Measuring air entrainment and flow bulking in skimming flow over steeply sloping stepped chutes

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Abstract

Air entrainment and flow bulking along a steeply sloping stepped chute are analysed as a function of the characteristic depth used for defining the free-surface. The results of this investigation show that both the mean air concentration and the bulked depth may be considerably influenced by the definition of the free surface. They also show that the region in the vicinity of the point of inception may be the most critical concerning flow bulking, and consequently the chute sidewall design height. Empirical models are also presented for predicting the maximum flow bulking on the chute, as a function of the normalized critical depth.

Introduction

The evaluation of the air-water flow properties is particularly important on stepped spillways over RCC dams experiencing moderate unit discharges, because large quantities of air entrain upstream of the spillway toe.

On air-water flows down smooth and stepped chutes, the characteristic depth is usually defined as the perpendicular distance from the pseudo-bottom formed by the step edges where the air concentration is 90% (e.g. Ruff and Frizell 1994, Matos 2000, Chanson 2001, Boes and Hager 2003).

In the present paper, the research is focused on the air entrainment and flow bulking along the chute, as a function of the characteristic depth used for defining the free-surface.

Experimental set-up

Experimental tests were conducted on a steeply sloping stepped chute (1V:0.75H) assembled at the National Laboratory of Civil Engineering (LNEC), Lisbon. Even though tests were conducted for step heights (h) of 2, 4 and 8 cm (Renna, 2004), the present results apply only to those for which significant bulking occurred, namely 4 and 8 cm high steps (Meireles, 2004). All tests corresponded to the skimming flow regime, with unit discharges (q_w) ranging between 0.050 and 0.200 m^2/s.

Experimental measurements of air concentration were carried out with an air concentration probe (resistivity probe) developed by the U.S. Bureau of Reclamation. Further details on the instrumentation can be found in Matos and Frizell (1997).

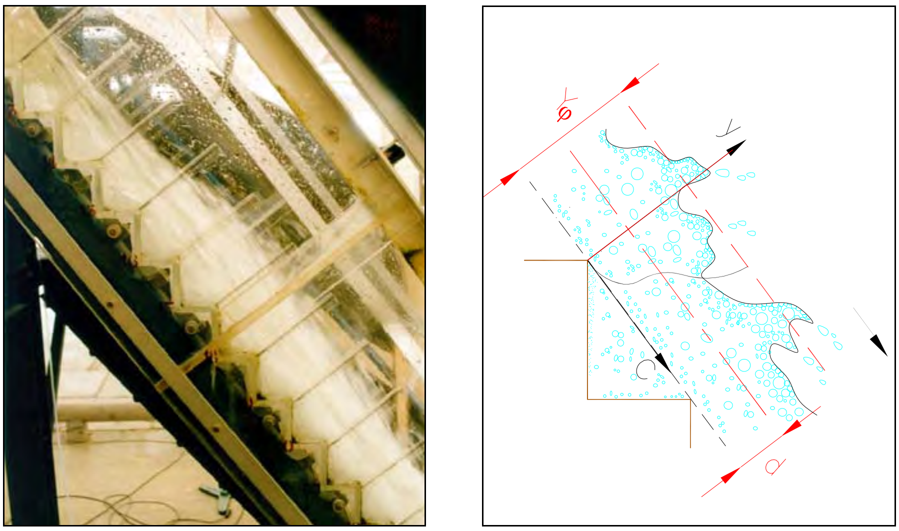
Air entrainment

The local air concentration C is defined as the time-averaged value of the volume of air per unit volume of air and water. The mean (depth-averaged) air concentration is defined as

$$\bar{C}_{\varphi} = \int_0^{Y_{\varphi}} C\, dy \qquad (1)$$

where y is measured perpendicular to the pseudo-bottom formed by the step edges and $Y\varphi$ is the depth where the air concentration is φ%.

For the hydraulic design of stepped chutes, φ is typically 90%. Due to the significant flow bulking downstream of the point of inception (Figure 1), Y_{90} was found to underestimate considerably the maximum height of large air-water mass projections.

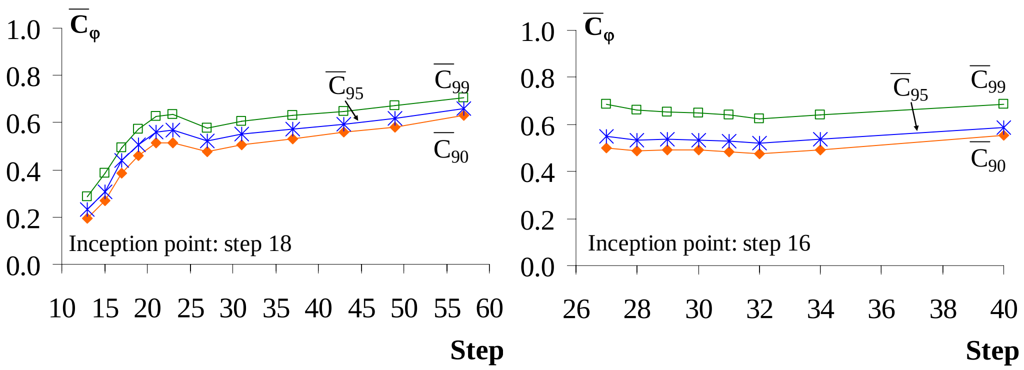


a) b)

Figure 1 - Flow bulking downstream of the inception point: a) photograph of the LNEC chute for h = 8 cm and q_w = 0.080 m^2/s; b) definition sketch.

The present study is focused on the analysis of the flow properties considering characteristic depths based on air concentrations larger than 90% (e.g., air concentrations of 95% and 99%, the respective depths being Y_{95} and Y_{99}).

Figure 2 illustrates the mean air concentration along the chute, for different values of φ. Figure 2a) refers to both rapidly and gradually varied flow regions whereas Figure 2b) focus on the gradually varied flow. Both figures illustrate the influence of the parameter φ on the mean air concentration. The ratios $\overline{C}_{95}/\overline{C}_{90}$ and $\overline{C}_{99}/\overline{C}_{90}$ are on average equal to 1.1 and 1.3, respectively. The major differences occur in the vicinity of the inception point of air entrainment, where $\overline{C}_{95}/\overline{C}_{90}$ and $\overline{C}_{99}/\overline{C}_{90}$ can attain 1.2 and 1.8, respectively. Far downstream, where the effect of flow bulking is mitigated, $\overline{C}_{95}/\overline{C}_{90}$ and $\overline{C}_{99}/\overline{C}_{90}$ decrease to 1.05 and 1.1, respectively.



a) b)

Figure 2 - Development of the mean air concentration: a) h = 4 cm and q_w = 0.080 m^2/s; b) h = 8 cm and q_w = 0.140 m^2/s.

Flow bulking

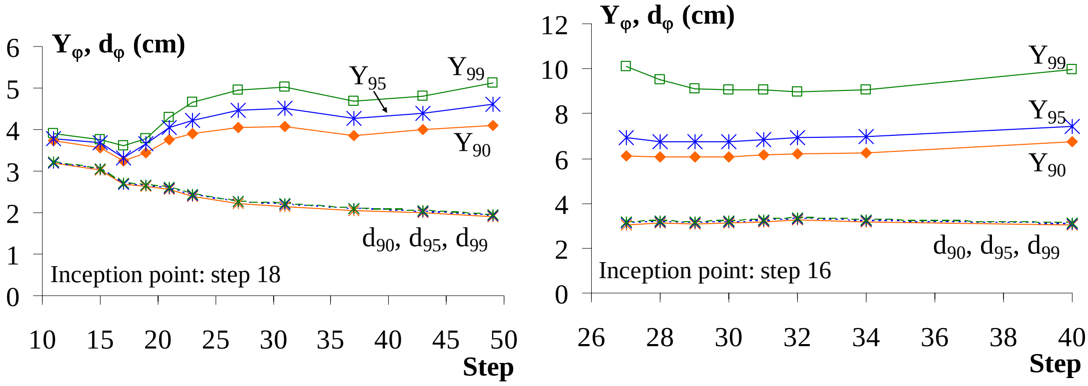
Due to air entrainment, the characteristic depths are significantly larger than the equivalent clear-water depth d_φ defined as:

$$d_\varphi = \left(1 - \overline{C}_\varphi\right) Y_\varphi \qquad (2)$$

The differences obtained between Y_{90}, Y_{95} and Y_{99} were significant, particularly those between Y_{90} and Y_{99} for 8 cm high steps (Figure 3). The ratio Y_{95}/Y_{90} was approximately 1.1 for both step heights whereas Y_{99}/Y_{90} was significantly influenced by the step height. The average value of Y_{99}/Y_{90} was equal to 1.2 for 4 cm high steps and 1.4 for 8 cm high steps. The results are similar to those presented by Boes and Minor (2000), who obtained $Y_{95}/Y_{90} \approx 1.12$ and $Y_{99}/Y_{90} \approx 1.4$ on chute slopes ranging from 30 to 50 degrees.

Further the experimental results show that the region in the vicinity of the point of inception may be the most critical concerning flow bulking.

The clear-water depth is almost independent of the parameter φ, unlike as observed for the mean air concentration and the characteristic depths. The maximum observed differences were merely 2.8% between d_{95} and d_{90}, and 6.1% between d_{99} and d_{90}. Therefore, no major differences on the plots of d_{90}, d_{95} and d_{99} are noticed in Figure 3.



a) b)

Figure 3 - Development of the characteristic depths: a) h = 4 cm and q_w = 0.080 m^2/s; b) h = 8 cm and q_w = 0.140 m^2/s.

The height of the chute sidewall (h_p) is usually based on the application of a safety factor (n) to Y_{90} (e.g. Boes and Minor 2000, Boes and Hager 2003, Ohtsu et al. 2004), namely as:

$$h_p = n\, Y_{90} \quad (3)$$

Ohtsu et al. (2004) suggested the use of n = 1.4, as per the experimental research by Boes and Minor (2000), based on the ratio Y_{99}/Y_{90}. Boes and Minor (2000) and Boes and Hager (2003) considered n = 1.2 for concrete dams with no concern of erosion and n = 1.5 for stepped emergency spillways on embankment dams prone to erosion.

The results of the present study show that the maximum relative characteristic depths $(Y_{95}/Y_{90})_{max}$ and $(Y_{99}/Y_{90})_{max}$ can be considerably larger than those proposed by other researchers, particularly for low normalized critical depths, d_c/h (Figure 4).

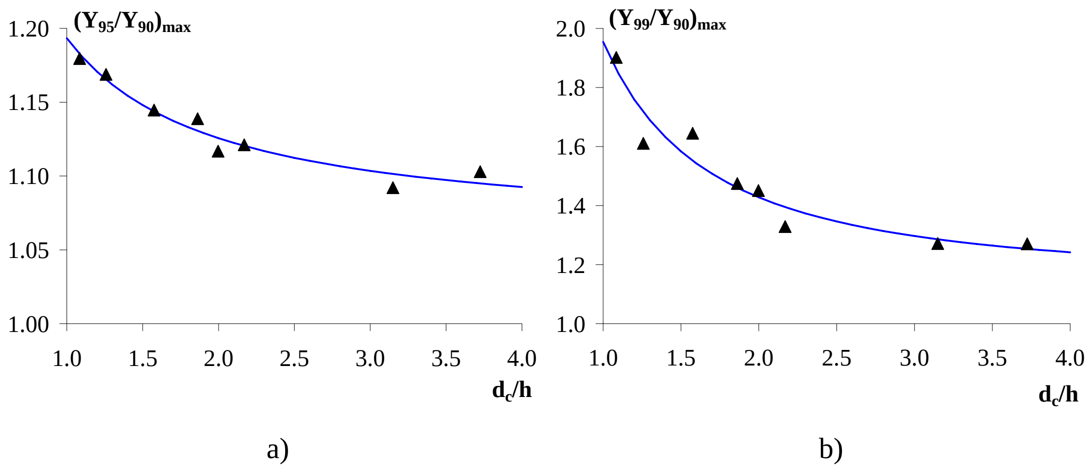


Figure 4 - Maximum normalized characteristic depths: a) $(Y_{95}/Y_{90})_{max}$; b) $(Y_{99}/Y_{90})_{max}$.

The maximum values of the ratios Y_{95}/Y_{90} and Y_{99}/Y_{90} may be obtained from:

$$\left(\frac{Y_{95}}{Y_{90}}\right)_{max} = 1.061 + 0.1322\left(\frac{d_c}{h}\right)^{-1.034} \quad (4)$$

$$\left(\frac{Y_{99}}{Y_{90}}\right)_{max} = 1.140 + 0.8143\left(\frac{d_c}{h}\right)^{-1.499} \quad (5)$$

Eq. (4) and (5) may be used for the chute sidewall design height of stepped chutes on typical RCC dam slopes, the latter if more restrictive conditions are required. The estimation of Y_{90} down the chute may be obtained from empirical models (e.g., Meireles 2004). Taking into account that aerated flow is not a well-mixed continuum (e.g., Falvey 1980, André 2004, Renna 2004, Wilhelms and Gulliver 2005), an accurate description of the intermittent wavy surface would also be of interest in future research.

Conclusions

The results of this investigation showed that both the mean air concentration and the bulked depth may be significantly influenced by the definition of the free surface. They also showed that the region in the vicinity of the point of inception may be the most critical concerning flow bulking. Empirical models were developed for estimating the maximum flow bulking as a function of the normalized critical depth, eventually providing a safer chute sidewall design.

Acknowledgments

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