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Discussion

Flow patterns in nappe flow regime down low-gradient stepped chutes

By L. TOOMBES and H. CHANSON, Journal of Hydraulic Research, IAHR, 2008, 46(1), 4–14.

Discussers:
J. THORWARTH, A. SCHLEISS, J. KÖNGETER and H. SCHÜTTRUMPF

The Authors provide a detailed description of the flow patterns and the characteristics of nappe flow low gradient stepped chutes. They clearly highlight the complex and complicated air-water flow on stepped chutes.

The Discussers investigated the flow characteristics of low-gradient pooled stepped chutes. If the steps are equipped with endsills, which is often the case in practical applications, the flow resistance is increased but flow instabilities may then occur. These have to be considered in design to avoid overtopping of side walls and damages of such hydraulic structures.

The Discussers experimentally studied the effect of an endsill of pool depth w on both the flow instabilities and the flow resistance. The hydraulic model tests were conducted at the Institute of Hydraulic Engineering and Water Resources Management of RWTH Aachen University, Germany, for chute angles of $\theta = 8.9°$ and $\theta = 14.6°$, and at École Polytechnique Fédérale de Lausanne, Switzerland for $\theta = 18.6°$. The complete results are presented by Thorwarth (2008).

The Discussers found that the flow patterns of pooled-steps differ from those on standard flat steps described by the Authors. They classified the flow in their experiments with chute angles of $\theta = 2.6°$ and $\theta = 3.4°$ as "nappe flow without hydraulic jumps". In the Discussers' study, the nappe flow regime changed also to a flow *with* hydraulic jumps when endsills where installed on the steps for the same discharge and step height.

The experiments indicated that any further increase of discharge on a pooled-stepped chute with nappe flow and hydraulic jumps will result in a strong self-induced unsteady flow. The hydraulic jump of one basin is suddenly blown out, initiating the release of a wave causing a sudden increase of the flow depth up to factor 2.5 beyond this point. The Discussers named this unsteady phenomenon 'Jump waves'. They clearly differ from so-called Roll waves described e.g. by Dressler (1949). The phenomenon of jump waves was already observed on the spillway of the Sorpe Dam (Chanson 2002, Thorwarth and Klein 2005) and on Ruetz River in Stubai Valley, Austria (Premstaller and Rutschmann 2007).

The Discussers developed a semi-analytic approach to predict the unsteady discharge region. Figure D1 shows these unsteady flow regions for $0.2 \leq w/h \leq 1.0$ with h as the step height, as compared to the flow regimes nappe flow (NA), transition flow (TRA) and skimming flow (SK), with the subtypes SK A and SK B for flat steps ($w/h = 0$) defined by Yasuda and Ohtsu (1999), and Ohtsu (2004).

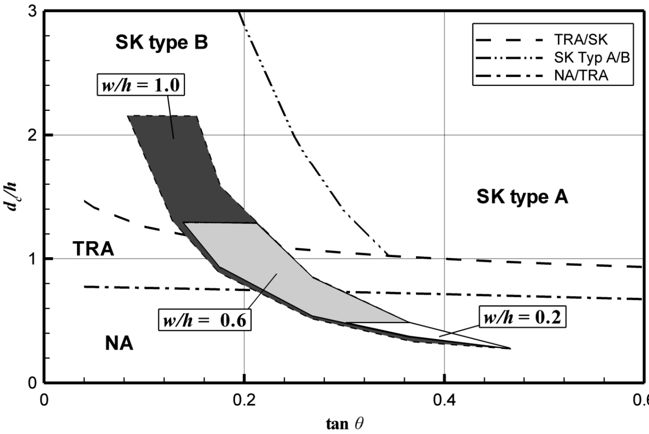

Figure D1 Flow regions of Jump waves predicted by semi-analytical approach for $0.2 \leq w/h \leq 1.0$ on pooled horizontal steps compared to flow regimes of flat steps for $w/h = 0$: nappe flow (NA), transition flow (TRA), skimming flow (SK), (- - - -) transition flow/skimming flow (Ohtsu *et al.* 2004), (—••—) skimming flow type A/type B (Ohtsu *et al.* 2004), (— - —) nappe flow/transition flow (Yasuda and Ohtsu 1999)

Figure D2 shows the result of the semi-analytical approach (data identical with those of Fig. D1), which is based on three criteria: (1) Lower discharge limit, (2) Upper discharge limit, and (3) Minimum weir height. These may be described as follows:

1. *Lower discharge limit*

The lower discharge limit (1) is characterised by hydraulic jumps with rollers touching the nappe on the upstream, and the weir on the downstream side. It can be predicted by empirical formulas for the nappe behind a sharp-crested weir and the roller dimensions of a hydraulic jump, leading to a function $q > f(l, \theta, w)$ and corresponding to the lower lines in Fig. D2, with q as discharge per unit width, l as step length, and d_c as critical flow depth.

2. *Upper discharge limit*

The upper discharge limit is defined by the discharge resulting in nappes with a throw length L_D longer than $0.75l$, based on experimentation. Then, the formation of hydraulic jumps is avoided. This flow pattern is described by a function $q < f(l, \theta, l_w)$ and

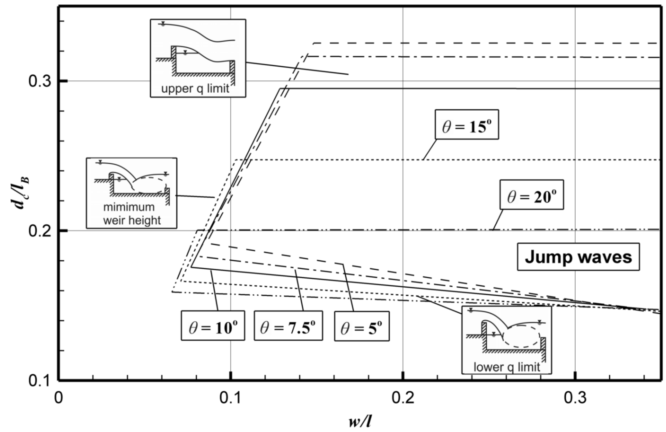

Figure D2 Flow regions of Jump waves predicted by semi-analytical approach, based on ratios of critical flow depth d_c and inner basin length l_B, and weir height w and step length l. Unsteady flow regions for various chute angle $\theta = 5°$ (— —), 7.5° (—•—), 10° (——-), 15° (- - - - -), 20° (—••—)

corresponds to the upper horizontal lines in Fig. D2, with l_w streamwise length of weir crest and l_B as inner basin length.

3. *Minimum weir height*
The formation of hydraulic jumps requires a minimum weir height: A tailwater depth of 1.3 d_2 caused by the weir, where d_2 is the sequent depth of the hydraulic jump, defines this limit. This results in a function $w > f(q)$, corresponding to the left lines in Fig. D2.

If the discharge satisfies all the above three criteria, self-induced unsteady flow with jump waves have to be expected. On pooled-steps with bottom angles higher than 25°, no jump waves are predicted. It may be concluded that hydraulic jumps occur if the Authors' model of 3.4° would be equipped with weirs of $w > 0.025$ m (for $q = 0.038$ m^2/s) and $w > 0.065$ m (for $q = 0.160$ m^2/s), respectively. Based on the semi-analytic approach, the Discussers predict jump waves on the Authors' model with endsills higher than 0.22 m on comparatively high discharges between 1.0 m^2/s $\leq q \leq$ 2.04 m^2/s.

Notation

d = flow depth (m)
d_2 = sequent depth of hydraulic jump (m)
d_c = critical flow depth (m): $d_c = (q^2/g)^{(1/3)}$
l_w = streamwise length of weir crest (m)
L_D = jet length (m)
l = step length (m)
h = step height (m)
l_B = inner basin length (m): $l_B = l - l_w$
q = discharge per unit width (m^2/s)
w = weir height (m)
θ = bottom angle of chute (°)

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Reply by the Authors

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The Authors acknowledge the pertinent discussion. To date, most studies on stepped spillways were conducted with flat horizontal steps in prismatic rectangular channels. The discussion provides insight into the hydraulics of stepped spillways with pooled steps.

The addition of end sills or end walls at the downstream step end modifies substantially the flow pattern. Chanson (1995, 2001) and Thorwarth (2008) discussed this aspect in particular. In a nappe flow regime, the presence of even a small end sill perturbs

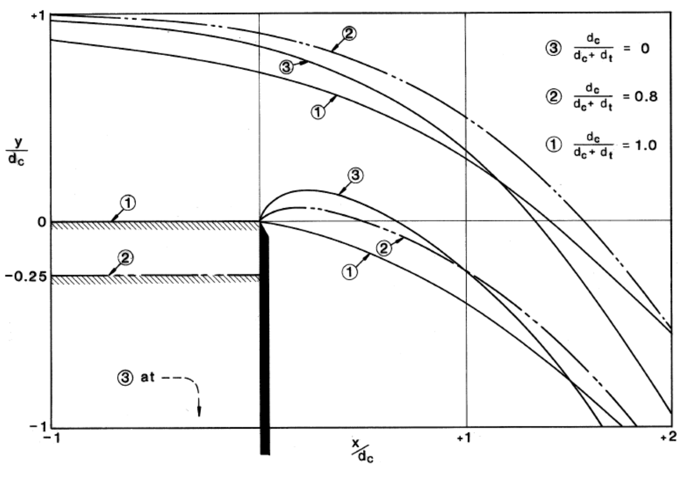

Figure R1 Effect of end sill on nappe trajectories: (1) flat horizontal step, (2) small end sill and (3) sharp-crested weir (after Rouse 1938) the flow characteristics considerably (Fig. R1). For medium discharges, the step pool may induce some flow instabilities, as observed at the Sorpe dam spillway (Germany) and at Gyrandra weir (Australia) (Chanson 2001). For large discharges, in the skimming flow regime, the step pool walls may enhance the rate of energy dissipation on the stepped chute, but the hydrodynamic loads on the walls can be significant and must be properly accounted for during the design. This may require solid physical modeling.

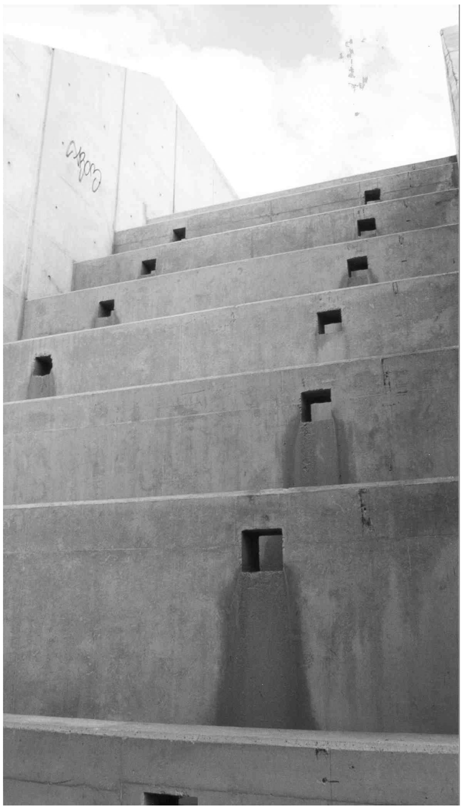

Figure R2 Stepped storm waterway next to railway bridge near Avignon (France) on 20th September 2000: Pooled steps ($w = 0.4$ m, $h = 0.7$ to 1 m), 45° slope — Note drainage holes (Courtesy Hubert Chanson)

Altogether, the discussion is a timely reminder of our limited expertise in stepped spillway hydrodynamics, especially for non-conventional designs like the pooled steps. Their design was common during the 19th and early 20th century (Schuyler 1909, Wegmann 1922, Schoklitsch 1937). Today the use of end sills and step pools remains a common technique to maximize the rate of energy dissipation over a short distance in small to medium-size structures. Figure R2 presents a step pool chute next to a railway embankment (on the left) and a major arterial road. The step pool design was selected to minimize the footprint of the chute and some 2 m high sidewalls were incorporated on all sides to prevent spray and splashing on the rails and road bitumen during the chute operation.

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