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V-Notch Weir Overflow: an Unsteady Calibration

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ABSTRACT: Thin-plate V-notch weirs are commonly used as measuring devices in flumes and channels. Herein, the discharge calibration of a large 90º V-notch weir was performed using an unsteady volume per time technique. The weir overflow was initially shut. The sudden opening of the gate was associated with an initial phase of transient water motion associated with a negative wave propagating in the reservoir and the free-falling motion of a mass of fluid in the close proximity of the overflow behind the initial wave. This initial phase was followed by a more gradual overflow motion which was affected by the seiche in the upstream reservoir. The integral form of the continuity equation was used to derive the relationship between flow rate and upstream water depth. The findings showed that the unsteady discharge calibration of the V-notch weir yielded similar results to a more traditional calibration approach based upon steady flow experiments, while allowing the rapid testing of a wide range of discharges.

Keywords: V-notch weirs, Unsteady calibration, Transient flow motion, Seiche, Physical tests

1 INTRODUCTION

A weir is a structure placed across a channel which raises the upstream water level and may be used to measure the flow rate. A range of measuring weirs were developed (Darcy and Bazin 1865, Bos 1976, Ackers et al. 1978). The V-notch thin-plate weir, also called triangular weir, has an overflow edge in the form of an isosceles triangle. The Australian Standards (1991) expresses the discharge calibration of the V-notch weir in the form:

$$Q = C_d \times \frac{8}{15} \times \tan\alpha \times \sqrt{2 \times g \times h^5} \qquad (1)$$

where Q = water discharge, C_d = dimensionless discharge coefficient, α = notch opening angle, g = gravity acceleration, h = upstream water depth above the notch (Fig. 1).

The contribution herein presents a novel approach to calibrate a large 90º V-notch weir using a volume per time approach. A series of relatively large-size tests were conducted to measure the upstream water level at high frequency following a sudden overflow opening. The results demonstrate the application of the technique while they highlight the effects of seiche motion in the upstream reservoir.

2 PHYSICAL FACILITY AND INSTRUMENTATION

2.1 *Equipment and instrumentation*

New experiments were performed in a 2.36 m long, 1.66 m wide and 1.22 m deep reservoir with a 400 mm high 90° V-notch thin-plate weir located at one end (Fig. 2). The weir was made out of brass and designed based upon the Australian Standards (1991) and International Organization for Standardization (1980). The notch was located 0.82 m above the reservoir invert. The weir overflow was initially closed with a fast-opening gate hinging outwards and upwards (Fig. 2 & 3).

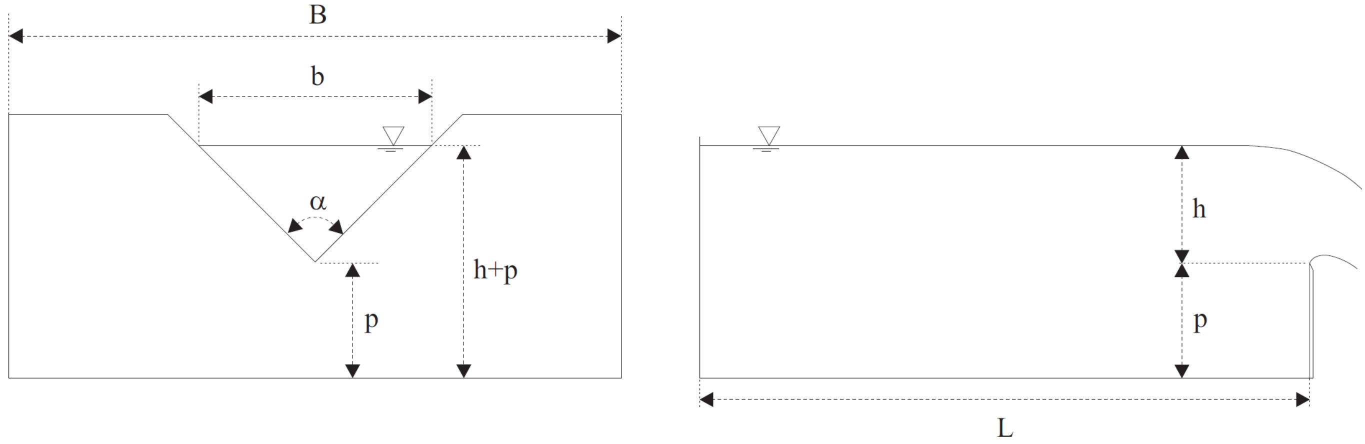

Figure 1. Definition sketch of a V-notch weir overflow

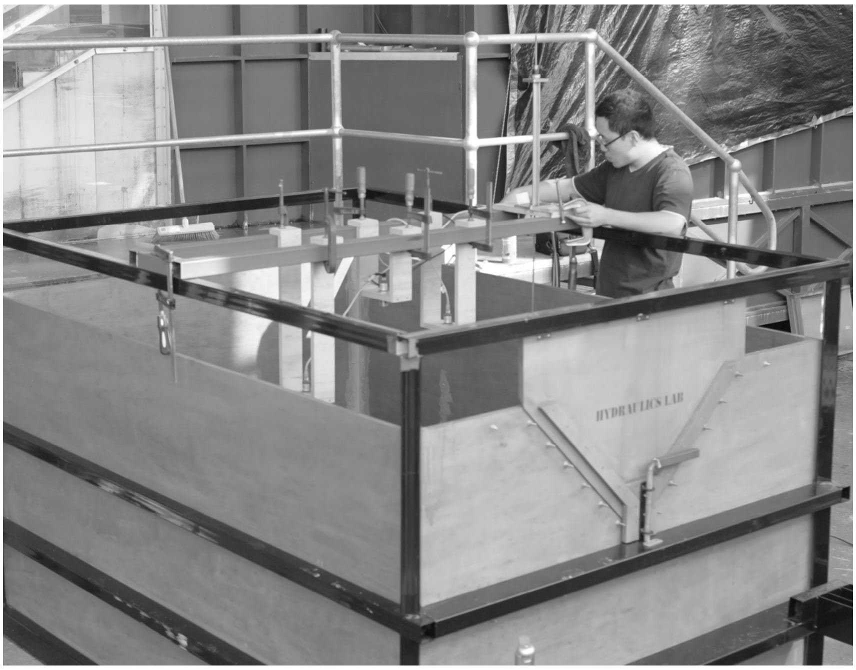

Figure 2. Reservoir and V-notch overflow, with the V-notch overflow gate closed (foreground right) - The displacement meters are mounted above the reservoir

The water depth was measured using a pointer gauge in steady flow conditions. The unsteady water depth was measured with three acoustic displacement meters Microsonic^{TM} Mic+25/ IU/TC. The sensors were located 1.11 m upstream of the weir. Their range was 250 mm and they were positioned in an overlapping fashion to cover the full height of the weir (400 mm). The data accuracy and response of the sensors were 0.18 mm and 50 ms respectively (http://www.microsonic.de). All the displacement sensors were synchronised and sampled simultaneously at 200 Hz. Additional visual observations were recorded with two HD digital video cameras, two dSLR cameras and a digital camera. The cameras were placed around the reservoir at various locations to cover both the water motion in the reservoir and the weir overflow during each run. Further details on the experiments, including some digital video movies, were reported in Chanson and Wang (2012).

2.2 *Physical investigations*

Prior to each run, the reservoir was filled slowly to the brink of the brass plate. The water was left to settle for at least 5 minutes prior to start. The experiment started when the gate was opened rapidly and the water level was recorded continuously for 500 s. The gate opening motion was recorded at 60 fps and the opening time was less than 0.15 s to 0.2 s. Such a rapid opening time was small enough to have a negligible effect on the water motion in the reservoir. After the sudden opening, the gate did not intrude into the overflow flow as illustrated in Figure 3.

Altogether five runs were conducted starting with an initially steady water level h_o above the lower edge of the notch: $h_o = 0.400 \pm 0.002$ m. The measured fluctuations in initial upstream water level were less than 0.3 mm prior to the gate opening.

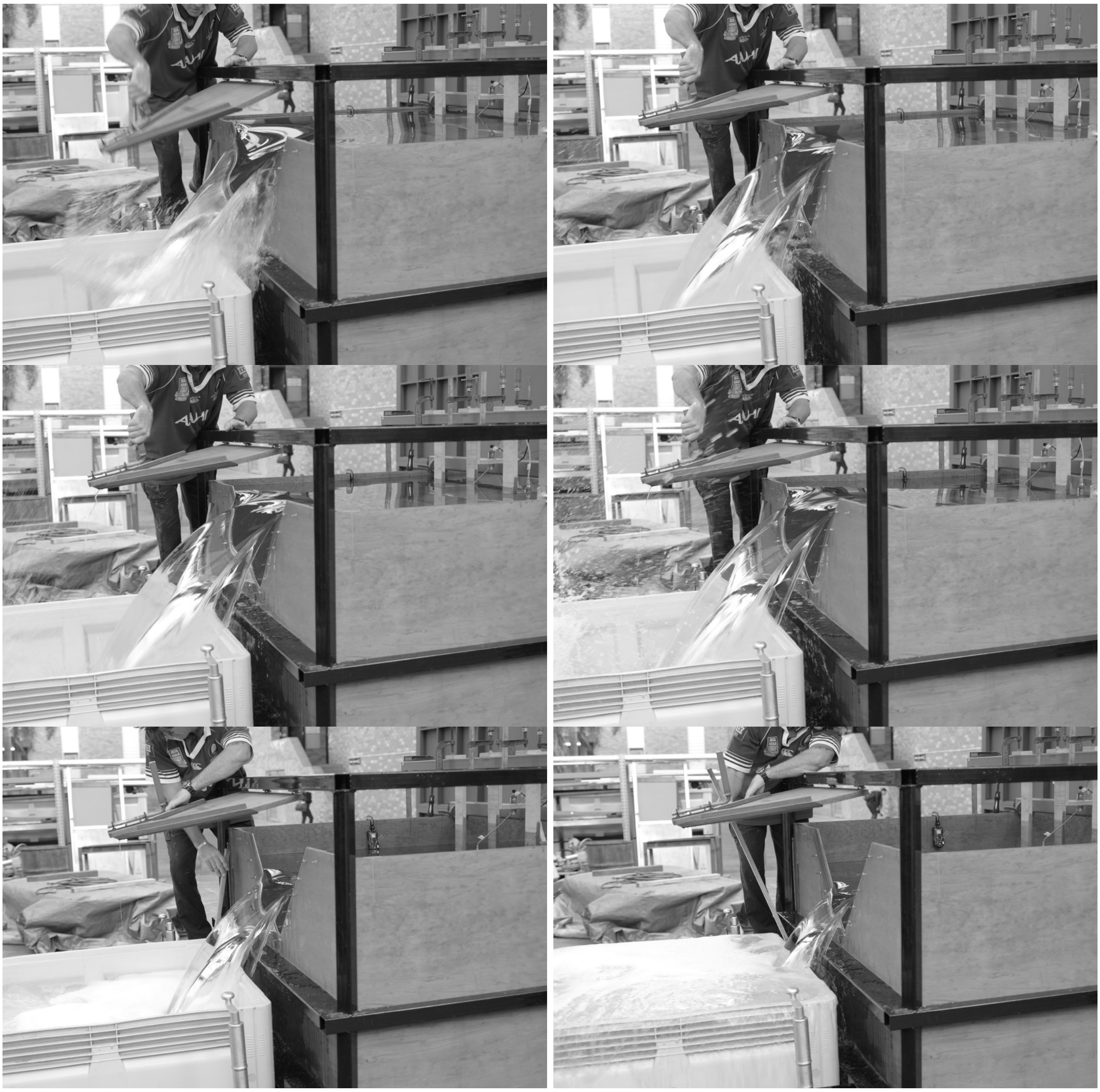

Figure 3. Overflow sequence (Run 1) - Camera: Pentax K-7, lens: Pentax FA31mm f1.8 Ltd, shutter 1/80 s - From Left to Right, Top to Bottom: $t = t_o$, t_o+0.19 s, t_o+0.38 s, t_o+0.58 s, t_o+8 s, t_o+18 s

3 BASIC OBSERVATIONS

The gate opening was rapid. Figure 3 illustrates a typical overflow sequence. The unsteady overflow consisted initially of a transient phase followed by a gradually-varied overflow motion. The sudden gate opening caused the generation of a negative wave propagating upstream into the reservoir (Fig. 4) and a free-falling motion in the close vicinity the overflow behind the wave. Figure 4 illustrates an instantaneous snapshot. The initial phase lasted less than 0.45 s: that is, for $t\times(g/h_o)^{1/2} < 2.23$ with t = 0 at the start of the gate opening. Only a limited mass of water was reached by the initial wave; the rest of reservoir was still unaffected by the sudden opening. The negative wave leading edge had a quasi-circular arc shape illustrated in Figure 4. The resulting equipotential lines in a plan view highlighted the flow contraction under the action of gravity. The free-surface shape appeared somehow similar to the inlet shape of a minimum energy loss (MEL) structure with its curved profile (Apelt 1983). The design of a MEL structure was developed to pass large floods with minimum energy loss, hence with minimum upstream flooding (Chanson 2003). The MEL weir inlet is curved in plan to converge smoothly the chute flow (Fig. 5). Figure 5 shows the inlet of a minimum energy loss (MEL) spillway inlet. Note the analogy of shape between Figures 4 and 5.

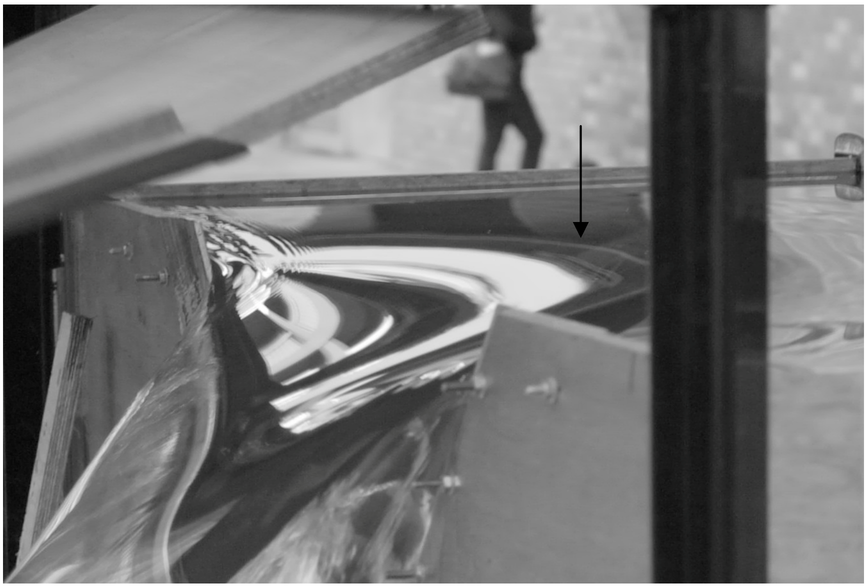

Figure 4. Negative wave and initial free-falling motion behind observed for $t \times (g/h_o)^{1/2} < 2.2$ (Run 1) - The arrow points to the negative wave leading edge

Figure 5. Inlet of the minimum energy loss (MEL) weir spillway of Lake Kurwongbah (Petrie QLD, Australia) on 22 May 2009 during a small overflow

The initial phase was followed by a gradually-varied phase during which the overflow presented a quasi-steady flow motion. Some typical time-variations of the upstream water depth are illustrated in Figure 6. The ensemble-averaged water depth data were best fitted by:

$$\frac{h}{h_o} = \frac{12.72}{\left(t \times \sqrt{\frac{g}{h_o}} + 37.62 \right)^{0.696}} \quad \text{for } 2.5 < t \times (g/h_o)^{1/2} < 2{,}400 \quad (2)$$

with a normalised correlation coefficient of 0.9999. During the initial phase, the time-variation of the water depth exhibited a different shape as shown in Figure 6 (Right).

The rapid gate opening generated some disturbance in the reservoir with the propagation of a three-dimensional wave illustrated in Figure 4. The reflections of the negative wave on sidewalls and end walls yielded some complicated three-dimensional wave motion associated with some seiche. Both longitudinal and transverse sloshing motions were observed. Figure 7 presents a typical water depth signal. The data highlighted some pseudo-periodic oscillations about a mean data trend (Fig. 7). Some frequency analyses of the de-trended water depth signals were performed. The results compared favourably with the first mode of natural sloshing in the longitudinal and transverse directions of the intake basin, whose frequencies were respectively:

$$F_L = \frac{2 \times L}{\sqrt{g \times (p + h)}} \qquad (3A)$$

$$F_B = \frac{2 \times B}{\sqrt{g \times (p + h)}} \qquad (3B)$$

where L = reservoir length, B = reservoir width and p = notch elevation above reservoir invert (Fig. 1).

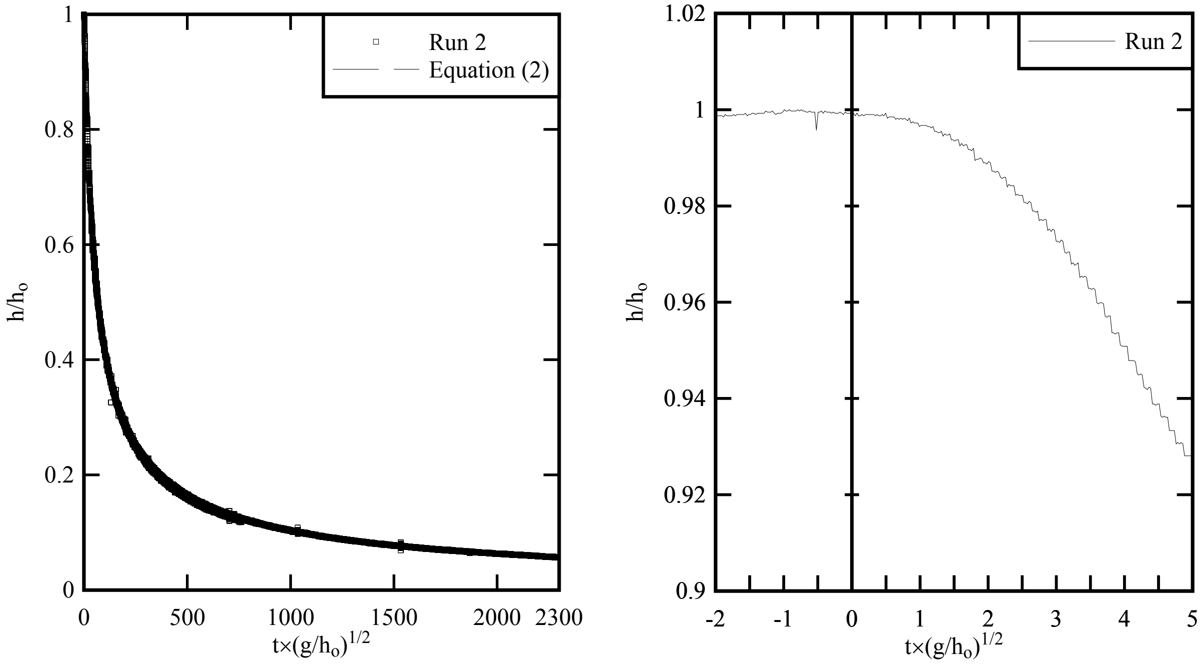

Figure 6. Dimensionless time-variations of the upstream water depth (Run 2) - Left: comparison between data and Equation (2); Right: Details of the initial instants

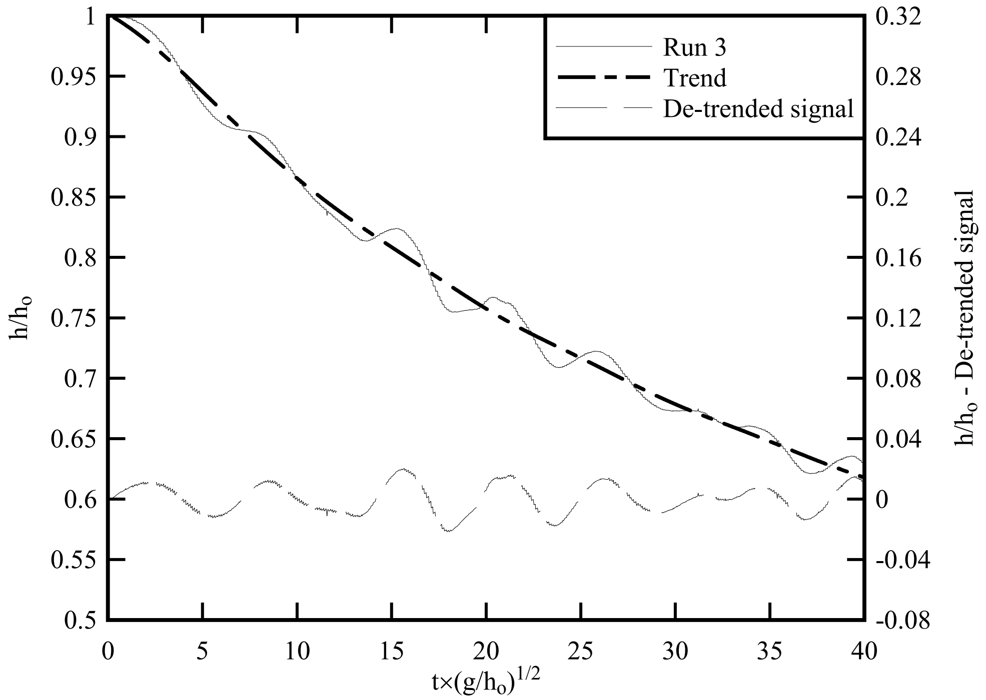

Figure 7. Dimensionless time-variations of the upstream water depth: raw signal and de-trended water depth signal (Run 5)

4 DISCUSSION

The instantaneous discharge Q through the V-notch weir was estimated using the integral form of the equation of conservation of mass for the water reservoir:

$$\frac{dVol}{dt} = -Q \qquad (4)$$

where t = time and Vol = instantaneous volume of water in the reservoir:

$$Vol = L \times B \times (h + p) \qquad (5)$$

with p = weir notch height above invert (Fig. 1). Equation (5) implicitly assumes that the reservoir free-surface was horizontal and neglects the local drop in water surface in the close vicinity of the overflow where the fluid particles are accelerated. The approximation was deemed reasonable considering the large reservoir surface area. Combining Equations (4) and (5), this gives an expression for the instantaneous overflow discharge:

$$Q = -L \times B \times \frac{d\,h}{dt} \qquad (6)$$

In the present study, Equation (6) was calculated based upon the smoothed water depth data. All the data are presented in Figure 8 by preserving every Nth point where N is the smoothing window size in points: e.g., N = 300 for a smoothing window of 300 points. Chanson and Wang (2012) tested systematicaly three smoothing window sizes: 300, 600 and 1,200 points. Qualitatively a smoothing window of 300 points was relevant immediately after the gate opening, while a smoothing window of 1,200 points was best suited during the gradually-varied phase.

Overall the data were best correlated by:

$$\frac{Q}{\sqrt{g \times h_o} \times {h_o}^2} = 0.58 \times \frac{8}{15} \times \sqrt{2 \times \left(\frac{h}{h_o}\right)^5} \qquad (7)$$

and Equation (7) is shown in Figure 8.

The data analysis yielded basically a dimensionless discharge coefficient $C_d = 0.58$. The result was close to a number of earlier studies in steady flow conditions (Lenz 1943, Trokolanski 1960, Herschy 1995). Simply the present findings showed that the unsteady discharge calibration of the V-notch weir yielded similar results to a more traditional calibration approach based upon steady experimental conditions.

For completeness, some unsteady experiments were conducted with a large two-dimensional orifice flow discharging vertically (Chanson et al. 2002). The results followed closely the following discharge equation:

$$\frac{Q}{\sqrt{g \times h_o} \times A} = C_d \times \sqrt{2 \times \frac{h}{h_o}} \qquad (8)$$

where A = orifice cross-section area and $C_d = 0.58$ (Chanson et al. 2002). Since $A = h^2$ for a 90° V- notch weir, Equation (8) yields a result somehow similar to Equation (7).

Note that the present approach enabled the calibration of the weir over a relatively wide range of water discharges (Fig. 8). Lastly, the physical tests were conducted for $0.022 \text{ m} < h < 0.40 \text{ m}$. Although the results herein focused on water depths within the range $0.025 \text{ m} < h < 0.40 \text{ m}$, the Reynolds number became less than 1×10^4 for $h < 0.038$ m. It is conceivable that viscous scale effects might affect the findings for the smallest water discharges.

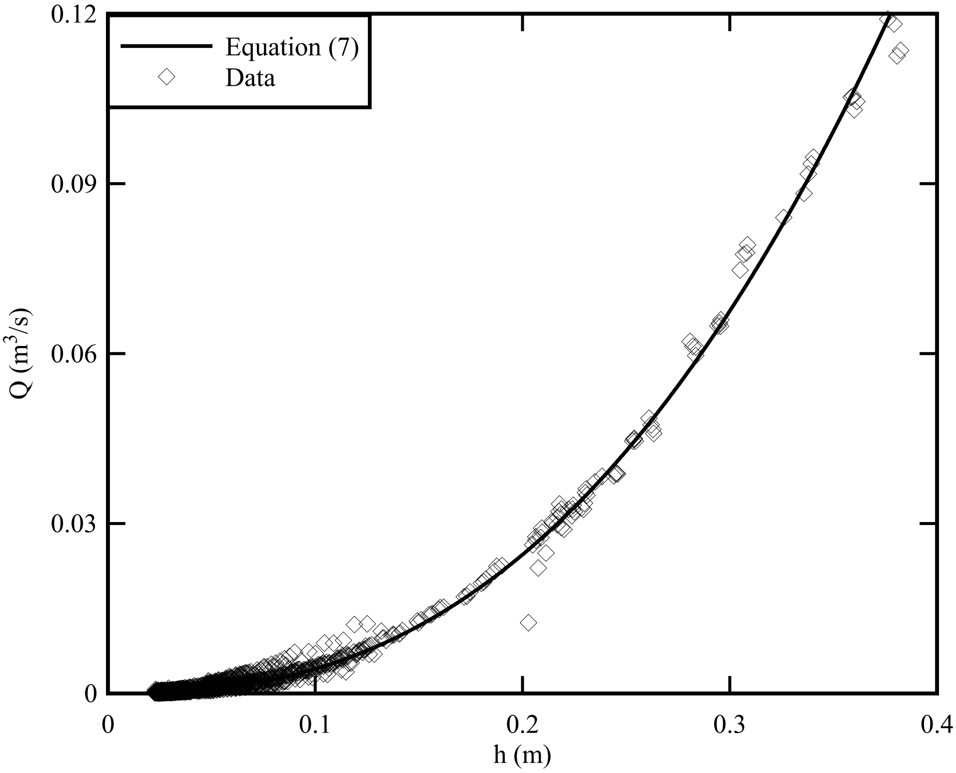

Figure 8. Relationship between instantaneous discharge Q and upstream water depth h - Comparison between data and Equation (7)

5 CONCLUSION

A large 90º V-notch thin plate weir was calibrated using an unsteady volume per time technique. The V-notch weir overflow was initially closed. The sudden opening of the overflow gate induced an initial phase dominated by the upstream propagation of a negative wave into the reservoir and the free-falling motion of a volume of fluid in the vicinity of the overflow. The water volume affected by the sudden opening was encompassed by a quasi-circular free-surface arc. Later the overflow motion became gradually-varied while some seiche was observed in the reservoir. The dominant frequencies of the water depth fluctuations compared favourably with the first mode of natural sloshing in the longitudinal and transverse directions of the reservoir, even though the wave motion was three-dimensional.

The relationship between water discharge and upstream water depth was derived from the integral form of the continuity equation based upon high-frequency water depth signal. The results yielded a dimensionless discharge coefficient C_d = 0.58 close to previous studies of 90º V-notch weirs and to an unsteady orifice experimental study. The present findings showed that the unsteady discharge calibration of the V-notch weir yielded similar results to a more traditional calibration approach based upon steady flow experiments. The present technique enabled further a calibration of the weir for a relatively wide range of upstream water levels.

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NOTATION

C_d dimensionless discharge coefficient
B reservoir width
F_B frequency of first mode of natural sloshing in the transverse direction
F_L frequency of first mode of natural sloshing in the longitudinal direction
g gravity acceleration
h upstream water depth measured above the notch
h_o initial upstream water depth measured above the notch
L reservoir length
p notch elevation above reservoir invert
Q water discharge
t time since gate opening start
Vol water volume in the reservoir
α opening angle of the notch
ρ fluid density

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