Experimental Thermal and Fluid Science 74 (2016) 368–381

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Interaction between free-surface aeration and total pressure on a stepped chute

Gangfu Zhang, Hubert Chanson *

The University of Queensland, School Civil Engineering, Brisbane, QLD 4072, Australia

A R T I C L E I N F O

Article history:
Received 21 September 2015
Received in revised form 10 December 2015
Accepted 12 December 2015
Available online 30 December 2015

Keywords:
Air bubble entrainment, Total pressure
Turbulence
Coupling
Physical modelling
Stepped spillways

A B S T R A C T

Stepped chutes have been used as flood release facilities for several centuries. Key features are the intense free-surface aeration of both prototype and laboratory systems and the macro-roughness caused by the stepped cavities. Herein the air bubble entrainment and turbulence were investigated in a stepped spillway model, to characterise the interplay between air bubble entrainment and turbulence, and the complicated interactions between mainstream flow and cavity recirculation motion. New experiments were conducted in a large steep stepped chute ($\theta = 45°$, $h = 0.10$ m, $W = 0.985$ m). Detailed two-phase flow measurements were conducted for a range of discharges corresponding to Reynolds numbers between 2×10^5 and 9×10^5. The total pressure, air–water flow and turbulence properties were documented systematically in the mainstream and cavity flows. Energy calculations showed an overall energy dissipation of about 50% regardless of the discharge. Overall the data indicated that the bottom roughness (i.e. stepped profile) was a determining factor on the energy dissipation performance of the stepped structure, as well as on the longitudinal changes in air–water flow properties. Comparative results showed that the cavity aspect ratio, hence the slope, has a marked effect on the residual energy.

1. Introduction

Stepped spillways have been used as flood release facilities for several centuries [11]. In the past few decades, advances in construction materials and techniques led to a regained interest in stepped spillway design [1,20,10,12]. The steps contribute to some dissipation of the turbulent kinetic energy and reduce or eliminate the need for a downstream stilling structure [15]. Stepped spillway flows are characterised by strong turbulence and air entrainment (Fig. 1). Early physical studies were conducted by Horner [29], Sorensen [43], and Peyras et al. [36] with a focus on flow patterns and energy dissipation. Many studies focused on steep chute slopes typical of concrete gravity dams ([39,9,34,8]. More recent studies were conducted on physical models with moderate slopes typical of embankment structures [35,30,22,5,6,45,50].

A key feature of stepped chute flows is the intense free-surface aeration observed in both prototype and laboratory (Figs. 1 and 2). A number of laboratory studies investigated systematically the air–water flow properties at step edges [32,17,44,7,4]. A few studies measured the two-phase flow properties inside and above the step cavities [26,23]. The stepped cavities act as macro-roughness, with intense cavity recirculation. To date the findings hinted a strong interplay between air bubble entrainment and turbulence, and complicated interactions between mainstream flow and cavity recirculation motion, although no definite conclusion has been drawn in terms of stepped spillway design.

The goal of this contribution is to examine the air bubble entrainment and turbulence in a stepped spillway model. New experiments were conducted in a large steep chute ($\theta = 45°$) equipped with 12 flat impervious steps ($h = 0.10$ m, $W = 0.985$ m). Detailed two-phase flow measurements were conducted for a range of discharges corresponding to the transition and skimming flow regimes. The total pressure, air–water flow and turbulence properties in the mainstream and cavity flows were documented systematically. It is the aim of this work to quantify the interplay between air bubble entrainment, turbulence and energy dissipation.

2. Experimental facility and instrumentation

New experiments were conducted in a large-size stepped spillway model located at the University of Queensland (Figs. 2 and 3). The facility consisted of a 12.4 m long channel. Three pumps driven by adjustable frequency AC motors delivered a controlled discharge to a 5 m wide, 2.7 m wide and 1.7 m deep intake basin

---

* Corresponding author. Fax: +61 (7) 33 65 45 99.
E-mail address: h.chanson@uq.edu.au (H. Chanson).
URL: http://www.uq.edu.au/~e2hchans/ (H. Chanson).

http://dx.doi.org/10.1016/j.expthermflusci.2015.12.011
0894-1777/

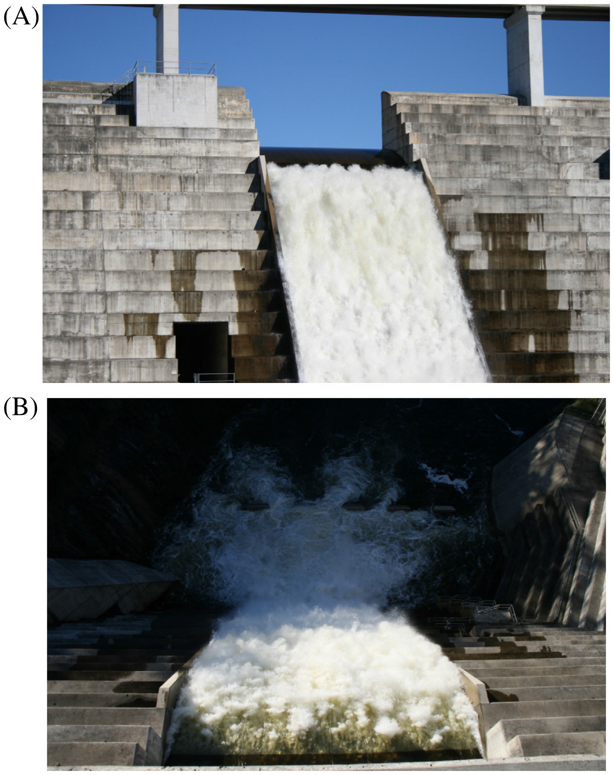

Fig. 1. Hinze dam stepped spillway in operation on 2 May 2015 ($\theta = 51.3°$, $h = 1.2$ m, $q = 2.15$ m^2/s, $Re = 8.5 \times 10^6$). (A) View from downstream and (B) view from the spillway crest.

equipped with a carefully designed diffuser, followed by two rows of flow straighteners. The intake basin was connected to the test section through to a 2.8 m long 5.08:1 sidewall contraction. The entire setup resulted in a smooth and waveless inflow for discharges up to 0.30 m^3/s. The stepped chute was controlled by a broad-crested weir at the upstream end (Fig. 2A). The broad crest was horizontal, 0.6 m long and 0.985 m wide with a vertical upstream wall and an upstream rounded nose (0.058 m radius). During initial tests, the weir ended with a sharp edge (see below). Later a downstream rounded edge (0.018 m radius) was installed and all experiments were conducted with the downstream edge rounding. The stepped chute consisted of twelve 0.1 m high and 0.1 m long smooth flat steps made of plywood (Fig. 2). Each step was 0.985 m wide. The stepped chute was followed by a horizontal tailrace flume ending into a free overfall.

The discharge was deduced from detailed velocity and pressure measurements above the broad crested weir using a Dwyer® 166 Series Prandtl–Pitot tube connected to an inclined manometer, giving total head and piezometric head data [52]. The results yielded the following relationship between the discharge per unit width q and the upstream head above crest H_1:

$$q = \left(0.897 + 0.243 \times \frac{H_1}{L_{\text{crest}}}\right) \times \sqrt{g \times \left(\frac{2}{3} \times H_1\right)^3} \qquad (1)$$

where g is the gravity constant and L_{crest} is the crest length ($L_{\text{crest}} = 0.60$ m) (Fig. 3). Clear-water flow depths were measured with a pointer-gauge on the channel centreline as well as dSLR photography (Canon™ 400D) through the sidewalls.

The air–water flow measurements were conducted using a dual-tip phase detection probe developed at the University of Queensland. The probe was capable of recording rapidly varying air–water interfaces based upon changes in resistivity and consisted of two identical tips, with an inner diameter of 0.25 mm, separated longitudinally by a distance Δx. The longitudinal separation Δx for each probe was 4.89 mm, 6.50 mm, 8.0 mm, and 8.42 mm. The probe sensors were excited by an electronic system and the signal output was recorded at 20 kHz per sensor for 45 s, following previous sensitivity analyses [47,25].

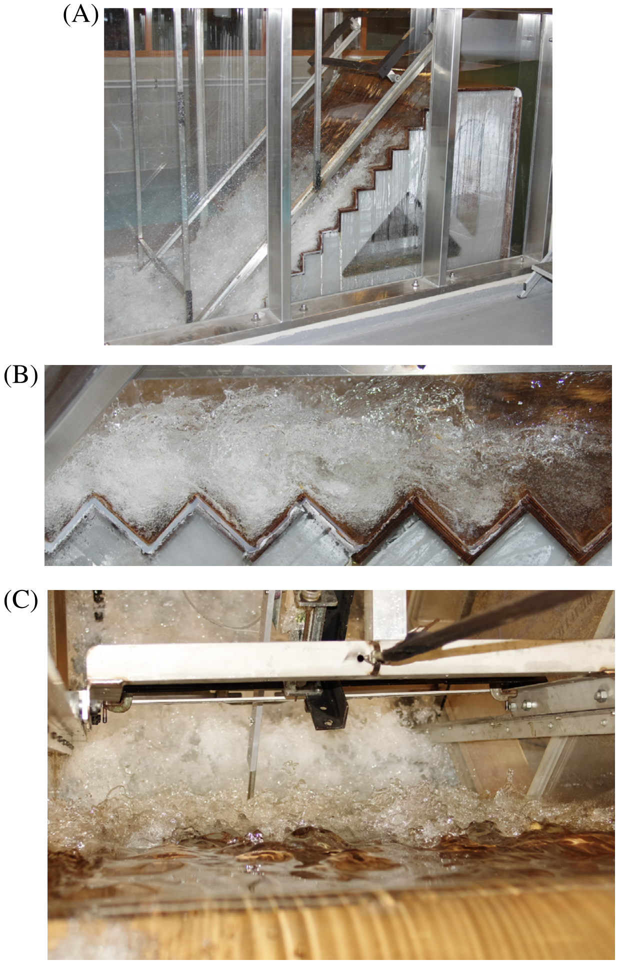

Fig. 2. Skimming flows above the stepped spillway model ($\theta = 45°$, $h = 0.1$ m, $l = 0.1$ m). (A) General view – flow conditions: $d_c/h = 1.08$, $Re = 4.4 \times 10^5$, (B) skimming flow above cavity recirculations, with flow direction from right to left – flow conditions: $d_c/h = 1.2$, $Re = 5.2 \times 10^5$ and (C) looking downstream at the upper spray region and splash structures, with the broad-crested weir overflow in foreground – flow conditions: $d_c/h = 1.5$, $Re = 7.2 \times 10^5$.

The instantaneous total pressure was measured with a MeasureX MRV21 miniature pressure transducer, its sensor featuring a silicon diaphragm with minimal static and thermal errors. The transducer was custom designed and measured relative pressures between 0 and 0.15 bars with a precision of 0.5% full scale. The signal was amplified and low-pass filtered at a cut off frequency of 2 kHz. The total pressure sensor was mounted alongside the dual-tip conductivity probe to record simultaneously the instantaneous total pressure and void fraction. The probes were sampled at 5 kHz per sensor for 180 s, following Wang et al. [49]. The data were sampled above each step edge downstream of the inception point of free-surface aeration.

A trolley system used to position the probes was fixed by steel rails parallel to the pseudo-bottom between step edges. The vertical movement of the probes was controlled by a Mitutoyo™ digital ruler within ±0.01 mm and the error on the horizontal position was less than 1 mm.