European Journal of Mechanics B/Fluids 28 (2009) 191–210

Contents lists available at ScienceDirect

European Journal of Mechanics B/Fluids

www.elsevier.com/locate/ejmflu

Current knowledge in hydraulic jumps and related phenomena. A survey of experimental results

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ARTICLE INFO

Article history:
Received 10 December 2007
Received in revised form 12 June 2008
Accepted 23 June 2008
Available online 1 July 2008

Keywords:
Hydraulic jumps
Undular hydraulic jumps
Positive surges
Tidal bores
Unsteady turbulence
Air bubble entrainment
Boussinesq equation
Two-phase flow properties
Dynamic similarity
Scale effects

ABSTRACT

The hydraulic jump is the sudden transition from a high-velocity open channel flow regime to a subcritical flow motion. The flow properties may be solved using continuity and momentum considerations. In this review paper, recent advances in turbulent hydraulic jumps are developed: the non-breaking undular hydraulic jump, the positive surge and tidal bore, and the air bubble entrainment in hydraulic jumps with roller. The review paper demonstrates that the hydraulic jump is a fascinating turbulent flow motion and the present knowledge is insufficient, especially at the scales of environmental and geophysical flows.

1. Introduction

Hydraulic jumps are commonly experienced in rivers and canals, in industrial applications and manufacturing processes, as well as in the kitchen sink. A hydraulic jump is the sudden transition from a supercritical open channel flow regime to a subcritical flow motion. For a horizontal rectangular channel and neglecting boundary friction, the continuity and momentum principles give [1]:

$$\frac{d_2}{d_1} = \frac{1}{2} \times \left(\sqrt{1 + 8 \times Fr_1^2} - 1\right) \tag{1}$$

$$\frac{Fr_2}{Fr_1} = \frac{2^{3/2}}{\left(\sqrt{1 + 8 \times Fr_1^2} - 1\right)^{3/2}} \tag{2}$$

where the subscripts 1 and 2 refer to the upstream and downstream flow conditions respectively, Fr is the Froude number: $Fr = V/\sqrt{g \times d}$, d and V are the flow depth and velocity respectively, and g is the gravity acceleration. The hydraulic jump is typically classified in terms of its inflow Froude number $Fr_1 = V_1/\sqrt{g \times d_1}$ that is always greater than unity [1,2]. For a Froude number slightly above unity, the hydraulic jump is characterised a smooth rise of the free-surface followed by a train of stationary free-surface undulations: i.e., the undular hydraulic jump (Fig. 1A). For larger Froude numbers, the jump is characterised by a marked roller, some highly turbulent motion with macro-scale vortices, significant kinetic energy dissipation and a bubbly two-phase flow region (Fig. 1B). The unsteady form of hydraulic jump is the positive surge that is also called a hydraulic jump in translation. A glossary of relevant terms is given at the end of the article.

Historically, significant contributions to the fluid dynamics of hydraulic jumps included the physical modelling of Bidone [11], the theoretical solution of the momentum principle by Bélanger [1], the experiments of Darcy and Bazin [10] (Fig. 2), the solutions of Boussinesq [12] and the work of Bakhmeteff [13] (see review in [14]). Although a laminar jump may occur for very-low inflow Reynolds number $Re = \rho \times V_1 \times d_1/\mu$ (e.g. [15]). most situations are turbulent flows. Fig. 1 presents two photographs of turbulent hydraulic jumps.

In this review, recent advances in turbulent hydraulic jumps are developed. It is the purpose of this contribution to show the complicated features of hydraulic jump flows commonly encountered in geophysical and environmental flows, and this is supported by relevant experimental evidences. The non-breaking undular hydraulic jump is discussed first. Then the case of the hydraulic jump

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[1] The paper derives from a plenary lecture paper presented at the 16th Australasian Fluid Mechanics Conference [H. Chanson, Hydraulic jumps: Bubbles and bores. in: Proc. 16th Australasian Fluid Mechanics Conference AFMC, Gold Coast, Australia, 2–7 December, Plenary Address, 2007, pp. 39–53 (CD-ROM) [95]].

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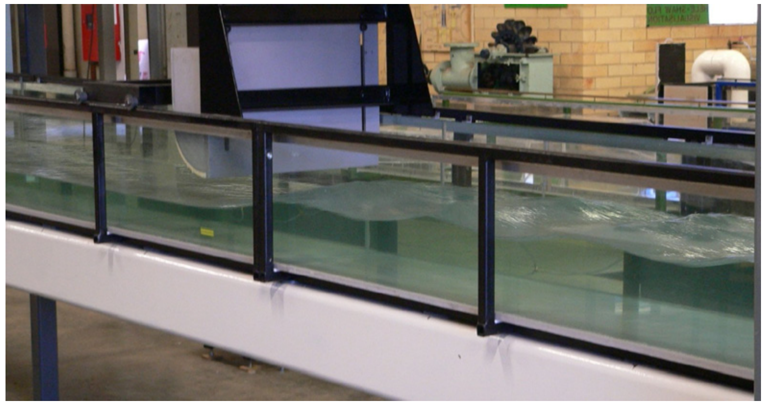
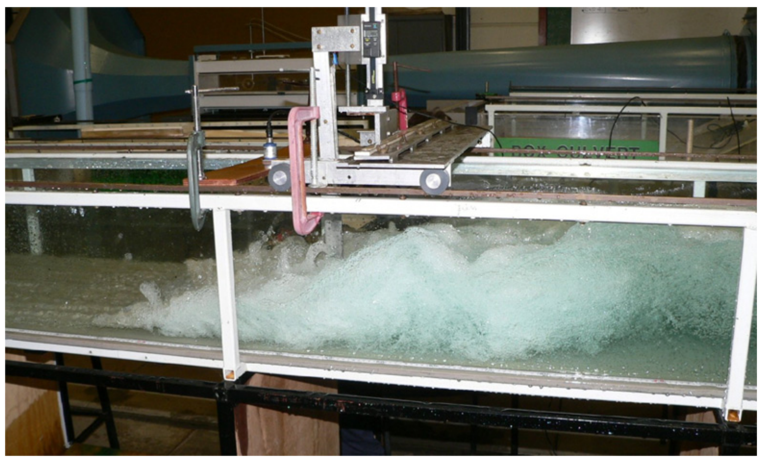
doi:10.1016/j.euromechflu.2008.06.004



(A)



(B)

Fig. 1. Photographs of hydraulic jump flows. (A) Undular hydraulic jump – flow conditions: $Fr_1 = 1.35$, $d_1 = 0.090$ m, $Re = 1.1 \times 10^5$ – flow from left to right. (B) Hydraulic jump with roller – flow conditions: $Fr_1 = 7.0$, $d_1 = 0.024$ m, $Re = 8.1 \times 10^4$ – flow from left to right.

Table 1
Summary of recent experimental studies of undular hydraulic jumps

	Channel	Instrumentation
Chanson and Montes [3]	$L = 20$ m, $B = 0.25$ m, F/D inflow	Prandtl–Pitot tube (⌀3.3 mm)
Montes and Chanson [4]	$L = 12$ to 20 m, $B = 0.2$ to 0.3 m, F/D inflow	Prandtl–Pitot tubes
Chanson [5]	$L = 20$ m, $B = 0.25$ m, F/D inflow	Pitot–Preston tube (⌀3.3 mm)
Ohtsu et al. [6]	$L = 5$ to 20 m, $B = 0.1$ to 0.8 m, P/D & F/D inflow	Micro-propeller (⌀3 mm), Prandtl–Pitot tube, 1D-LDV
Chanson [7]	$L = 3.2$ m, $B = 0.5$ m, P/D inflow	Prandtl–Pitot tube (⌀3.3 mm)
Lennon and Hill [8]	$L = 4.9$ m, $B = 0.3$ m, F/D inflow	Particle Image Velocimetry
Ben Meftah et al. [9]	$L = 15$ m, $B = 4$ m, F/D inflow	Acoustic Doppler Velocimetry

Notes. B: channel width; F/D: fully-developed; L: channel length, P/D: partially-developed.

in translation is considered: i.e., positive surges and tidal bores. The last section discusses the air bubble entrainment in hydraulic jumps with roller, its physical modelling, the dynamic similarities and scale effects.

2. Undular hydraulic jumps

Undular hydraulic jumps are characterised by a smooth rise of the free-surface followed by a train of well-formed stationary waves (Figs. 1A, 2B, 3). They are sometimes experienced in natural waterways and rivers at a break in bed slopes. A related situation is the "Morning Glory" cloud pattern observed in Northern Australia, sometimes called an undular jump [16,17].

Most hydraulic and fluid mechanics textbooks ignore the undular hydraulic jump in their section on open channel flows. A few studies of hydraulic jumps included some undular jump cases: e.g., Darcy and Bazin [10], Bakhmeteff and Matzke [18], Binnie and Orkney [19] (Fig. 2). Fawer [20] detailed clearly the main features of undular hydraulic jumps but his contribution was ignored for decades. Modern studies of undular jumps included Montes [21], Ryabenko [22], Chanson and Montes [3], Montes and Chanson [4], Ohtsu et al. [6]. These works showed that undular jumps may occur for upstream Froude numbers ranging from unity up to 3 to 4.

Recent experiments (Table 1) are re-analysed herein and the results provide some new understanding of the complicated flow patterns in undular hydraulic jumps.

2.1. Free-surface wave characteristics

Visual observations and detailed free-surface measurements showed that an undular jump is basically two-dimensional but next to the sidewalls (Fig. 3). The free-surface undulations are quasi-periodic, but the longitudinal profile is neither sinusoidal nor cnoidal. Fig. 3B presents the dimensionless free-surface profile for an experiment ($Fr_1 = 1.26$), where x is the distance measured