DISCUSSIONS AND CLOSURES

Discussion of "Two-Phase Flow Characteristics of Stepped Spillways" by Robert M. Boes and Willi H. Hager

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In skimming flows down stepped chutes, the flow is nonaerated at the upstream end. Free-surface instabilities are, however, observed and strong air-water mixing occurs downstream of the inception point of free-surface aeration (Fig. 1). Detailed air-water flow measurements highlighted large amounts of entrained air and the authors did well to document some air-water flow properties, although they did not detail the air-water flow structure as did some recent studies (Chanson and Toombes 2003; Yasuda and Chanson 2003).

The discusser is very concerned by the inappropriate development of the air entrainment inception point location. The authors' analysis was based improperly upon the so-called "drawdown equation." That development is an integration of the backwater equation, implying a fully developed boundary layer flow, and it assumes a constant empirical Gauckler-Manning coefficient. As illustrated in Fig. 1, the flow upstream of the inception point of free-surface aeration is partially developed, and both backwater and Gauckler-Manning equations are not valid (e.g., Henderson 1966; Chanson 1999). In this discussion, it is shown that basic boundary layer calculations may be derived for uncontrolled spillway chutes and the result may be extended to pressurized intake.

At the upstream end of the chute, a bottom turbulent boundary layer develops (Fig. 1). The boundary layer development may be estimated as

$$\frac{\delta}{x} = a \times \left(\frac{x}{K}\right)^{-b} \qquad (1)$$

where δ=boundary layer thickness; x=streamwise distance from the start of the growth of the boundary layer; K=roughness height; and a and b=constants (e.g., Bauer 1954; Cain and Wood 1981). For s stepped profile, the roughness height is $K=s \times \cos \phi$. The velocity distribution is of the form

$$\frac{u}{U_{\max}} = \left(\frac{y}{\delta}\right)^{1/n} \qquad (2)$$

where $U_{\max}$=free stream velocity in the ideal-fluid flow region (i.e., $\delta < y < d$) and y=distance normal to the pseudo-bottom formed by the step edges. The LDA velocity data of Ohtsu and Yasuda (1997) showed $n \sim 5$ in the developing boundary layer above a steep stepped chute. For an uncontrolled crest, the free-stream velocity is basically

$$U_{\max} = \sqrt{2 \times g \times x \times \sin \phi} \quad \text{uncontrolled crest} \qquad (3)$$

For a pressurized intake, the free-stream velocity equals

$$U_{\max} = \sqrt{2 \times g \times x \times \sin \phi \times \left(1 + \frac{E_0}{x \times \sin \phi}\right)} \quad \text{pressurized intake} \qquad (4)$$

where E_0=specific energy at the intake.

The location where the outer edge of the boundary layer reaches the free surface is called the inception point of air entrainment. Its position L_i is defined as the distance from the start of the growth of the boundary layer. At inception point ($x=L_i$), the combination of continuity and Bernoulli principles gives

$$\frac{q_w}{U_{\max} \times \delta} = \frac{n}{n+1} \qquad (5)$$

where q_w=flow rate per unit width. Combining with Eqs. (1) and (2), it yields

$$\left(\frac{L_i}{K}\right)^{(3/2)-b} = \frac{n+1}{n} \times \frac{1}{\sqrt{2} * a} \times \frac{q_w}{\sqrt{g \times \sin \phi \times K^3}} \quad \text{uncontrolled crest} \qquad (6)$$

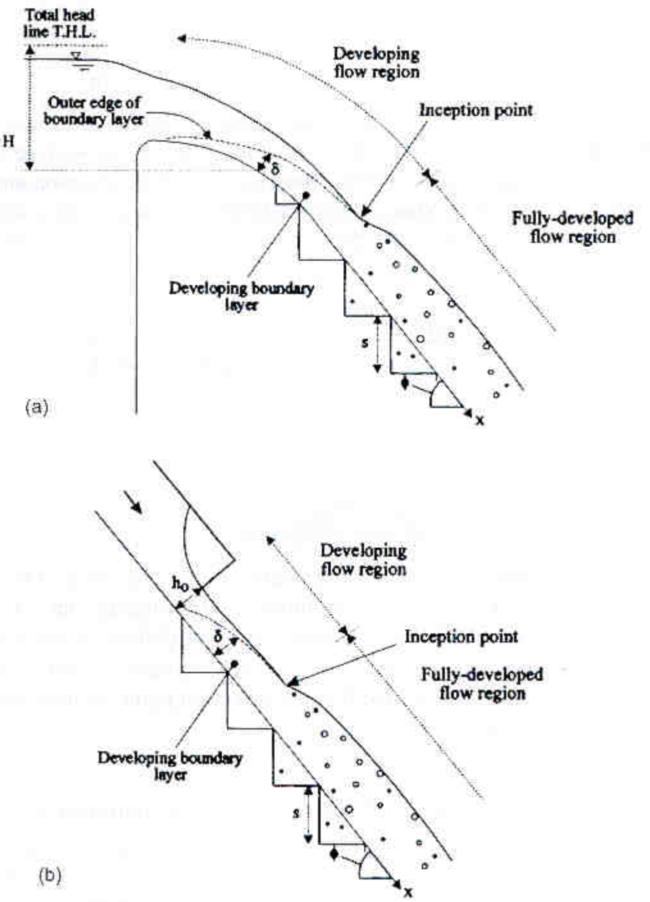

Fig. 1. Sketch of developing flow region above stepped chute: (a) uncontrolled crest; (b) gated spillway intake

Inflow conditions	References
Uncontrolled intake (model data)	Beitz and Lawless (1992), Bindo et al. (1993), Chanson and Tombes (2002), Frizell (1992), Haddad (1998), Horner (1969), Sorensen (1985), Tozzi (1992), Zhou (1996), Warheit-Lensing (1996)
Uncontrolled intake (prototype data)	Sanchez-Bribiesca and Gonzalez-Villareal (1996)
Pressurised intake (model data)	Boes (2000)

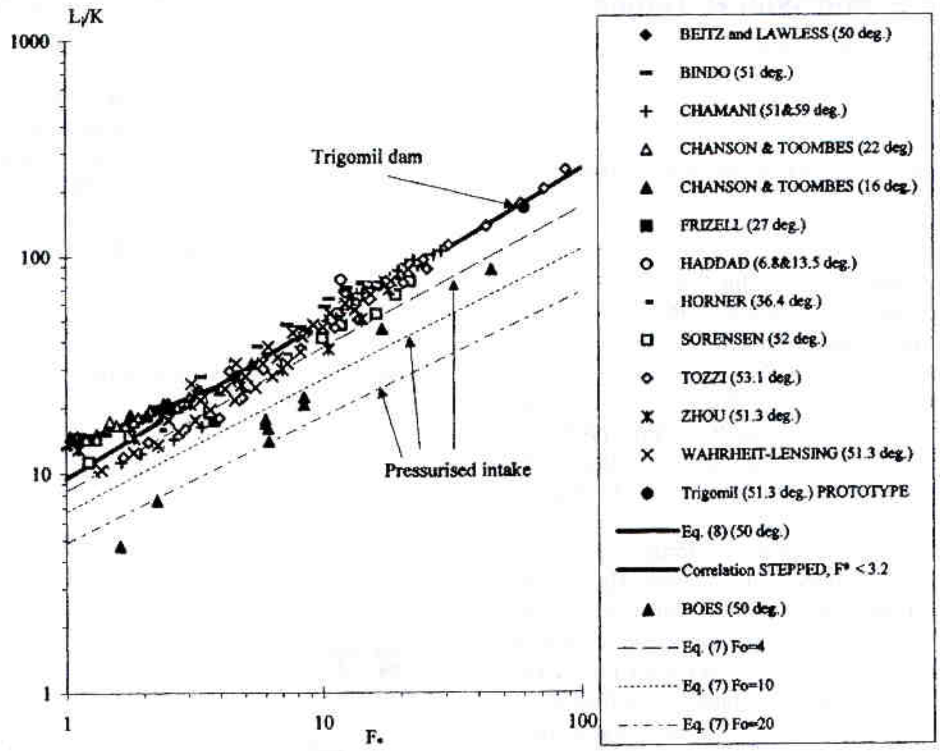

Fig. 2. Dimensionless location of inception point of free-surface aeration—comparison between experimental data and Eqs. (8) and (9) for $\phi = 50°$ [Beitz and Lawless (1992); Bindo et al. (1993); Chanson and Toombes (2002); Frizell (1992); Haddad (1998); Horner (1969); Sorensen (1985); Tozzi (1992); Zhou (1996); Wahrheit—Lensing (1996); Sanchez-Bribiesca and Gonzalez-Villareal (1996); and Boes (2000)]

$$\left(\frac{L_i}{K}\right)^{(3/2)-b} = \frac{n+1}{n} \times \frac{1}{\sqrt{2} \times a} \times \frac{q_w}{\sqrt{g \times \sin\phi \times K^3}} \times \frac{1}{\sqrt{1 + \frac{E_0}{L_i \times \sin\phi}}} \quad \text{pressurized intake} \tag{7}$$

For uncontrolled stepped chutes, Chanson (1995) compared successfully Eq. (6) with a large number of experimental data. For these data, the location of inception point was defined as the first apparition of "white waters" at the free surface. A statistical analysis of the data indicated that the inception point location was best correlated by

$$\left(\frac{(L_i)_{uc}}{s \times \cos\phi}\right)^{1.4} = 24.14 \times (\sin\phi)^{0.111} \times F^* \quad \text{uncontrolled crest} \tag{8}$$

where the subscript uc refers to uncontrolled crest inflow conditions and $F^* = q_w \sqrt{g * \sin\phi * (s * \cos\phi)^3}$. A comparison between Eqs. (6) and (8) gives $b = 0.1$.

With a pressurized intake, the outflow is thinner and faster than with an uncontrolled crest. In turn, the outer edge of the boundary layer is expected to reach the free surface more rapidly than on an uncontrolled chute for an identical flow rate and stepped geometry. The reasoning is confirmed by Eq. (7), which may be rewritten as

$$\frac{(L_i)_{pi}}{s \times \cos\phi} = \frac{(L_i)_{uc}}{s \times \cos\phi} \times \left(1 + \frac{F^*}{\frac{L_i}{s \times \cos\phi}} \times \left(\mathsf{F}_0^{-2/3} + \frac{1}{2} \times \mathsf{F}_0^{4/3}\right)\right)^{-0.357} \quad \text{pressurized intake} \tag{9}$$

where the subscript pi refers to pressurized intake inflow conditions and F_0=intake flow Froude number. In Eq. (9), right-hand side, the last term is a correction factor to account for the intake flow conditions.

Eqs. (8) and (9) are presented in Fig. 2. They are compared with experimental data obtained with pressurized intake and ungated spillway intake including large prototype data (Trigomil dam). The results (Fig. 2) demonstrate that the inception point is located significantly more upstream with pressurized intake inflows than with uncontrolled chutes. The difference increases with increasing inflow Froude number F_0. Fig. 2 shows further a good agreement between Eq. (8) and uncontrolled chute data, as well as between Eq. (9) and Boes' (2000) data. The latter were obtained with inflow Froude numbers ranging from 3 to 10.

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The authors have presented an important study on the two-phase flow characteristics of stepped spillways. The contributions given are of relevance for the design of this kind of hydraulic structure.

The discussers would like to present experimental results of research on hydrodynamic pressures acting on the steps, as well as some information on the risk of cavitation on stepped chutes.

According to the author's description, skimming flow is characterized by a coherent stream that skims over the steps, where the edges form a so-called "pseudo-bottom." The recirculation region delimited by the faces of the steps and the pseudo-bottom is mainly responsible for the flow resistance, and it can be described as an unsteady flow subjected to random fluctuations. Associated with this macroturbulent flow is the generation of pressure fluctuations on the solid boundaries, which can reach critical conditions for cavitation.

Pressure Field over a Stepped Spillway

Extensive pressure measurements have been carried out at the Polytechnic University of Catalonia aiming to characterize the pressure field induced by skimming flow over a stepped spillway.

The experimental data were gathered in a 0.8:1 (h:v) sloped stepped chute, 4.30 m high (from crest to toe), 0.60 m wide, under Froude similarity criteria. Three step heights (s) of 0.10, 0.07, and 0.05 m were investigated.

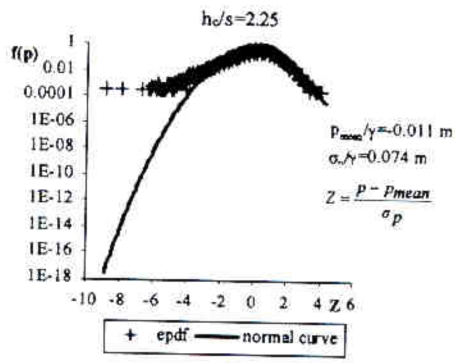

Fig. 1. Empirical probability density function (epdf) of the pressure fluctuations compared to normal distribution (656 s of run time, 65600 points). The pressure measurement is located at $L/K=35.15$ for $h_c/s=2.25$; p_{mean}/γ is the mean dynamic pressure and σ_p/γ is the root-mean-square of dynamic pressure fluctuations.