}\right)^2}{\left(\left(1+\frac{d_{crest}}{r}\right) \times Ln\left(1+\frac{d_{crest}}{r}\right)\right)^2}, \quad (3)$$

Equation (3) is compared to experimental data above a circular weir with a relative small radius of curvature (r = 0.01 m) in Figure 4, encompassing both attached and detached nappe data. The results showed some marked differences between attached and detached nappes. With attached nappe, the observed water depth at the weir crest provided a reasonable agreement, albeit as an under-estimate, of the dimensionless discharge coefficient based upon Equation (3). The trend was conservative. For detached nappe, the agreement was relatively poor, as expected, since the irrotational flow theory did not consider separation.

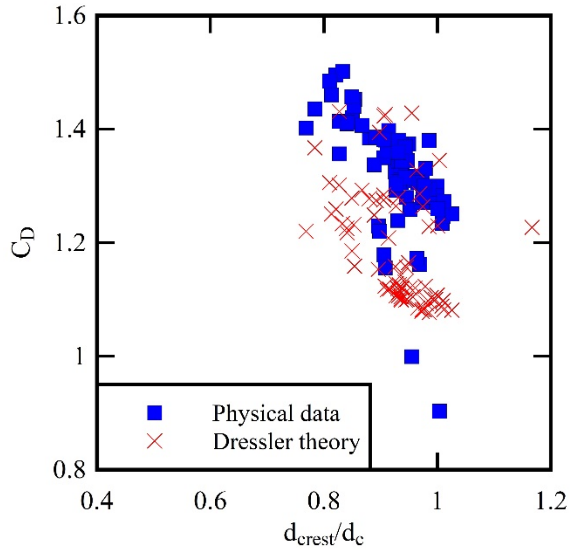

Figure 4. Dimensionless relationship between the water depth at the half-round circular weir crest and discharge coefficient - Comparison between irrotational flow theory and physical data (Chanson 2020, r = 0.01 m, P/r = 25, B/r = 40).

5. Discussion

5.1 Cyclic Flow Patterns

Long-duration observations showed the occurrence of cyclic flow patterns between attached nappe and detached nappe with an air cavity. The cyclic pattern was linked to the lack of ventilation. Visual, photographic and cinematographic observations showed that the air cavity opening was very rapid, lasting less than one second. The rapid transient was violent, sometimes accompanied by some loud low-frequency noise. The initial transition could be followed by a period of slower cavity expansion, which could span over 10-20 s. Following the air cavity expansion process, the filling of the air cavity was a much slower process, lasting several minutes.

The cavity filling was caused by the net air entrapment at the plunge point of the lower nappe into the pool of recirculating waters, seen in Figure 2 Middle. As the air cavity shrank, large transverse fluctuations of the lower nappe impingement perimeter were observed. Once completely attached, the flow over the weir accelerated rapidly, in part because of the centrifugal acceleration along the streamlines and the pressure on the downstream weir wall was negative. By continuity, the nappe thinned, it contracted laterally and transient interactions between the sidewalls and thin nappe could allow air between the weir wall and the water, leading to the sudden nappe detachment.

During the cyclic conditions, the cyclic flow patterns were associated with changes in the upstream water depth, water depth at the crest and relationship between the upstream head and discharge. A typical example is shown in Figure 5. Figure 5 presents instantaneous data derived from high-shutter speed dSLR photographs. A key physical feature was the major change in streamline pattern over the weir crest. With an attached nappe, the upstream water surface elevation was the lowest and the discharge coefficient was the largest, as predicted by the irrotational flow theory (Vallentine 1969, Chanson 2014). For a constant water discharge, the fully-detached nappe was associated with the flattest streamlines at the crest, the largest upstream water elevation and the smallest discharge coefficient.

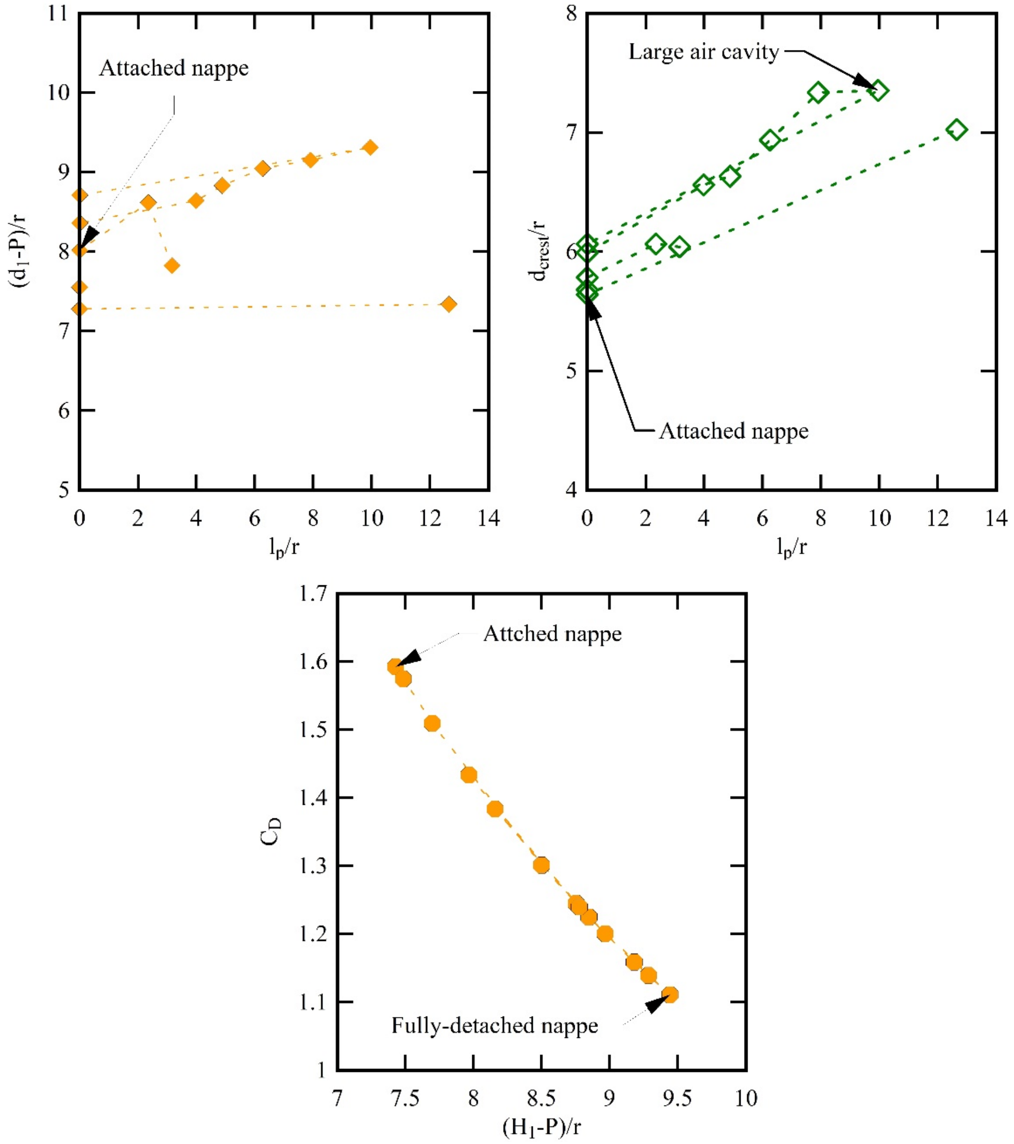

Figure 5. Instantaneous flow properties during cyclic flow patterns above a half-round circular weir. Flow conditions: Re = 3×10^5, Test duration: 1,000 s - Top left: upstream water depth d_1. Top right: water depth at crest d_{crest}. Bottom: relationship between upstream total head and discharge.

5.2 Modelling Challenges

The half-round circular weir overflow is a seminal free-surface flow above a very simple geometry (Castro-Orgaz and Hager 2017). For low discharges, the theoretical modelling provided excellent agreement with the physical observations (Rouse 1932, Fawer 1937, Matthew 1963). On another hand, at larger discharges, the physical modelling of half-round circular weir, performed in two dozen of independent laboratories, yielded contrasted outcomes (Tullis et al. 2019). Despite an identical geometry, these physical studies could not agree on the weir performances because of physical non-linearities, caused by the absence of ventilation (Chanson 2020, Present study). The present data set, with a larger weir geometry, added to the data scatter.

A similar outcome would be expected from numerical modelling, as a few CFD performance assessments of simple flow situations led to very challenging outcomes (Sagaut et al. 2008, Stewart et al. 2012). For example, with a simplified steady flow loop with a nozzle, "*the simulations showed considerable variation from each other and from experiment*" (Stewart et al. 2012). Traditionally, numerical modelling is validated against physical data (Rizzi and Vos 1998, Roache 1998). But, how can we validate a CFD model in a chaotic turbulent flow, such as the flow over a half-round circular weir crest with cyclic flow conditions? What would be a correct validation process?

These fundamental questions, and their answers, are critical to the modelling of flow-induced vibrations to any hydraulic structure, including a half-round circular-crested weir, sometimes with the horizontal banding on the overflowing nappe or low frequency rumble noise that can be heard from far away.

6. Conclusions

New physical experiments were undertaken with a seminal free-surface flow, i.e. the overflow at an un-ventilated half-round circular weir. The study was undertaken across a wide range of Reynolds numbers. The observations indicated that the overflow nappe could be attached, detached with an air cavity underneath or re-attached with nappe separation depending upon the discharge, hence the Reynolds number. The quantitative observations showed some hysteresis with different data for a given Reynolds number, depending whether the experiments were conducted with increasing or decreasing discharges

The physical results showed some large data scatter, consistent with prior studies on smaller size models (Tullis et al. 2019). The scatter was directly linked to the occurrence of nappe instabilities. For a range of intermediate Reynolds numbers, some cyclic flow pattern was observed although the flow rate remained constant. Such a cyclic behaviour of the weir was caused by the absence of nappe ventilation. Long-duration observations showed that large instabilities could occur at relatively very low frequencies, affecting both the flow properties above the weir and the upstream flow characteristics.

The present data set may constitute a challenging reference validation test case for advanced CFD modelling of free-surface flow. The physical complexity of the fluid dynamic patterns would emphasise any major limitations of CFD codes which would not detect the transient hydrodynamic processes.

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References

British Standard (1943). "Flow Measurement." *British Standard Code BS 1042:1943*, British Standard Institution, London.

Castro-Orgaz, O., and Chanson, H. (2014). "Depth-Averaged Specific Energy in Open-Channel Flow and Analytical Solution for Critical Irrotational Flow over Weirs." *Journal of Irrigation and Drainage Engineering*, ASCE, Vol. 140, No. 1, Paper 04013006, 8 pages (DOI: 10.1061/(ASCE)IR.1943-4774.0000666).

Castro-Orgaz, O., and Hager, W.H. (2017). "*Non-hydrostatic Free Surface Flows*." Advances in Geophysical and Environmental Mechanics and Mathematics, Springer, 696 pages.

Chanson, H. (2014). "*Applied Hydrodynamics: An Introduction*." CRC Press, Taylor & Francis Group, Leiden, The Netherlands, 448 pages & 21 video movies

Chanson, H. (2020). "Half-round Circular Crested Weir: On Hysteresis, Instabilities and Head-Discharge Relationship." *Journal of Irrigation and Drainage Engineering*, ASCE, Vol. 146, No. 6, Paper 04020008, 7 pages & 3 video movies (DOI: 10.1061/(ASCE)IR.1943-4774.0001473).

Chanson, H., and Montes, J.S. (1998). "Overflow Characteristics of Circular Weirs: Effect of Inflow Conditions." *Journal of Irrigation and Drainage Engineering*, ASCE, Vol. 124, No. 3, pp. 152-162 (DOI: 10.1061/(ASCE)0733-9437(1998)124:3(152)).

Dressler, R.F. (1978). "New Nonlinear Shallow-Flow Equations with Curvature." *Journal of Hydraulic Research*, IAHR, Vol. 16, No. 3, pp. 205-222.

Fawer, C. (1937). "Etude de Quelques Ecoulements Permanents à Filets Courbes." ('Study of some Steady Flows with Curved Streamlines.') *Thesis*, Lausanne, Switzerland, Imprimerie La Concorde, 127 pages (in French).

Leng, X., Simon, B., Khezri, N., Lubin, P., and Chanson, H. (2018). "CFD Modelling of Tidal Bores: Development and Validation Challenges." *Coastal Engineering Journal*, Vol. 60, No. 4, pp. 423-436 (DOI: 10.1080/21664250.2018.1498211).

Matthew, G.D. (1963). "On the Influence of Curvature, Surface Tension and Viscosity on Flow over Round-Crested Weirs." *Proc. Instn. Civil. Engrs., London*, Vol. 25, pp. 511-524. Discussion: 1964, Vol. 28, pp. 557-569.

Montes, J.S. (1998). "*Hydraulics of Open Channel Flow*." ASCE Press, New-York, USA, 697 pages.

Ramamurthy, A.S., and Vo, N.D. (1993). "Application of Dressler Theory to Weir Flow." *Journal of Applied Mechanics*, Trans. ASME, Vol. 60, No. 1, pp. 163-166.

Roache, R.L. (1998). "*Verification and Validation in Computational Science and Engineering*." Hermosa Publishers, Albuquerque NM, USA, 446 pages.

Rodi, W., Cconstantinescu, G., and Stoesser, T. (2013). "*Large-Eddy Simulation in Hydraulics*." IAHR Monograph, CRC Press, Taylor & Francis Group, Leiden, The Netherlands, 252 pages.

Rouse, H. (1932). "The Distribution of Hydraulic Energy in weir Flow with Relation to Spillway Design." *M.Sc. thesis*, Dept. of Civil Engineering, M.I.T., USA, 68 pages.

Sagaut, P., Deck, S., and Larcheveque, L. (2008). "Numerical Simulation Data: from Validation to Physical Analysis." *Proc. 11ème Congrès Francophone de Techniques Laser CFTL 2008*, Poitiers Futuroscope, France, 16-19 Sept., J.M. Most, L. David, F. Penot and L.E. Brizzi Eds., Invited plenary, pp. 29-43

Sarginson, E.J. (1972). "The Influence of Surface Tension on Weir Flow." *Journal of Hydraulic Research*, IAHR, Vol. 10, No. 4, pp. 431-446.

Stewart, S.F.C., Paterson, E.G., Burgreen, G.W., Hariharan, P., Giarra, M., Reddy, V., Day, S.W., Manning, K.F., Deutsch, S., Berman, M.R., Myers, M.R., and Malinauskas, R.A. (2012). "Assessment of CFD Performance in Simulations of an Idealized Medical Device: Results of FDA's First Computational Interlaboratory Study." *Cardiovascular Engineering and Technology*, Vol. 3, No. 2, pp. 139-160 (DOI: 10.1007/s13239-012-0087-5).

Tullis, B.P., Crookston, B.M., and Bung, D.B. (2019). "Weir head-discharge relationships: A multilab exercise." *Proc. 38th IAHR World Congress*, Panama City, 1-6 Sept., IAHR Publication, Lucas Calvo Ed., pp. 486-500 (DOI: 10.3850/38WC092019-0806).

Vallentine, H.R. (1969). "*Applied Hydrodynamics*." Butterworths, London, UK, SI edition.

Vo, N.D. (1992). "Characteristics of Curvilinear Flow Past Circular-Crested Weirs." *Ph.D. thesis*, Concordia University, Montreal, Canada.