Discussion of "Hydraulic Design of Stepped Spillways" by Robert M. Boes and Willi H. Hager

September 2003, Vol. 129, No. 9, pp. 671–679.
DOI: 10.1061/(ASCE)0733-9429(2003)129:9(671)

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In skimming flows down stepped chutes, Chanson et al. (2002) presented a comprehensive reanalysis of flow resistance based upon more than 38 model studies and 4 prototype investigations totaling more than 700 data points with channel slopes ranging from 5.7° up to 55°. Different research facilities yielded different results and researchers continue to disagree on the reasons for these differences (Chanson 2000). The authors highlighted nicely the difficulties to estimate flow resistance on stepped chutes, although it is a key design parameter. Here the discusser argues that differences in flow resistance data may be linked to different inflow conditions. A careful reanalysis of large-size experimental results suggests that lower flow resistance was observed in experimental facilities with pressurised intake.

Skimming flows are characterized by significant form losses. Observations highlighted strong interactions between the main stream turbulence, the step cavity recirculation zones, and the free-surface (Chanson and Toombes 2002a; Yasuda and Chanson 2003). Flow resistance data for large-size model data ($s > 0.020$ m, $R > 1E+5$) are presented in Fig. 1 in terms of the equivalent Darcy friction factor f, where s is the step height, ϕ is the angle between the pseudobottom formed by the step edges and the horizontal, and R is the flow Reynolds number defined in terms of the hydraulic diameter D_H. Details of each study are summarized in Table 1. Fig. 1 presents 179 data. For steep chutes ($\phi > 15°$), the friction factor data presented no obvious correlation with the relative step roughness height $s*\cos\phi/D_H$. Reynolds, Froude, nor Weber numbers (Chanson et al. 2002). They compared favorably, however, with a simplified analytical model of the pseudoboundary shear stress that may be expressed, in dimensionless form, as

$$f_d = \frac{2}{\sqrt{\pi}} * \frac{1}{\xi} \tag{1}$$

where f_d=equivalent Darcy friction factor estimate of the form drag; $1/\xi$=dimensionless expansion rate of the shear layer. Eq. (1) predicts $f_d \approx 0.2$ for $\xi = 6$, which is close to observed friction factors (Fig. 1). However, skimming flow resistance data appeared to be distributed around three dominant values: $f \approx 0.105$, 0.17, and 0.30 as shown in Fig. 2. Fig. 2 presents the probability distribution function of Darcy friction factor where the histogram columns represent the number of data with friction factors within the interval: e.g., the probability of friction factors from 0.18 to 0.20 is represented by the column labeled 0.18. The intervals were selected with a constant logarithmic increment. The first and last columns indicate the number of data with friction factors less than 0.08 and greater than 1.0, respectively.

The discusser hypothesizes that flow resistance in skimming flows is not an unique function of flow rate and stepped chute geometry, and that there is some analogy with form drag behind bluff bodies. For the flow behind a cylinder, the drag coefficient is known to be a function of the upstream turbulence affecting the boundary layer separation for a given Reynolds number. (For infinitely long smooth cylinders, the effect is best observed for Reynolds numbers about 1 $E+5$ to 1 $E+6$.) For ventilated cavities behind wedges and wings, several regimes were associated with different drag coefficients for the same inflow conditions, depending upon the amount of ventilation (Silberman and Song 1961;

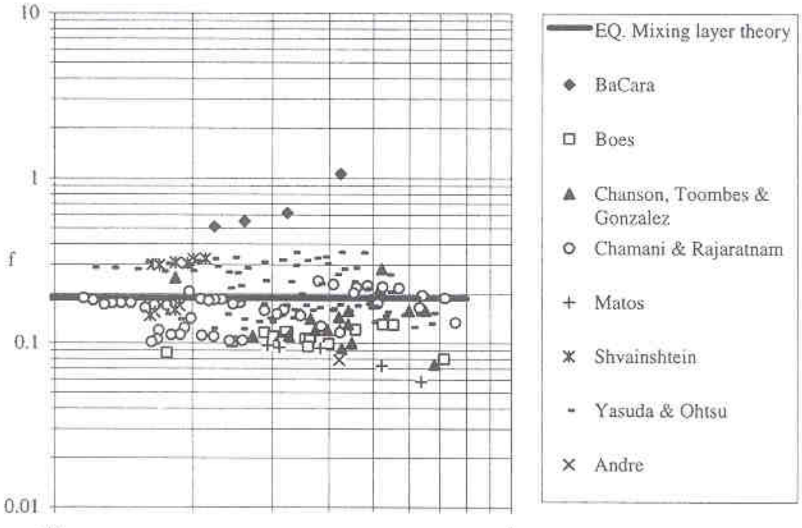

Fig. 1. Darcy friction factor of skimming flows on stepped chute {179 data}

Table 1. Reanalyzed Experimental Data of Flow Resistance

Legend	Reference	Flow conditions	Remarks
Andre	Andre et al. (2003)	$\phi=30^\circ$, $s=0.06$ m, b=0.5 m	Air–water flow measurements. Pressurized intake inflow.
BaCaRa	BaCaRa (1991)	$\phi=53.1^\circ$, $s=0.06$ m, $b=1.5$ m $\phi=53.1^\circ$, $s=0.024$ m $\phi=59^\circ$, $s=0.024$ m $\phi=63.4^\circ$, $s=0.024$ m	Clear-water (nonaerated) flow. Uncontrolled ogee inflow with small steps in ogee development.
Boes	Boes (2000)	$\phi=30^\circ$, $s=0.046$, 0.092 m, $b=0.5$ m $\phi=50^\circ$, $s=0.031$, 0.093 m, $b=0.5$ m	Air–water flow measurements. Pressurized intake inflow.
Chamani and Rajaratnam	Chamani and Rajaratnam (1999)	$\phi=51.3^\circ$, $s=0.313$, 0.125 m, $b=0.3$ m $\phi=59^\circ$, $s=0.313$ to 0.125 m, $b=0.3$ m	Air–water flow measurements. Uncontrolled smooth ogee crest inflow.
Chanson, Toombes, and Gonzalez	Chanson and Toombes (2001)	$\phi=21.8^\circ$, $s=0.10$ m, $b=1$ m	Air–water flow measurements. Uncontrolled broad-crested weir inflow.
	Gonzalez and Chanson (2004)	$\phi=15.9^\circ$, $s=0.05$ and 0.10 m, $b=1$ m	Air–water flow measurements. Uncontrolled broad-crested weir inflow.
Matos	Matos (2000)	$\phi=53.1^\circ$, $s=0.08$ m, $b=1.0$ m	Air–water flow measurements. Uncontrolled smooth ogee crest inflow.
Shvainshtein	Shvajnshtejn (1999)	$\phi=38.7^\circ$, $s=0.05$ m, $b=0.48$ m $\phi=51.3^\circ$, $s=0.0625$ m, $b=0.48$ m	Clear-water (nonaerated) flow. Uncontrolled smooth ogee crest inflow.
Toombes and Chanson	Toombes and Chanson (2000)	$\phi=3.4^\circ$, $s=0.143$ m, $b=0.25$ and 0.5 m	Air–water flow measurements. Pressurized intake inflow.
	Chanson and Toombes (2002b)	$\phi=3.4^\circ$, $s=0.0715$ m, $b=0.5$ m	Air–water flow measurements. Pressurized intake inflow.
Yasuda and Ohtsu	Ohtsu et al. (2000)	$\phi=55^\circ$, $s=0.025$ m, $b=0.4$ m	Air–water flow measurements. Uncontrolled broad-crested weir inflow.
	Yasuda and Ohtsu (1999)	$\phi=5.7^\circ$, $s=0.006$ to 0.010 m, $b=0.4$ m $\phi=11.3^\circ$, $s=0.006$ to 0.10 m, $b=0.4$ m $\phi=19^\circ$, $s=0.002$ to 0.08 m, $b=0.4$ m $\phi=30^\circ$, $s=0.004$ to 0.07 m, $b=0.4$ m $\phi=55^\circ$, $s=0.003$ to 0.064 m, $b=0.4$ m	Measurements in downstream stiling basin. Uncontrolled broad-crested weir inflow.

Note: ϕ=bed slope; s=step height; and b=channel width.

Uncontrolled broad-crest	Yasuda & Ohtsu, Chanson, Toombes & Gonzalez
Uncontrolled smooth ogee crest	Chamani & Rajaratnam
Uncontrolled ogee crest, with small first steps in ogee development	BaCaRa, Shvainshtein, Matos
Pressurised intake	Andre, Boes

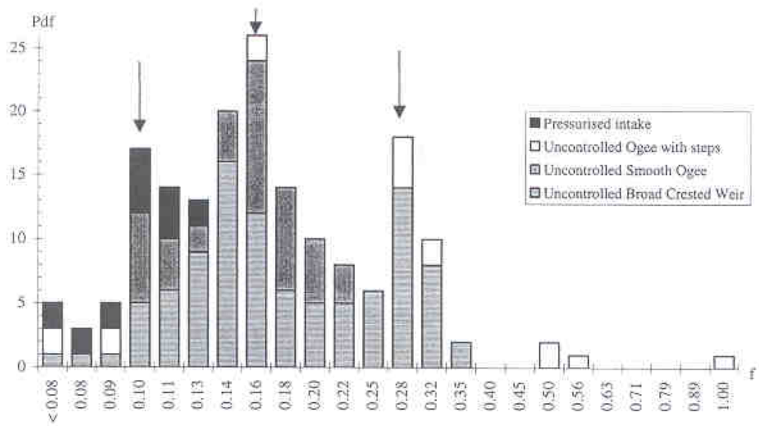

Fig. 2. Probability distribution function of chute friction factor (179 data)

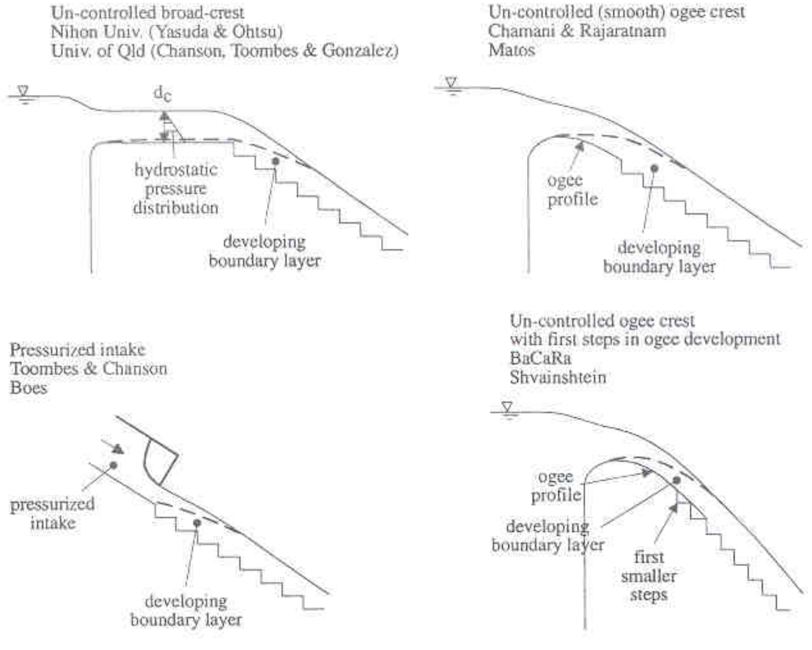

Fig. 3. Sketch of inflow conditions of stepped chutes

Laali and Michel 1984; Michel 1984; Verron and Michel 1984). On stepped chutes, it is proposed that the form drag process may present several modes of excitation that are functions of the inflow conditions. At each step edge, shear instabilities may generate different cavity wake regimes, associated with different drag coefficients. In Fig. 2, the dominant values $f \approx 0.105$, 0.17, and 0.30 would correspond to three dominant modes (or regimes) of excitation induced by different inflow conditions (Fig. 3). Fig. 3 illustrates basic inflow configurations. With an uncontrolled ogee profile, the pressure distribution is atmospheric in the entire flow at design flow conditions by definition of the ogee development (Henderson 1966; Chanson 1999). With an uncontrolled broad-crest, the pressure is hydrostatic at the crest. For a pressurised intake, the inflow pressure distribution is greater than hydrostatic.

Fig. 2 shows that experiments with pressurized intake yielded consistently lower flow resistance than for uncontrolled inflow conditions. For example, the reanalysis of data from Boes (2000) and Andre et al. (2003) gives $f \sim 0.1$, which is about three times smaller than the third dominant value ($f=0.30$, Fig. 2). Similarly, skimming flow experiments by Chanson and Toombes (2002b) down a flat slope ($\phi=3.4°$, $s=0.07$ m) with pressurized intake yielded friction factors three times smaller than data of Yasuda and Ohtsu (1999) on a 5.7° stepped slope with uncontrolled broad-crest.

Overall flow resistance data ranged typically between 0.1 and 0.3 (Figs. 1 and 2), although the friction factor is affected by the inflow conditions and by the rate of air entrainment. The drag reduction process was well-documented in smooth chutes (Chanson 1994), and it was recently demonstrated on stepped chutes (Chanson 1993, 2004).

ACKNOWLEDGMENTS

The discusser thanks Professor C. J. Apelt (University of Queensland) for helpful discussions.

References

Andre, S., Manso, P. A., Schleiss, A., and Boillat, J. L. (2003). "Hydraulic and stability criteria for the rehabilitation of appurtenant spillway structures by alternative macro-roughness concrete linings." *Proc., 21st ICOLD Congress, Montreal, Canada, Q. 82, R. 6*, 63–93.

BaCaRa. (1991). "Etude de la dissipation d'energie sur les evacuateurs à marches [Study of the energy dissipation on stepped spillways]." *Rapport d'Essais*, Projet National BaCaRa, CEMAGREF-SCP, Aix-en-Provence, France (in French).

Boes, R. M. (2000). "Zweiphasenstroömung und Energieumsetzung auf Grosskaskaden." PhD thesis, VAW-ETH, Zürich, Switzerland.

Chamani, M. R., and Rajaratnam, N. (1999). "Characteristics of skimming flow over stepped spillways." *J. Hydraul. Eng.* 125(4), 361–368.

Chanson, H. (1993). "Stepped spillway flows and air entrainment." *Can. J. Civ. Eng.*, 20(3), 422–435.

Chanson, H. (1994). "Drag reduction in open channel flow by aeration and suspended load." *J. Hydraul. Res.*, IAHR, 32(1), 87–101.

Chanson, H. (1999). *The hydraulics of open channel flows: An introduction*, Butterworth-Heinemann, London.

Chanson, H. (2000). "Hydraulics of stepped spillways: Current status." *J. Hydraul. Eng.* 126(9), 636–637.

Chanson, H. (2004). "Drag reduction in skimming flow on stepped spillways by aeration." *J. Hydraul. Res.*, IAHR, 42(3), 316–322.

Chanson, H., and Toombes, L. (2001). "Experimental investigations of air entrainment in transition and skimming flows down a stepped chute: Application to embankment overflow stepped spillways." *Research Report No. CE158*, Dept. of Civil Engineering, Univ. of Queensland, Brisbane, Australia.

Chanson, H., and Toombes, L. (2002a). "Air-water flows down stepped chutes: Turbulence and flow structure observations." *Int. J. Multiphase Flow* 27(11), 1737–1761.

Chanson, H., and Toombes, L. (2002b). "Energy dissipation and air entrainment in a stepped storm waterway: Experimental study." *J. Irrig. Drain. Eng.* 128(5), 305–315.

Chanson, H., Yasuda, Y., and Ohtsu, I. (2002). "Flow resistance in skimming flows and its modelling." *Can. J. Civ. Eng.* 29(6), 809–819.

Gonzalez, C. A., and Chanson, H. (2004). "Interactions between cavity flow and main stream skimming flows: An experimental study." *Can. J. Civ. Eng.* 31(1), 33-44.

Henderson, F. M. (1966). *Open channel flow*, MacMillan, New York.

Laali, A. R., and Michel, J. M. (1984). "Air entrainment in ventilated cavities: Case of the fully developed 'half cavity'." *J. Fluids Eng., Trans ASME*, Sept., 106, 327–335.

Matos, J. (2000). "Hydraulic design of stepped spillways over RCC dams." *Intl Workshop on Hydraulics of Stepped Spillways*, Zürich, Switzerland, H. E. Minor and W. H. Hager, eds., Balkema, Rotterdam, The Netherlands, 187–194.

Michel, J. M. (1984). "Some features of water flows with ventilated cavities." *J. Fluids Eng., Trans ASME*, Sept., 106, 319–326.

Ohtsu, I, Yasuda, Y., and Takahashi, M. (2000). "Characteristics of skimming flow over stepped spillways." *J. Hydraul. Eng.*, 126(11), 869–871.

Shvajnshtejn, A. M. (1999). "Stepped spillways and energy dissipation." *Gidrotekh. Stroit.*, 5, 15–21 (in Russian).

Silberman, E., and Song, C. S. (1961). "Instability of ventilated cavities." *J. Ship Res.*, 5(1), 13–33.

Toombes, L., and Chanson, H. (2000). "Air-water flow and gas transfer at aeration cascades: A comparative study of smooth and stepped chutes." *Int. Workshop on Hydraulics of Stepped Spillways*, Zürich, Switzerland, Balkema, Rotterdam, The Netherlands, 77–84.

Verron, J., and Michel, J. M. (1984). "Base-vented hydrofoils of finite span under a free surface: An experimental investigation." *J. Ship Res.*, 28(2), 90–106.

Yasuda, Y., and Chanson, H. (2003). "Micro- and macroscopic study of two-phase flow on a stepped chute." *Proc., 30th IAHR Biennial Congress*, Thessaloniki, Greece, J. Ganoulis and P. Prinos, eds., vol. D, 695–702.

Yasuda, Y., and Ohtsu, I. (1999). "Flow resistance of skimming flow in stepped channels." *Proc., 28th IAHR Congress*, Graz, Austria, session B14, (CD-ROM).

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September 2003, Vol. 129, No. 9, pp. 671–679.
DOI: 10.1061/(ASCE)0733-9429(2003)129:9(671)

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The authors are to be complimented for presenting extensive experimental data on characteristics of aerated skimming flow over stepped spillways along with hydraulic design aspects of stepped spillways. The authors have focused their attention on various aspects, including onset of skimming flow, aeration characteristics, residual energy, and training wall design.

Considering the applicability of the design guidelines, the discussers would like to know the height of stepped spillway in the experimental setup for all 3 cases. Further, the authors may clarify regarding the limiting height of prototype stepped spillways up to which the design guidelines presented in this paper could be applied.

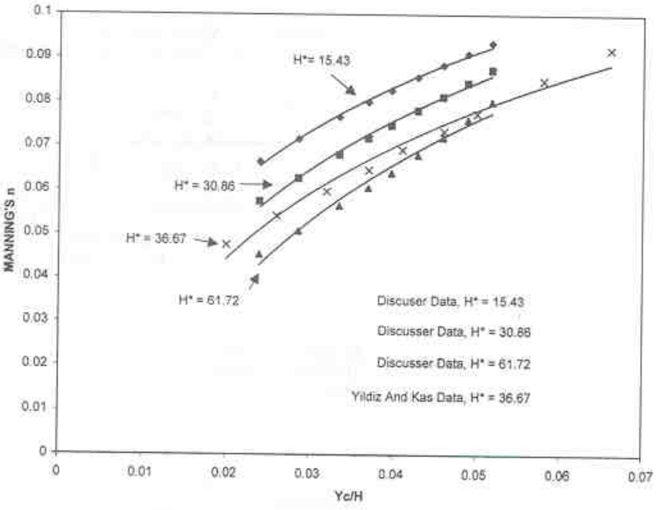

Fig. 1. Variation of Manning's n for different H^* values

The discussers would also like to know the number of steps provided in each case and the location of first step along the spillway profile. Can the authors suggest any readily usable explicit guidelines from hydraulic considerations for deciding on the step height, apart from the given RCC lift thickness? Some other investigators, including Rice and Kadavy (1996), Yildiz and Kas (1998), Chamani and Rajaratnam (1999) have indicated that the step height s affects the energy dissipation over stepped spillway.

Eq. (24) includes K, the roughness height perpendicular to the pseudobottom, which can be considered to be a representative term for step height s. In the last paragraph on energy dissipation, it is mentioned that Fig. 12 gives an idea of main parameters involved in the expression of relative residual energy. However, Fig. 12 does not indicate effect of any step height parameter on relative residual energy head ratio $[H_{\text{res}}/H_{\text{max}}]$. Fig. (1) shows a plot compiled by discussers based on experimental data obtained by Ghare (2003) and Yildiz and Kas (1998), which show the effect of step height on Manning's equivalent n for a stepped spillway. In this plot H^* is considered a ratio of spillway height to step height. Can authors provide any other dimensionless plot that covers all the main parameters including step height s affecting the performance of the stepped spillway under skimming flow regime?

Proposed Eq. (24) is based on the results obtained from Eqs. (20) and (21). Hence the use of Eq. (24) appears to be a tedious process. As indicated by the authors in Fig. (12), the variation in relative residual energy head ratio for $\Phi=40°$ and $50°$ is not appreciable; hence a simpler relationship for relative residual energy can be presented eliminating Φ as a variable. The resulting relationship would be applicable for Φ greater than 40°. Without a properly designed energy dissipation system on the downstream side, the hydraulic design of a stepped spillway system would be incomplete. The discussers would like to know the opinion of the authors regarding the applicability of the conventional conjugate depth relationship for stilling basin design in case of a stepped spillway where highly aerated flow near the toe of the spillway is encountered.

References

Chamani, M. R., and Rajaratnam, N. (1999). "Characteristics of skimming flows over stepped spillways." *J. Hydr. Engrg.* 125(4), 361–367.