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Discussion of "Flow Characteristics of Skimming Flows in Stepped Channels" by I. Ohtsu, Y. Yasuda, and M. Takahashi

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The discussers congratulate the authors for their systematic study of skimming flows on stepped channels with different slopes and step heights. Their experimental data provide a solid database that might lead to better and improved design criteria. Important outcomes include some estimate of the friction factors for skimming flows and a design flowchart for stepped canals. Despite these outstanding results, the discussers would like to comment constructively on further design criteria for skimming flows and to provide additional flow-resistance results and a discussion on the physical processes.

The authors proposed a chart for the design of stepped chutes that can be applied to a wide range of channel slopes ($5.7° \leqslant \theta \leqslant 55°$) and step heights ($0.1 < S/d_c \leqslant (S/d_c)_s$), where $(S/d_c)_s$ represents the upper limit for skimming flow regime in terms of relative step height. For larger values, the flow will be a transition flow regime. However hydraulic designers must also consider a minimum value of S/d_c, below which the steps no longer act as large roughness. A detailed review of large roughness flows demonstrated that the flow resistance decreases with decreasing relative roughness height (Chanson 1995, pp. 92–96). When the relative step height is small, the roughness of the steps becomes negligible and the flow resistance is drastically reduced. A reanalysis of experimental data on rockfill chutes and large roughness elements suggests a lower limit for the relative step height:

$$\frac{S}{d_c} > \frac{1}{15 \cdot \cos\theta} \tag{1}$$

Further, fully developed flow conditions must be achieved before the downstream end of the stepped chute. An ideal fluid flow region ("potential core") is not acceptable, because of its high kinetic energy. This yields a further design criterion in terms of chute length L and channel slope θ:

$$\frac{S}{d_c} > \frac{1}{0.1193 \cdot \cos\theta \cdot (\sin\theta)^{0.259} \cdot \left(\dfrac{L}{S \cdot \cos\theta}\right)^{0.935}} \tag{2}$$

These criteria [Eqs. (1) and (2)] must be added to the design flowchart proposed by the authors. Basically skimming flows must be fully developed before the downstream end of the chute, and the step roughness must be large enough to generate significant form drag (Chanson 2001).

In terms of flow resistance, the authors presented friction factor data for a wide range of slopes ($5.7 \leqslant \theta \leqslant 55°$) and discharges ($0.1 < S/d_c \leqslant 1.2$), implying maximum flow resistance for slopes around 19°. The discussers performed further experimental measurements in skimming and transition flows in three large-size stepped chutes ($\theta = 3.4$, 16, and 22°) with large step heights ($0.05 \leqslant S \leqslant 0.143$ m) operating at large Reynolds numbers (Table 1). Air-water flow properties were recorded systematically at step edges and between step edges using single-tip and double-tip conductivity probes (Chanson and Toombes 2002a,b; Gonzalez and Chanson 2004). On one chute ($\theta = 16°$), two step heights were tested to assess the dynamic similarity of a geometrically scaled stepped chute based on a Froude similitude with undistorted scale. The geometric scaling ratio was 2:1. Table 1 summarizes the investigated flow conditions. Most skimming flow conditions coincided with the Type A subregime. Transition flow conditions are included for completeness. On the basis of measured air-water flow distributions, equivalent friction factors were estimated as

$$f_e = \frac{8 \cdot g}{q_w^2} \cdot \left(\int_{y=0}^{y=y_{0.9}} (1 - C)\,dy\right)^3 \cdot S_f \tag{3}$$

where f_e=equivalent Darcy friction factor for air water flow; C=local void fraction; y=flow depth measured normal to the pseudoinvert; $y_{0.9}$=depth at $C=0.90$; g=gravity acceleration; q_w=water discharge per unit width; and S_f=friction slope. Experimental results are presented in terms of f_e as a function of S/d_c in Fig. 1. In transition flows [Fig. 1(a)], the flow resistance estimates were on average, larger than those observed in skimming flows [Fig. 1(b)]. Maximum friction factors in transition flow occurred for the 16° slope, but the data scatter does not permit any definite conclusion. In skimming flows, present data were consistent with the reanalysis of prototype and laboratory data by Chanson et al. (2002c) and with the authors' data. The present data set showed

Table 1. Experimental Conditions for Detailed Air-Water Flow Measurements at University of Queensland [Sources: Chanson and Toombes (2002a,b); Gonzalez and Chanson (2004)]

Slope, θ (degree)	Step height, S (m)	Discharge, q_w (m^2/s)	S/d_c	Reynolds number	$d\cdot \sin\theta/S$ skimming flow only	Remarks
3.4	0.143	0.038 to 0.163	1.0 to 2.7	1.5 to 6.5E+5	—	$B=0.5$ m
	0.0715	0.08 to 0.150	0.54 to 0.82	3.2 to 6E+5	0.04	
15.9	0.1000	0.05 to 0.26	0.52 to 1.58	2E+5 to 1.1E+6	0.13 to 0.14	$B=1.0$ m
	0.0500	0.02 to 0.20	0.31 to 1.45	8E+4 to 8E+5	0.16 to 0.29	
21.8	0.1000	0.04 to 0.182	0.66 to 1.83	1.6 to 7.3E+5	0.13 to 0.22	B=1.0 m

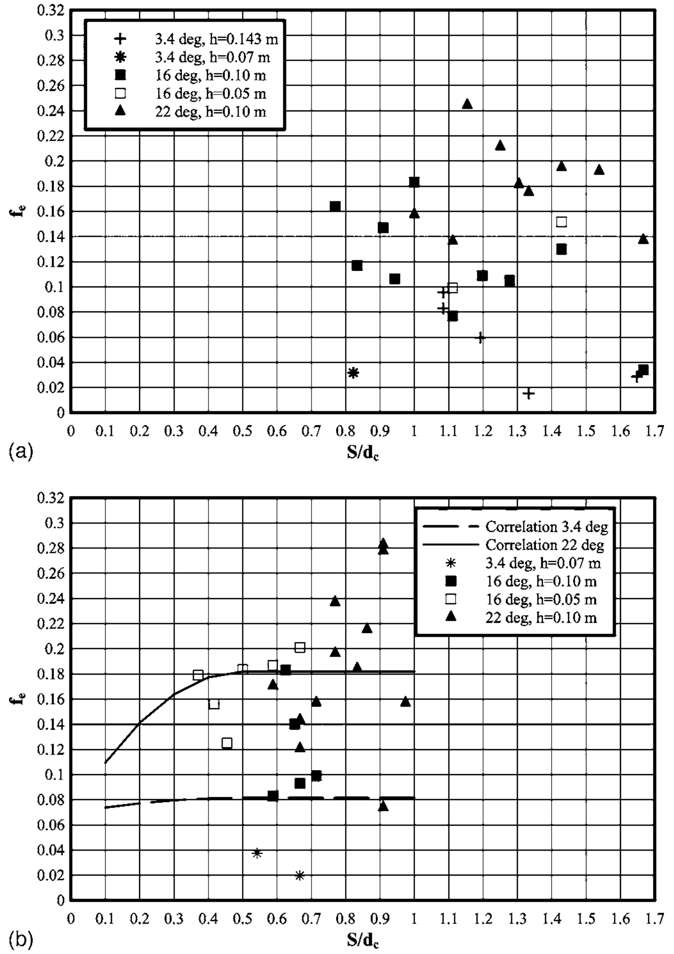

Fig. 1. Equivalent Darcy friction factors in moderate slope stepped chute: (a) Transition flow data; (b) Skimming flow data—comparison with author's correlation [Eq. (12)]

an increase in flow resistance with increasing bed slope for $3.4 \leq \theta \leq 22°$ [Fig. 1(b)], as observed by Ohtsu and Yasuda (1997). On the 16° chute, present friction factor data yielded, on average, $f_e = 0.18$ for $h = 0.05$ m, but $f_e = 0.12$ for $h = 0.10$ m, possibly suggesting some form of scale effects for the smallest geometry ($h = 0.05$ m).

In skimming flows, what are the physical mechanisms leading to maximum flow resistance for chute slopes around 19° (authors' data) to 22° (present data)? On smooth-invert chutes, flow resistance is predominantly skin friction, but it is a form drag process in skimming flows. At each step, the cavity flow is driven by the developing shear layer and the transfer of momentum across it (Fig. 2). For the main stream, the equivalent boundary shear stress equals the maximum shear stress $\tau_{\max}$ in the shear layer. The dimensionless pseudoboundary shear stress may be averaged along the step cavity and expressed in terms of a Darcy-Weisbach friction factor:

$$f = \frac{\sin\theta}{S} \cdot \int_{x=0}^{S/\sin\theta} \frac{8 \cdot \tau_{\max}}{\rho \cdot V^2} \cdot dx \tag{4}$$

where V=free-stream velocity. Eq. (4) represents the average dimensionless shear stress between cavity flow and the main stream. Gonzalez and Chanson (2004) demonstrated that flow resistance was reasonably well approximated by the integration of Eq. (4) along step cavities. In skimming flows, energy dissipation mechanisms include cavity recirculation, momentum exchange with the free stream, and interactions between free-surface and mainstream turbulence, whereas interactions between the mixing layer and horizontal step face, and skin friction at the step downstream end may contribute to further energy dissipation on moderate slopes (Fig. 2). At each step edge, highly coherent small-scale vortices are formed abruptly at the step corner because of the large gradient of vorticity at the corner. The initial region of the mixing layer is dominated by a train of sequential small-scale vortices that eventually pair to form large-scale vortical structures that are advected downstream. It is argued that the distance from the step edge to the impingement of the shear layer onto the step face is an important length, because some feedback might occur nearly instantaneously from the impingement to the singularity region of the shear layer in the vicinity of the step edge (e.g., Lin and Rockwell 2001). Experimental studies of turbulent flows past two-dimensional cavities showed that cavity resonance is primarily a function of the ratio of the boundary layer thickness to cavity length: i.e., $d \cdot \sin\theta/S$ for a stepped chute, where d=equivalent clear-water depth. The discussers hypothesize that some maximum in flow resistance must be related to some kind of flow instability. The three-dimensional nature of recirculating vortices is believed to play a role to further the rate of energy dissipation (André et al. 2004; Chanson and Gonzalez 2004). The discussers demonstrated quantitatively the means to enhance the flow resistance with turbulence manipulation (Chanson and Gonzalez 2004). Further present findings suggest that experimental observations of flow resistance may experience scale effects even on large-size facilities. Extrapolation to prototypes of flow resistance data collected in small-size models should be avoided.

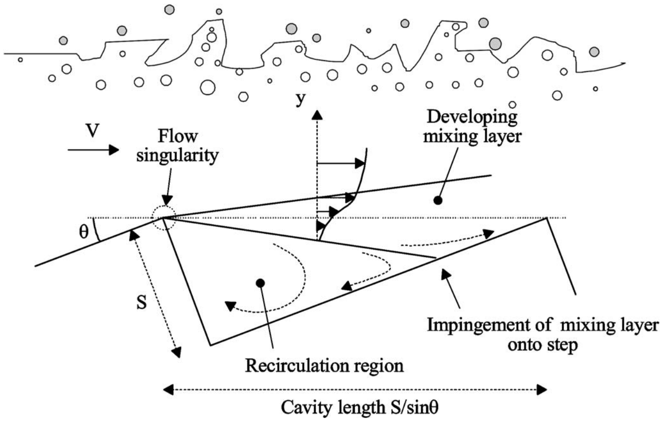

Fig. 2. Schematic of shear flow and cavity recirculation in skimming flow on moderate slope stepped chute

In summary, the discussers congratulate the authors for their authoritative data set. They hope that the present discussion will contribute to safer stepped chute design. The discussers would like to point out that the energy dissipation performances of stepped canals with moderate slopes are far from being totally understood and that further experimental research is needed.

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The writers are to be congratulated for systematically investigating skimming flow characteristics. Skimming flow regime is generally considered in the design of stepped spillways. The concept of classifying the skimming flow regime into two types—i.e., Type A and Type B—and providing an equation for their delineation is very interesting and commendable.

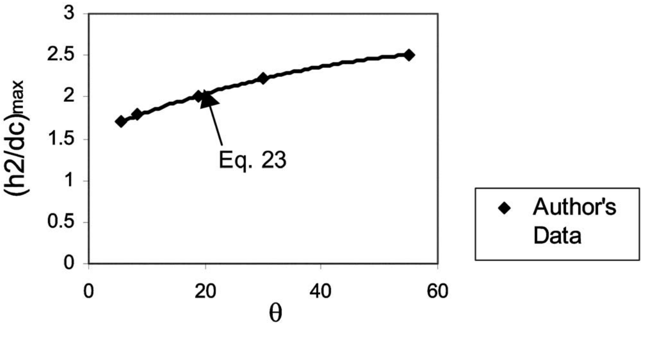

Fig. 1. Relationship between $(h_2/d_c)_{\max}$ and θ

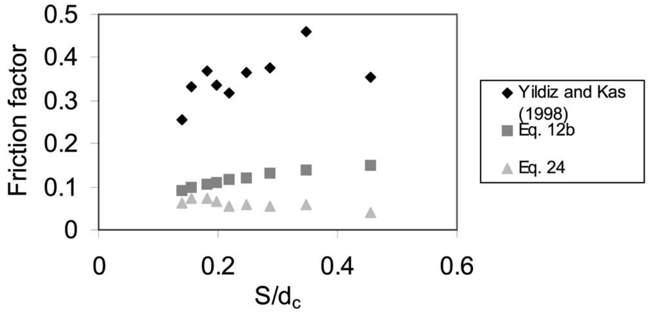

Fig. 2. Friction factor

The writers have given a detailed procedure for the design of stepped spillways, including the procedure for determining step height. The discussers are of the opinion that a criterion for deciding whether the provision of steps on the spillway will be economical for the available data in terms of dam height, discharge per unit length of spillway, and slope of downstream face is required before working the detailed design of steps. Further, Eq. (15) and Eq. (16) are applicable for $H_{\mathrm{dam}}/d_c \geqslant 5.0$; and as shown in Fig. 11, energy loss in skimming flow for lower values of H_{dam}/d_c is less. Therefore, provision of steps on a spillway may not be beneficial for low-height dams and for larger q_w. In India, many of the dams (Upper Wardha Dam, Arunavati Dam, and Bembla Dam in Maharashtra State) have values of $H_{\mathrm{dam}}/d_c \leqslant 5.0$. The writers are requested to comment on this.

The discussers (Tatewar and Ingle 2000) have developed a criterion for determining step height on the basis of adopting a value of the Froude number at the toe of the spillway such that the length of the required stilling basin is a minimum.

As stated by the writers, in the quasi-uniform region, the end depth of jump h_2/d_c becomes maximum and then remains constant for larger values of h_{dam}/d_c for given values of S/d_c and θ (Fig. 4). The discussers studied the variation of these maximum values of h_2/d_c with respect to θ and established the relation between $(h_2/d_c)_{\max}$ and θ, as shown in Fig. 1 and given by Eq. (1):

$$(h_2/d_c)_{\max} = -0.0002\theta^2 + 0.0278\theta + 1.5583 \tag{1}$$

(θ in degree, $R^2=0.998$).

The writers have given equations for calculating the friction factor f, for skimming flow. These equations are very useful for estimating energy loss over a stepped channel. To study the effect of air entrainment on the friction factor, the friction factor estimated from Eq. (12) is compared with the friction factor of air-entrained skimming flow estimated for the experimental data of Yildiz and Kas (1998). The values of the friction factor (f_b) that are based on the depth of air-entrained flow show much higher values. As suggested by Matos (1997), the correction as given by Eq. (2) is applied for the friction factor (f_b) to predict the friction factor (f) that is based on clear water depth of flow:

$$f/f_b = (1 - C_{\mathrm{mean}})^3 \tag{2}$$

The corrected values of the friction factor show good agreement with Eq. (12) (Fig. 2).