ENERGY DISSIPATION IN STEPPED WATERWAY

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1. INTRODUCTION

Stepped waste-waterways (also called 'byewash') were commonly used to assist with energy dissipation of the flow during the 19th century and early 20th century (CHANSON 1995a). Nowadays stepped spillways are often associated with roller compacted concrete (RCC) dams. The stepped geometry is appropriate to the RCC placement techniques and enhances the rate of energy dissipation compared to a smooth chute design (CHANSON 1994).

A stepped channel geometry is also commonly used in small-slope channels : for river training, in sewers, in storm waterways, at bottom outlets channels. Unfortunately there is little information on the rate of energy dissipation in such flat channels.

The authors present the results of a new series of investigations conducted in a 25-m long channel with a 4-degree slope. The flow characteristics and rate of energy dissipation with a smooth bed and with a stepped bottom are compared.

2. EXPERIMENTAL SET-UP

Experiments were performed in a 25-m long channel with a 4.0 degree slope located at the University of Queensland (fig. 1). The flume (0.5-m wide) is made of planed wooden boards (k_s = 1 mm) and the sidewalls are 0.4-m high. Waters are supplied by a pump controlled by a variable-speed electronic controller enabling a fine discharge adjustment in a closed-circuit system. Flow to the flume is fed by a smooth convergent. At the nozzle, the velocity, depth and width are respectively V_o, d_o = 0.03 m and W = 0.5 m.

The water discharge is measured with a Dall™ tube flowmeter, calibrated on site. The accuracy on the discharge measurement is about 2%. Clear-water depths and velocities are recorded with pointer gauges and a Pitot tube. Air-water flow properties are measured with conductivity probes. Full details of the instrumentation were reported by CHANSON (1995b) and CHANSON and CUMMINGS (1996).

A first series of experiments was conducted with the smooth-bed geometry (fig. 1(A), table 1). Subsequently 12 identical steps (h = 0.17 m, l = 2.4 m) were installed in the flume. A second series of experiments was then performed with the stepped channel profile (fig. 1(B), table 1).

3. EXPERIMENTAL RESULTS - FLOW PATTERNS

Smooth channel flow

For the smooth chute experiments, the flow pattern consists of a developing flow region followed by a fully-developed flow region in which the flow is decelerated (fig. 1). At the upstream end of the channel, velocity measurements showed that the boundary layer growth is best correlated by :

Fig. 1 - Sketch of the channel
(A) Smooth bed geometry (B) Stepped geometry

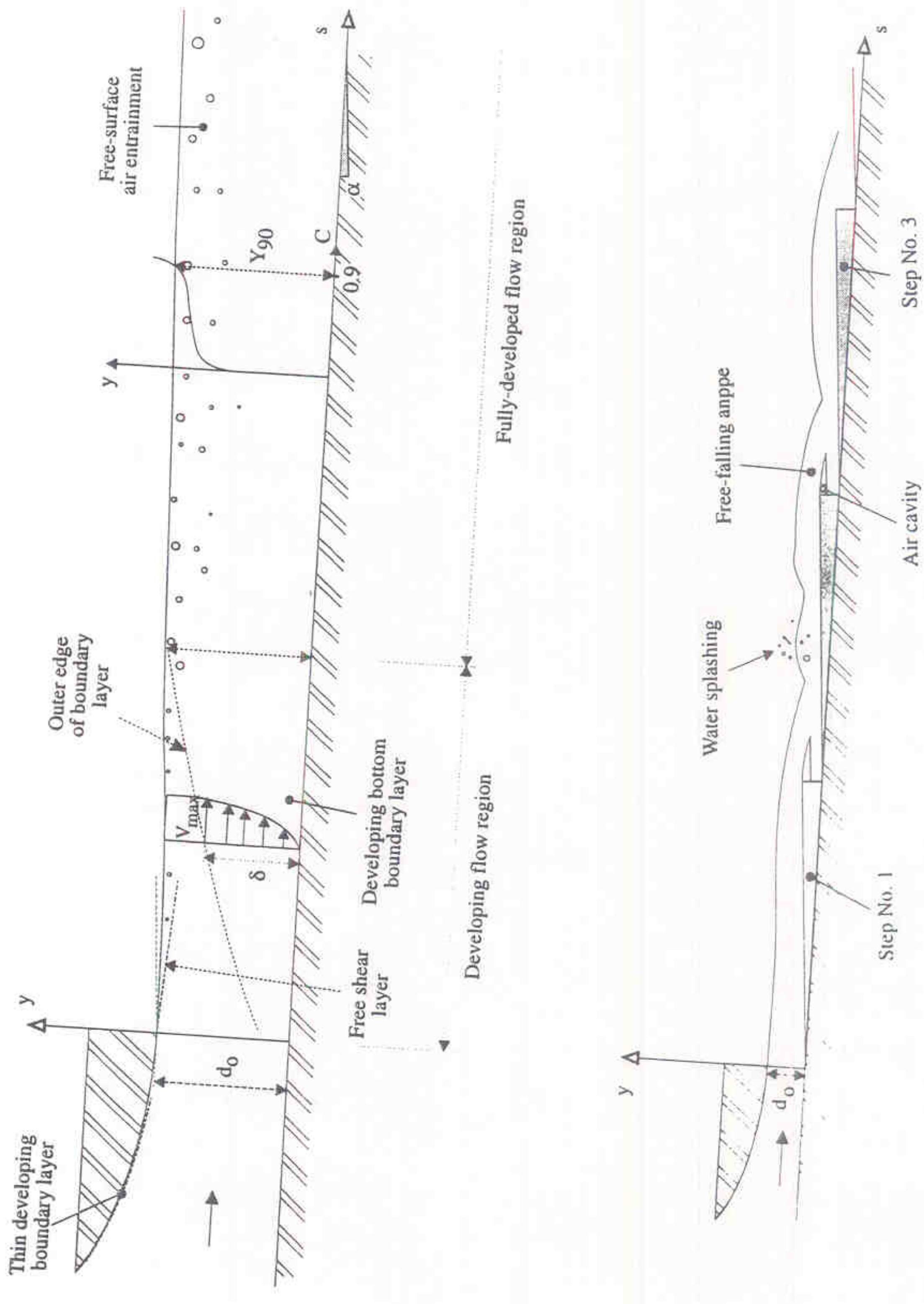


Fig 2 - Free-surface profile for $q_w = 0.08\ m^2/s$, $d_o = 0.03$ m.

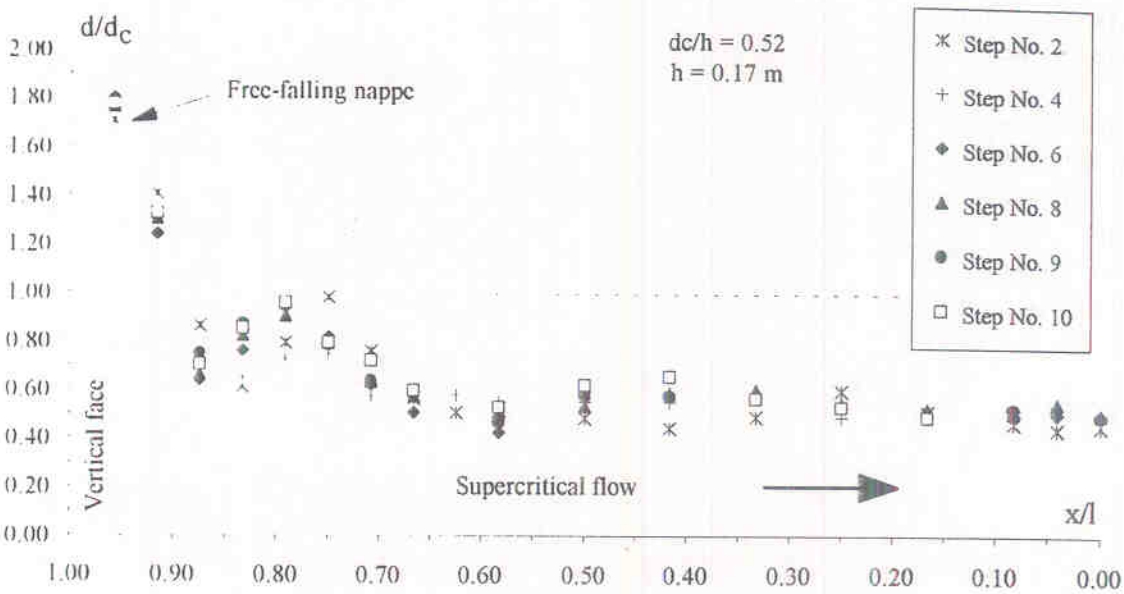


Table 1 - Experimental flow conditions

Ref. (1)	Slope α (deg.) (2)	q_w m^2/s (3)	V_o m/s (4)	d_o m (6)	Comments (7)
Smooth chute	4.0			0.03	W = 0.5 m. Painted timber (k_s = 1 mm).
		0.142	4.7		Run MC2 ([a]).
		0.150	5.0		Runs P5 ([a]) and PDC1 ([b]).
		0.156	5.2		Run MC3 ([a]).
		0.164	5.5		Run MC4 ([a]).
Stepped chute	4.0			0.03	W = 0.5 m. Horizontal timber steps (h = 0.17 m, l = 2.4 m).
		0.038	1.27		Nappe flow regime NA3 (without Hydraulic Jump).
		0.080	2.7		Idem.
		0.130	4.3		Idem.
		0.150	5.0		Idem.
		0.163	5.4		Idem. Loud noise generated by air cavity at first drop.

References : ([a]) : CHANSON (1995b); ([b]) : CHANSON and CUMMINGS (1996).
Notes : d_o = approach flow depth; h = step height; k_s = equivalent roughness height; l = horizontal step length; q_w = water discharge per unit width; V_o = approach flow velocity.

$$\frac{\delta}{k_s} = 1.020E\text{-}2 * \left(\frac{s}{k_s} + 757\right)^{0.973} \qquad \text{\{Smooth chute flow\}} \quad (1)$$

where δ is the boundary layer thickness, k_s is the roughness height, and s is the distance from the nozzle.

Free-surface aeration was measured along the channel (CHANSON and CUMMINGS 1996).

The flow is characterised by a rapid aeration in the first section of the flume (i.e. $s < 4$ m). For $q_w = 0.15$ m^2/s, the maximum mean air concentration is about 12% (defined in terms of 90% air concentration). For $s > 4$ m, the flow is very-gradually de-aerated, with still about 8.5% of mean air content at $s = 23$ m (for $q_w = 0.15$ m^2/s).

Stepped channel flow

With the stepped chute configuration, experimental observations indicate that the flow is *supercritical* all along the 25-m long flume for all the flow conditions (table 1). I.e., the waters flow as a nappe flow regime without hydraulic jump (regime NA3, CHANSON 1995a). No hydraulic jump is observed. After the first three drops, the free-surface profiles become nearly identical at each downstream step (fig. 2).

Note that the air cavity below the free-falling nappes was not ventilated. For some particular discharges (i.e. $q_w = 0.163$ m^2/s), loud noise was generated by the air cavity at the first drop (i.e. between steps No. 1 and 2). The noise could be stopped by introducing a rod in the nappe, acting as a splitter device.

At the first drops, the jet impact induced significant water splashing and jet deflection, followed by the propagation of *shock waves* intersecting further downstream on the channel centreline. *Sidewall standing waves* were observed also at the impact of the nappes. Both flow patterns are sketched on figure 3.

For $q_w = 0.13$ m^2/s, the shock waves developing on the horizontal face of step No. 2 intersected at the brink of the step (i.e. edge of second drop). And a "rooster tail" wave was observed on the centreline of the second free-falling nappe, "riding" over the upper nappe free-surface.

For $q_w < 0.13$ m^2/s, the shock waves intersected upstream of the step brink on step No. 2 and no "rooster tail" wave was observed. For $q_w > 0.13$ m^2/s, the shock waves did not intersect before the brink of the step No. 2. And on step No. 3, the shock waves were observed to intersect at the step edge, inducing a "rooster tail" wave on the centreline of the third free-falling nappe.

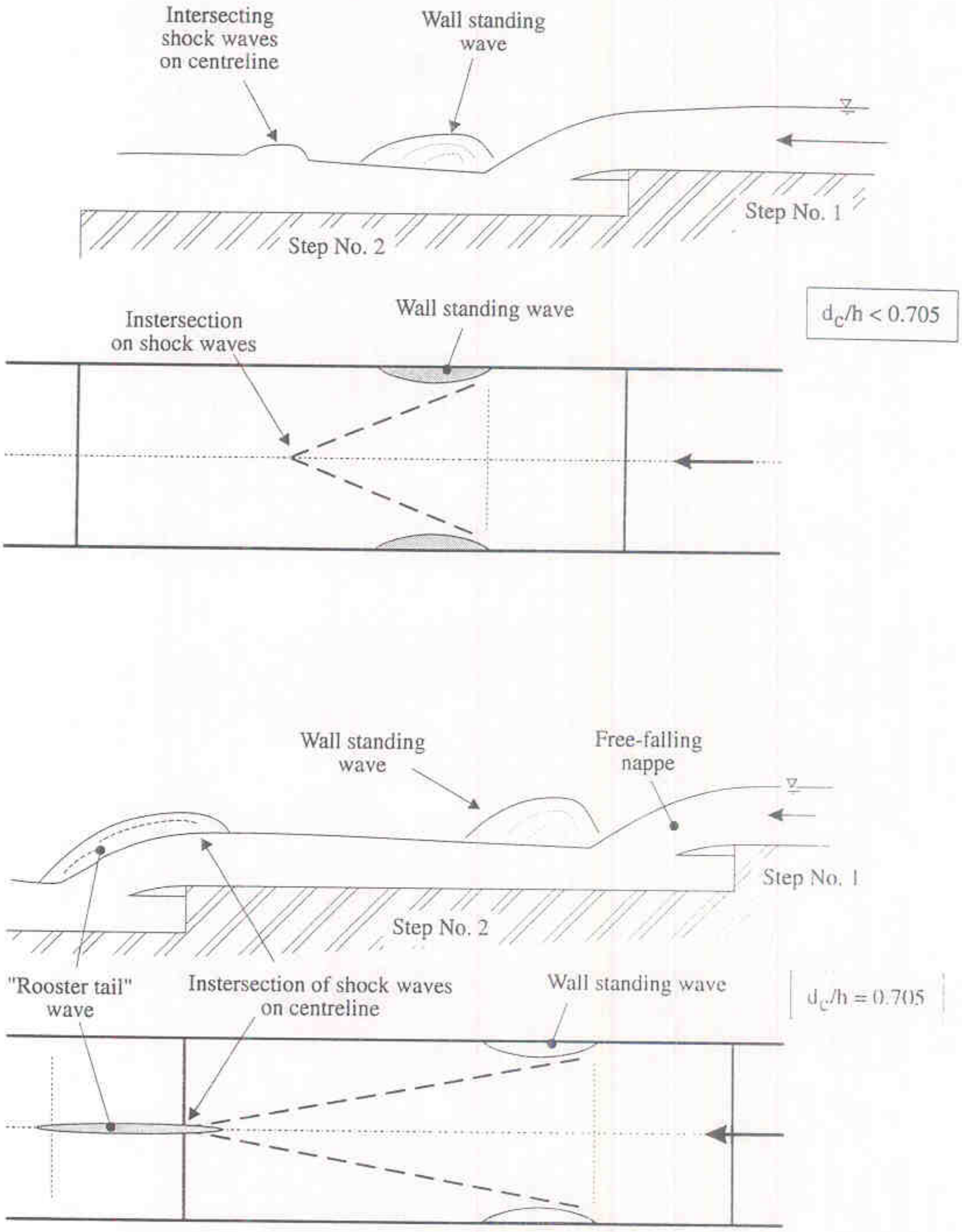
4. EXPERIMENTAL RESULTS - ENERGY DISSIPATION

The rate of energy dissipation in smooth and stepped channel flows is shown on figure 4. The data are plotted as $\Delta H/H_o$ versus s/d_c where H_o is the upstream total head, s is the longitudinal distance from nozzle (fig. 1) and d_c is the critical flow depth. Note that the results are based on equivalent clear-water flow depth data for the smooth chute (white symbols, $\Delta d/d < 0.5\%$) and on pointer gauge data for the stepped chute ($\Delta d/d < 5\%$), where d is the flow depth measured normal to the bottom.

Figure 4 indicates that the rate of energy dissipation is important in both smooth and stepped chute flows. In the upstream channel section (i.e. $s/d_c < 150$), larger energy dissipation is observed with the stepped geometry, in particular at large flow rates. At the downstream end of the chute, the rate of energy dissipation is nearly comparable between smooth chute data (i.e. $\Delta H/H_o \sim 0.8$) and stepped chute data ($\Delta H/H_o \sim 0.85$ to 0.9).

With stepped chute flows, it is thought that the absence of hydraulic jump might limit the rate of energy dissipation. At the first steps, significant losses may be associated with jet deflection, shock wave generation and splashing. Further downstream, energy dissipation occurs by nappe impact and skin friction in the supercritical flow.

Fig. 3 - Free-surface flow patterns at the first steps (stepped chute experiments)



6. CONCLUSION

New experiments were performed to compare the flow characteristics between a smooth bed and a stepped bottom in a small-slope channel ($\alpha = 4$ degrees) downstream of a gated intake. Experimental results show that the stepped chute flow is a nappe flow regime without hydraulic jump. Shock waves, jet deflection and standing waves are observed on each step. Energy dissipation takes place rapidly in the upstream part of the flume. Further downstream the rate of energy dissipation is comparable for smooth-bed and stepped-bottom experiments.

The results may be applied to storm waterways and stepped channels downstream of bottom outlets. They suggest that existing theories, derived for steep stepped chutes, cannot be applied to small-slope channels.

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REFERENCES

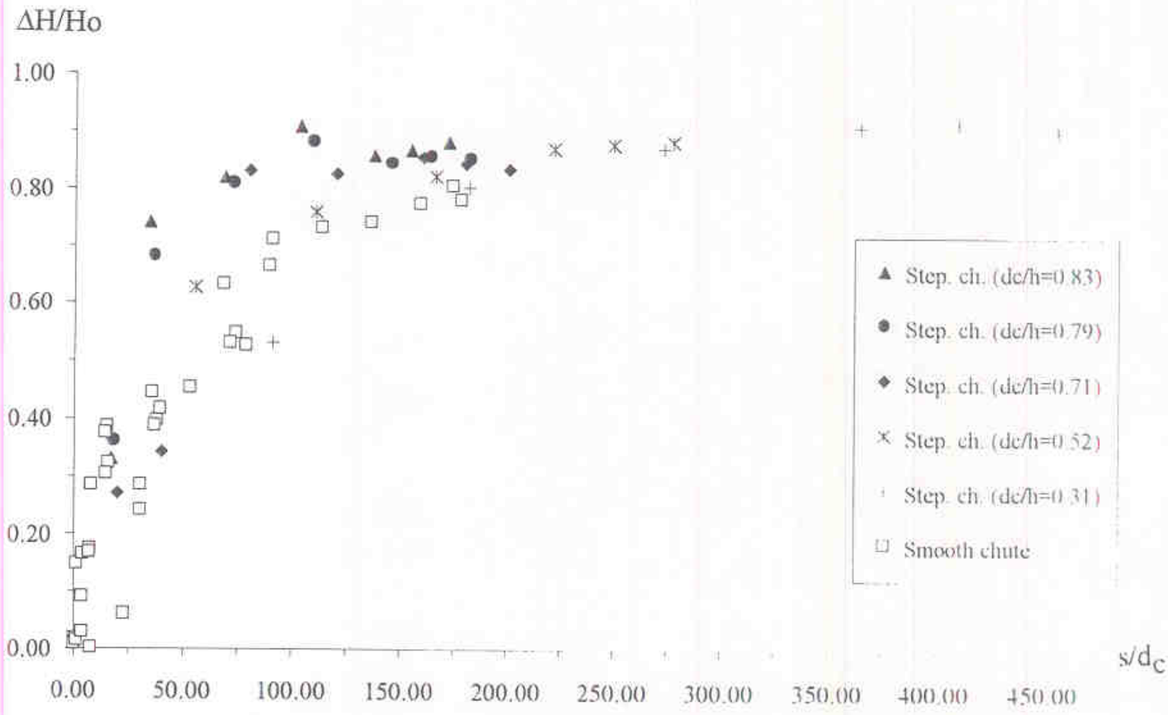
CHANSON, H. (1994). "Comparison of Energy Dissipation between Nappe and Skimming Flow Regimes on Stepped Chutes." *Jl of Hyd. Res.*, IAHR, Vol. 32, No. 2, pp. 213-218. Errata : Vol. 33, No. 1, p. 113. Discussion : Vol. 33, No. 1, pp. 114-143.

CHANSON, H. (1995a). "Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways." *Pergamon*, Oxford, UK, Jan., 292 pages.

CHANSON, H. (1995b). "Air Bubble Entrainment in Free-surface Turbulent Flows. Experimental Investigations." *Report CH46/95*, Dept. of Civil Engineering, University of Queensland, Australia, June, 368 pages.

CHANSON, H., and CUMMINGS, P.D. (1996). "Air-Water Interface Area in Supercritical Flows down Small-Slope Chutes." *Research Report No. CE151*, Dept. of Civil Engineering, University of Queensland, Australia, Feb., 67 pages.

Fig. 4 - Rate of energy dissipation : comparison between the smooth and stepped chutes



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