Prediction of the transition nappe/skimming flow on a stepped channel

Prédiction de la transition écoulement en nappe/ écoulement turbulent dans un canal en marches d'escalier

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ABSTRACT

On a stepped channel, two distinct flow regimes may occur : nappe flow for low discharges and flat slopes, and skimming flow for larger flow rates. A simple analytical method to predict the onset of skimming flow is presented. The method is based upon the change of momentum direction at the impact of the jet on the downstream step. The results of the analysis are compared with existing experimental data. The onset of skimming flow is expressed in terms of the initial Froude number and jet angle. The generalisation of the study results enables to predict the onset of skimming flow and hence the risk of jet deflection at the first upstream step.

RÉSUMÉ

Dans un canal en marches d'escalier, on distingue deux types de régimes : écoulement en nappe à faibles débits et faibles pentes, et écoulement extrèmement turbulent pour des débits plus importants. L'auteur présente une estimation analytique de la transition entre ces deux régimes. La méthode est basée sur l'analyse du changement de direction de la quantité de mouvement à l'impact sur la marche aval. Les résultats théoriques sont comparés avec des résultat expérimentaux. On exprime la transition entre les deux régimes en fonction du nombre de Froude et de l'angle du jet. La généralisation de cette étude permet de prédire les risques de déflection dans les premières marches d'un coursier en marches d'escalier.

Introduction

Stepped channels have been used for more than 2500 years but recently new construction materials (e.g. roller compacted concrete, strengthened gabions) have renewed interest in stepped chutes (CHANSON 1994). Stepped channels are commonly used as RCC dam spillways, for gabion weirs, river training, irrigation channels, storm waterways and debris dams (e.g. CHANSON 1995). Experimental investigations (e.g. SORENSEN 1985, PEYRAS et al. 1992) showed that stepped chute flows can be divided into two regimes: nappe flow for low discharges and skimming flow for higher discharges (Fig. 1). The nappe flow regime is defined as a succession of free-falling nappes. The flowing water bounces from one step to the next as a series of small free falls (Fig. 1(A)). In the skimming flow regime, the water flows down the chute as a coherent stream, skimming over the steps edges and cushioned by the recirculating vortices trapped between the main stream and the steps (Fig. 1(B)). For safety reasons, the flow conditions near the transition between nappe and skimming flow regime must be avoided (if possible). Transitory hydrodynamic fluctuations which occur as the flow oscillate between nappe and skimming flow regimes might induce improper or dangerous flow behaviour, and unnecessary vibration of the structure. CHANSON (1995)

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described two failure cases (i.e. the Arizona Canal dam in 1905 and the New Croton dam in 1955) during which the spills occurred with flow conditions near the transition between nappe and skimming flow. The flow behaviour induced additional fluctuating load and effort on the structures, and the resulting fatigue is presumed to have resulted in failures.

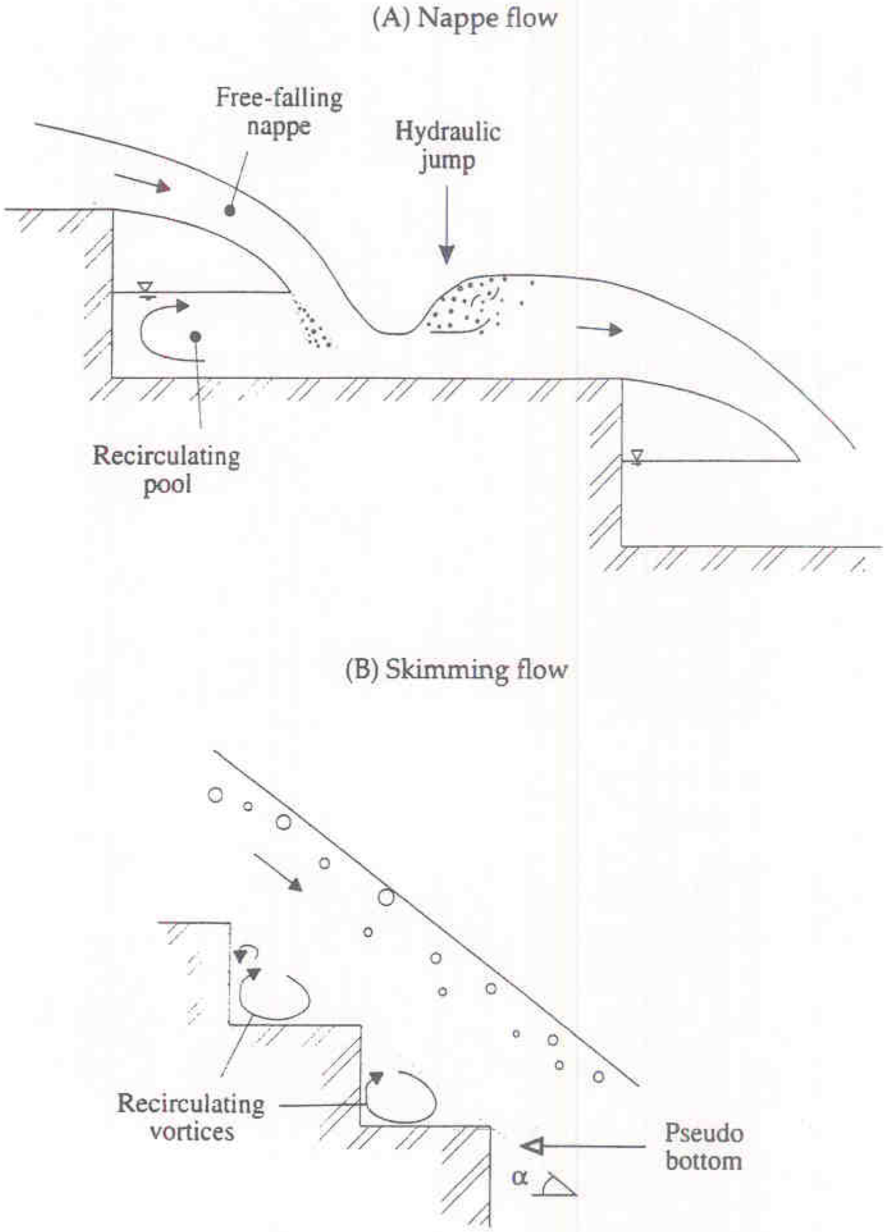

Fig. 1. Nappe flow and skimming flow on a stepped channel.

Onset of skimming flow

On a stepped chute with low discharge, the water flows as a succession of waterfalls (i.e. nappe flow regime). A sufficient increase in the discharge or chute slope will result in the onset of skimming flow[1]. The phenomenon is similar to the cavity filling of spillway aeration devices and ventilated cavities.

[1] The "*onset of skimming flow*" is defined by the disappearance of the cavity beneath the free-falling nappes, the water flowing as a quasi-homogeneous stream (CHANSON 1995)

For steady quasi-uniform flow in a rectangular prismatic channel, a recent study (CHANSON 1994) suggested that the skimming flow regime occurs for discharges larger than a critical value, "empirically correlated" by:

$$\frac{(d_c)_{onset}}{h} = 1.057 - 0.465 \cdot \frac{h}{1} \qquad \text{Onset condition (1)}$$

where h is the step height, l is the step length and $(d_c)_{onset}$ is the characteristic critical depth. The skimming flow regime occurs for $d_c > (d_c)_{onset}$, where d_c is the critical flow depth. Two points must be clarified with respect to equation (1): [A] it was deduced for slopes ranging from 11 to 52 degrees, and [B] it does not apply to non-uniform flows. E.g., at the upstream end of a stepped chute, the water could flow as thick free-falling nappes with an accelerating motion before entering the skimming flow regime.

A fundamental difference between nappe and skimming flows is the pressure distribution across the flow. In nappe flow, the free-falling nappes are gravitationless and the pressure gradient across the nappe is nearly zero (or negative in absence of ventilation). And in a skimming flow the pressure distribution is quasi-hydrostatic.

The transition between nappe and skimming flows implies a very-strong redistribution of the pressure field. The change of pressure distribution is associated with a change of streamline directions. In a skimming flow the streamlines are nearly parallel to the pseudo-bottom formed by the step edges. In a nappe flow, the streamlines follow a path "carved" by the step geometry.

In this paper, the onset of skimming flow is analysed. A simple analytical formulation is developed and compared with existing data. The method is later applied to the design of a stepped spillway crest.

Nappe calculations

Considering a nappe flow down a single-step structure (e.g. drop structure), the air cavity beneath the falling nappe will disappear when the circulating pool of water (beneath the jet) occupies the entire step cavity (Fig. 2). The recirculating pool of water is important as the associated pressure force provides a force parallel to the step surface which is required to change the jet direction from an angle θ_i to the horizontal.

For a ventilated nappe, the momentum equation resolved along the step surface is:

$$\frac{1}{2} \cdot \rho_w \cdot g \cdot d_p^2 - \frac{1}{2} \cdot \rho_w \cdot g \cdot d_1^2 = \rho_w \cdot q_w \cdot (V_1 - V_i \cdot \cos\theta_i) \qquad (2)$$

where the pool height d_p, the flow depth downstream of the jet impact d_1, the associated velocity V_1, the jet impact velocity V_i and the jet impact angle θ_i are defined on Figure 2, and ρ_w is the water density, g is the gravity constant and q_w is the discharge per unit width. Equation (2) assumes that the edges of the nappe have not disintegrated into spray, neglects the shear forces on the surfaces and assumes a hydrostatic pressure distribution at section 1 and at the vertical face of the step.

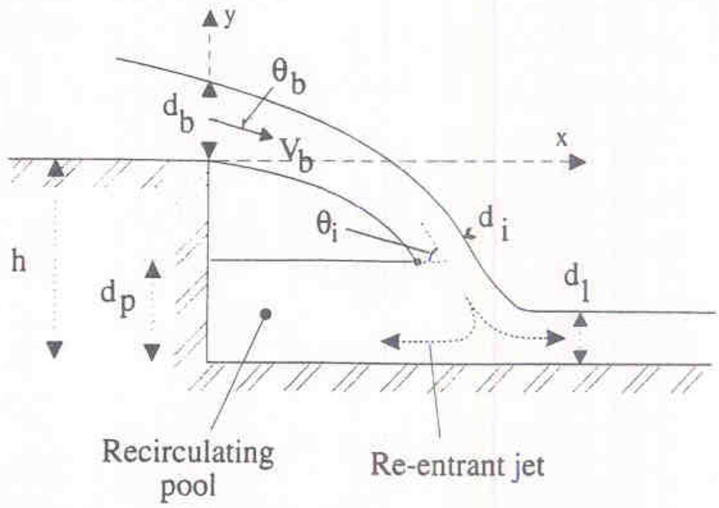

Fig. 2. Nappe flow trajectory at a drop structure.

The impact flow conditions can be deduced from simple trajectory calculations (CHANSON 1995):

$$\frac{d_i}{d_b} = \left(1 + \frac{1}{Fr_b^2}\right)^{-1/2} \tag{3}$$

$$\frac{V_i}{V_b} = \sqrt{1 + \frac{1}{Fr_b^2}} \tag{4}$$

$$\frac{\cos\theta_i}{\cos\theta_b} = \left(1 + \frac{1}{Fr_b^2}\right)^{-1/2} \tag{5}$$

where d_b is the flow depth at the step brink, V_b is the flow velocity at the brink, the initial angle of the streamlines with the horizontal is θ_b (Fig. 2), Fr_b is the Froude number at the step edge.
At the jet impact with the step, and assuming that the velocity entering the control volume is approximately the same as leaving it, the momentum equation (eq. (2)) yields:

$$\frac{d_p}{d_i} = \sqrt{1 + 2 \cdot \frac{V_i^2}{g \cdot d_i} \cdot (1 - \cos\theta_i)} \tag{6}$$

The disappearance of the air cavity occurs when the pool height equals the step height. It yields:

$$\frac{(d_c)_{onset}}{h} = \frac{Fr_b^{2/3} \cdot \sqrt{1 + \frac{1}{Fr_b^2}}}{\sqrt{1 + 2 \cdot Fr_b^2 \cdot \left(1 + \frac{1}{Fr_b^2}\right)^{3/2} \cdot \left(1 - \frac{\cos\theta_b}{\sqrt{1 + \frac{1}{Fr_b^2}}}\right)}} \tag{7}$$

Nappe flow occurs for $d_c < (d_c)_{onset}$

Table 1. Characteristics of experimental studies.

Ref. (1)	Slope (deg.) (2)	Scale (3)	Step height h (m) (4)	Nb of steps (5)	Discharge q_w (m^2/s) (6)	Remarks (7)
Standard studies						
ESSERY and HORNER (1978)	11 to 40		0.03 to 0.05	4 to 18		CIRIA tests.
SORENSEN (1985)	52.05	1/10	0.061	11	0.006 to 0.28	Monksville dam spillway model. W = 0.305 m. WES crest profile with smaller first steps.
BaCaRa (1991)	53.1	1/10	0.06	18	0.026 to 0.207	Creager crest profile with 5 smaller first steps. W=1.5 m.
BEITZ and LAWLESS (1992)	51.3 & 48.0	1/60	0.02	10	6E-4 to 0.093	Burton Gorge dam spillway model. Smooth crest with smaller first steps.
MONTES (1994)	36.8 & 45		0.03			Smooth crest with smaller first steps.
Gabion models						
STEPHENSON (1988)	18.4 to 45		0.15	1 to 4		Gabion stepped chute. W = 0.38 m.
PEYRAS et al. (1992)	18.4, 26.6, 45	1/5	0.20	3, 4, 5	0.04 to 0.27	Gabion stepped chute. W = 0.8 m.
KELLS (1995)	45	1/5		3		Gabion steps with impervious horizontal capping.

W = channel width

Predicting the onset of skimming flow

Equation (7) enables to predict the onset of cavity filling for various flow conditions and step geometries. Usually, once the water flows as a skimming stream, the angle of the streamlines with the horizontal equals the chute slope α. Replacing θ_b by α in equation (7), it is possible to compare equation (7) and experimental data on long prismatic channels.

Figure 3 presents equation (7) plotted as a function of the channel slope for several initial Froude numbers, assuming $\theta_b = \alpha$. Model data (Table 1) obtained with quasi-uniform flows are shown also. Figure 3 indicates that equation (7) predicts the same trend as the observations although it overestimates slightly but consistently the flow rate at which the air cavity fills. The differences can be accounted by considering the assumptions underlying the calculations and the various measurement errors. The largest differences are observed with gabion stepped models (KELLS 1995, PEYRAS et al. 1992, STEPHENSON 1988).

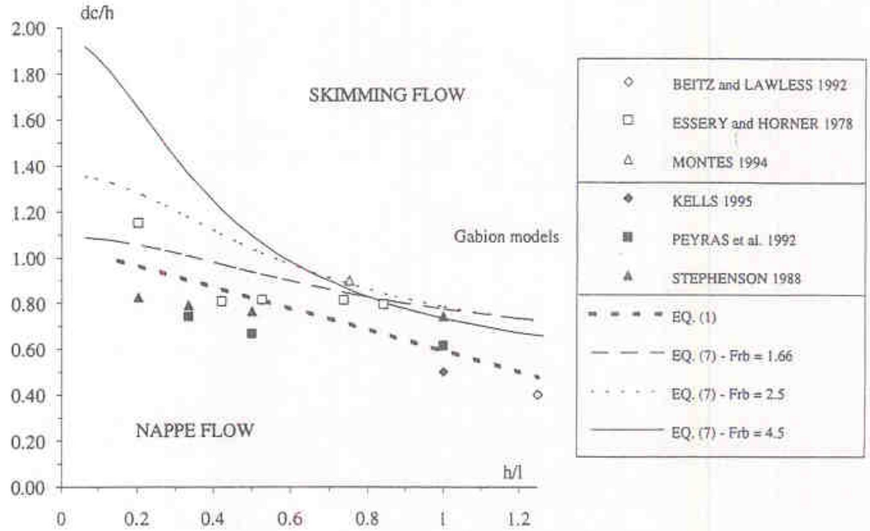

Fig. 3. Criterion for the onset of skimming flow on stepped channel assuming $\theta_b = \alpha$ Comparison with model data (Table 1) - Gabion model data are in black symbols.

A gabion[2] model is a stepped structure made of rockfill blocks enlaced in a wire mesh. Usually the step height equals one or twice the gabion height. With gabion models, it is recognised that the seepage flow (through the gabions) and the large skin friction of the gabion surface affects the flow characteristics at the jet impact and along the horizontal step face. These flow interactions might explain the larger differences with gabion model data.
Generally, equation (7) agrees reasonably well with the non-gabion stepped models and overestimates by 20 to 40% the onset of skimming flow on gabion stepped models.
Usually, the flow conditions near the transition between nappe and skimming flow must be avoided. Designers are advised to consider the accuracy of equation (7) as +/- 20%, and more for gabion structures.

Application to the crest design of stepped spillways

In the past, various shapes of spillway crest were used for the crest of stepped spillways. For concrete weirs, the ogee crest is usually fitted to a smooth profile such as a WES profile (Monksville dam, SORENSEN 1985) or a Creager profile (M'Bali dam, BINDO et al. 1993). With RCC dams a wide crest is preferred so that it can facilitate the truck traffic used in the supply of concrete and for the compacting process by rollers. In Queensland (Australia), some stepped diversion weirs have been designed with provision for an inflatable rubber dam. In such cases negative pressures on the crest must be avoided since they produce destabilising conditions for the inflatable dam. These designs require usually a relatively long flat crest, inclined upwards. Most gabion stepped weirs do not have a smooth crest but a flat crest followed directly by the first step.
The shape of the crest profile is very important with respect to achieving proper flow behaviour on the first steps. Several model observations showed the possibility of deflecting jets of water (i.e. nappe flow) at the first steps if the steps are too high, although the flows became skimming further downstream (e.g. SORENSEN 1985, BaCaRa 1991, BEITZ and LAWLESS 1992, BINDO et al. 1993).
Considering the first step edge downstream of a smooth crest, the flow properties at the brink (i.e. d_b, V_b) shown on figure 4(B) can be deduced from the Bernoulli equation if the smooth crest is short enough to neglect the effect of the developing boundary layer. To a first approximation, the angle θ_b can be estimated as the local channel slope.
The prediction of a correct filling of the first step cavity can be deduced from equation (7) (i.e. $d_c > (d_c)_{onset}$). If the first step cavity is completely filled, the pressure force of the vertical and horizontal faces of the step acting on the flow will counterbalance the hydrostatic pressure force of the main stream flow. The water will flow (i.e. skim) over the recirculating fluid without water deflection. But if the cavity below the jet is not filled (i.e. $d_c<(d_c)_{onset}$), the water leaving the step edge will drop as a free-fall jet and hit the horizontal face of the next step, with deflecting jets of waters which then might "by-pass" (i.e. skip over) the following step(s).
The writer applied equation (7) to the 1:10-scale model studies of SORENSEN (1985) and BaCaRa (1991). The models were fitted with a WES-profile and a Creager profile respectively. For a geometry including the smooth profile followed by a standard step height (h = 0.061 m and 0.06 m respectively), equation (7) predicts : 1- nappe flow and jet deflection at the first step for the lowest experimental discharges (q_w = 0.026 m^2/s and 0.05 m^2/s). And 2- a proper skimming flow behaviour is predicted for the geometries with smaller first steps. This result is in agreement with the experimental observations for both studies.

[2] A gabion consists of rockfill material enlaced by a basket or a mesh.

Figure 4 summarises the conditions for the onset of skimming flow (and the risks of deflecting jets) as a function of the Froude number and jet angle at the first brink. The results suggest that, for a given discharge, the risk of water deflection at the first step can be reduced by lowering the first step height (and increasing locally d_c/h), by placing the first step as upstream as possible (to reduce the upstream Froude number) and possibly by changing the profile curvature near the first step (to modify the initial jet angle θ_b). These simple conclusions are in complete agreement with the experimental observations of BaCaRa (1991) and other researchers. Equation (7) and Figure (4) provide in addition a simple tool to predict the occurrence of jet deflection at the first steps when a skimming flow regime is required.

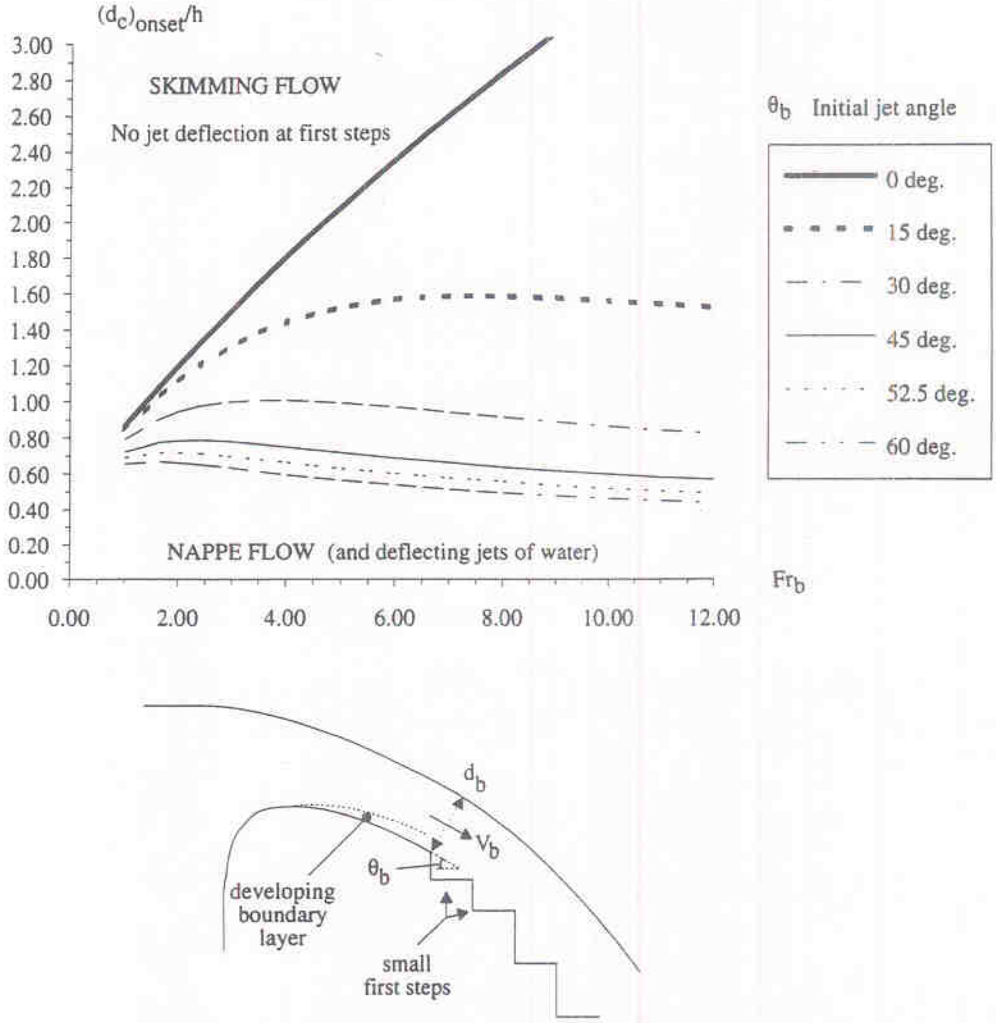

Fig. 4. Onset of skimming flow as a function of the initial Froude number Fr_b and initial jet angle θ_b.

Conclusion

Two distinct flow regimes may occur on a stepped chute : nappe and skimming flow. The transition between the two regimes is analysed to predict the flow conditions for the filling of the recirculating cavity (i.e. the onset of skimming flow). The study provides an analytical expression for predicting the onset of skimming flow as a function of the flow properties at the brink of the step. For quasi-uniform flows, the numerical results are very close to experimental observations, although they underestimate consistently the flow rate at the onset of skimming flow for gabion models. Note that equation (7) is a simple analytical prediction for the onset of skimming flow. It was verified with model data (Fig. 3) and it is believed that it is valid also on prototype.

The results of the analysis can be applied also to the design of the first step. For skimming flow, deflecting jets of water (i.e. nappe flow) must be avoided at the first steps. Figure 4 provides some quantitative information to select the height of the first steps. General guidelines for improved performances include reducing the height of the first step, introducing the first step as far upstream as possible and, possibly, optimising the ogee profile shape upstream of the stepped chute.

It must be emphasised that equation (7) is developed for horizontal flat steps. It does not apply to pooled steps nor to complex step geometries.

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Notations

The following symbols are used in this paper:

d	flow depth (m) measured normal to the channel bottom;
d_c	critical depth (m) – for a rectangular channel: $d_c = \sqrt[3]{q_w / g}$;
$(d_c)_{onset}$	critical depth (m) characterising the onset of skimming flow;
d_p	height (m) of the recirculating pool behind the nappe;
Fr	Froude number: $Fr = V / \sqrt{g \cdot d}$;
g	gravity constant (m/s^2);
h	height of steps (m);
l	step length (m);
q	discharge per unit width (m^2/s);
V	velocity (m/s);
α	channel slope;
θ	angle between the streamlines and the horizontal;
ρ	density (kg/m^3);

Subscript

b	flow conditions at the brink of the step;
i	flow conditions at the impact of the nappe with the recirculating pool of water;
w	water flow;
1	flow conditions downstream of the jet impact.

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