

AIR ENTRAINMENT IN SKIMMING FLOW ON STEPPED SPILLWAYS: THE EFFECT OF AN ABRUPT SLOPE CHANGE

M.J. Ostad Mirza^{1,2}, M. Pfister¹, A.J. Schleiss¹, and J. Matos²

¹Laboratory of Hydraulic Constructions (LCH),
Ecole Polytechnique Fédérale de Lausanne (EPFL),
CH - Lausanne 1015
SWITZERLAND

² Department of Civil Engineering, Architecture and Georesources
Instituto Superior Técnico, University of Lisbon
Lisbon, 1049-001
PORTUGAL

E-mail: mohammadjavad.ostadmirza@epfl.ch

Abstract: Numerous stepped spillways were built during the last decades. In particular, a stepped spillway may be integrated economically into the downstream face of a RCC gravity dam, or on valley flanks besides embankment or rockfill dams, where slope changes may naturally be implemented due to topography and economic reasons. This paper presents and discusses preliminary results on the air entrainment in the vicinity of an abrupt change chute slope, namely the air concentration distribution and the mean air concentration. A significant influence was observed on the air entrainment pattern, with a decrease of the mean air concentration immediately upstream of the slope change, followed by a marked increase immediately downstream, and a subsequent decrease further down the flatter chute, approaching a practically constant value. Considerable larger air entrainment was observed shortly downstream of the slope change cross-section, in comparison with that found upstream, in the quasi-uniform flow.

Keywords: Stepped spillways, Slope change, Skimming flow, Air entrainment.

1. INTRODUCTION

A significant number of stepped spillways were built during the last decades, in particular linked to the application of the roller compacted concrete (RCC) dam construction technique. A stepped spillway may be integrated economically into the downstream face of a RCC gravity dam. In combination with embankment and rockfill dams, stepped spillways have been built on valley flanks besides the dam, where slope changes may naturally occur due to topography and economic reasons.

For a given stepped chute geometry, the general behavior of the flow may be characterized by three different regimes, namely nappe, transition and skimming flow (e.g., Ohtsu and Yasuda, 1997; Chanson, 2002). Nappe flow occurs at low flows and can be defined as a succession of free-falling nappes. In skimming flow, the water or air-water flows as a coherent stream over the pseudo-bottom formed by the outer step edges; beneath it three-dimensional vortices occur. Between the upper limit of nappe flow and the lower limit of skimming flow, a transition flow takes place. For typical hydraulic design of dam stepped spillways, a skimming flow regime occurs (Matos, 2000; Boes and Hager 2003a).

In the last couple of decades, a significant number of physical model studies were conducted on the hydraulics of skimming flow over constant sloping stepped spillways (e.g., Chamani and Rajaratnam 1999, Pegram et al, 1999, Sánchez-Juny et al, 2000, Matos 2000, Chanson, 2002, Boes and Hager 2003a,b, Frizell, 2006, Amador et al, 2009, Meireles et al., 2012, Pfister and Hager, 2011, Bombardelli et al., 2011, Bung, 2011, Felder and Chanson, 2009, Felder, 2013). In addition to the hydraulics of conventional stepped spillways, a variety of experimental studies have also been carried out on non-conventional geometries, such as stepped spillways with macro-roughness (e.g., André, 2004, André et al, 2004, Gonzalez et al, 2008, Bung and Schlenkhoff, 2010), or with non-uniform step heights (Felder and Chanson, 2011).

Despite some few exceptions, such as the Upper Stillwater dam in the USA (Houston, 1987) and lower Siah-Bishe dam in Iran (Baumann et al., 2006), most stepped spillways have been designed for a constant chute slope. Hence there is presently insufficient information available on the flow behaviour on abrupt slope changes on stepped spillways. The present study was conducted under different geometric and flow conditions in order to investigate the flow properties in the slope change region, in particular the air entrainment.

2. EXPERIMENTAL SETUP

A steep channel with variable slope, equipped with steps of constant height, was assembled at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). It consists of four 2 m long and 0.5 m wide modules, with a 0.6 m high transparent sidewall to allow for flow observation. Since the present study focuses on slope changes, the channel was divided in two separated parts, each of those including two modules of 4 m length. Each part was of different slope, with the upstream slope being steeper than the downstream slope (Figure 1a). The bottom slope of the upstream chute (i.e. pseudo-bottom angle) was set to $\varphi_1=50^\circ$ (1V:0.84H), while the downstream slope was set to $\varphi_2=18.6^\circ$ (1V:3H).

The flow rate was measured with an electromagnetic flow meter. The maximum unit discharge which could be provided is approximately $0.46 \text{ m}^2/\text{s}$. To allow for an independent variation of the inflow depth (d_0) and Froude number ($F_{r0} = q_w/(gd_0^3)^{1/2}$; q_w is the unit discharge and g is the gravitational acceleration), the flume inflow device consisted of a jet-box with a maximum opening of 12 cm. Applying this device, the pressurized pipe approach flow is transformed into a free surface flow. Thus the location of the inception of air entrainment is shifted upstream and the developing region of the flow is shorten, such that quasi-uniform flow conditions are reached on the upstream slope, for all step geometries and discharges. A dual fiber-optical probe developed by RBI Instrumentation, France, was mounted on an automatic positioning system for measuring the air concentration and velocity.

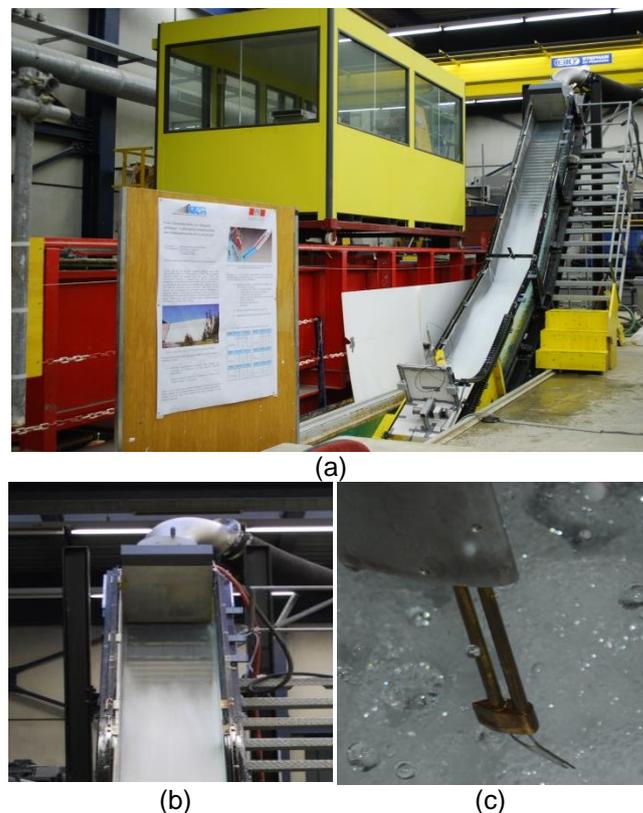


Figure 1 – Physical model of the stepped spillway with an abrupt slope change assembled at LCH-EPFL: a) General view; b) Initial reach of the chute and jet box, c) Dual fiber-optical probe in operation.

A series of observations and measurements were conducted in the skimming flow regime for unit discharges ranging between 0.35 and 0.46 m²/s, and relative critical depths d_c/h (d_c is the critical depth and h is the step height) ranging between 3.8 and 4.6. That range corresponds to Reynolds numbers ($Re = q_w/\nu$) varying between 3.4 and 4.6×10⁵ and inflow Weber number at the exit of the jet-box ($W_{e0} = V_{m0}/(\sigma \sin\phi/ \rho h)^{1/2}$) between 124 and 189, where ν is the kinematic viscosity of water, V_{m0} is the inflow depth averaged velocity at the exit of the jet-box ($V_{m0} = q_w/d_0$), σ is the interfacial surface tension, and ρ is the water density (Table 1). The air–water flow properties were measured at 20 streamwise cross-sections along the stepped spillway, namely in 5 step edges upstream and 15 step edges downstream of the slope change, from step number -9 to +15 (Figure 2). The measurements in each cross-section consisted of 30 points from about 0.005 m distance to the step edge, and subsequently increasing by 0.01 m.

Table 1 – Chute geometry and hydraulic conditions.

Parameters	Min.	Max.
$\phi(^{\circ})$	18.6 ⁽¹⁾	50 ⁽²⁾
h (m)	0.06	
q_w (m ² /s)	0.35	0.46
d_c/h (-)	3.8	4.6
d_0 (m)	0.082	0.093
F_{r0} (-)	4.0	6.4
Re (-)×10 ⁵	3.4	4.6
W_{e0} (-)	124	189

(1) Downstream chute slope, (2) Upstream chute slope.

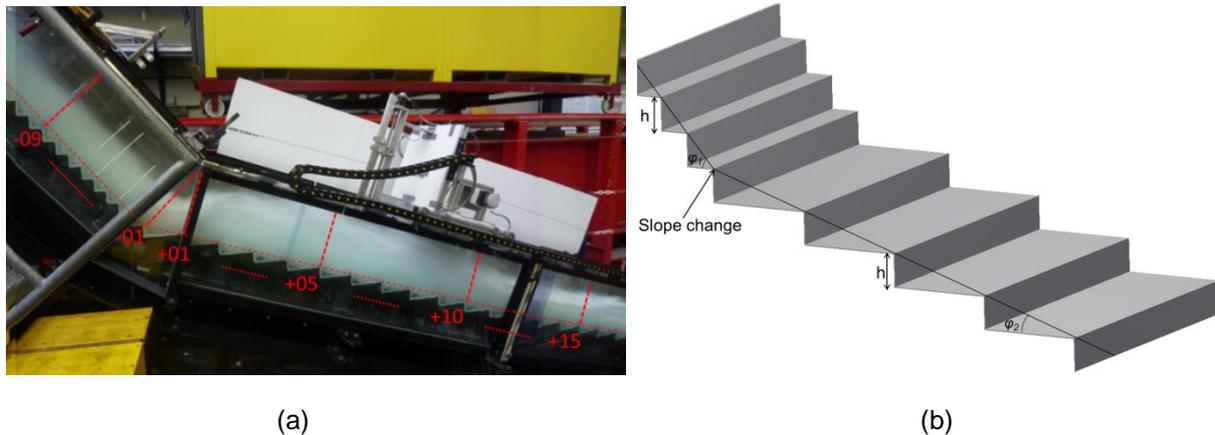


Figure 2 – a) Physical model of the stepped spillway with an abrupt slope change assembled at LCH-EPFL (50° to 18.6°, $h = 0.06$ m, $q_w = 0.46$ m²/s, $d_c/h = 4.6$); step numbers used in the following are indicated, b) sketch of slope change region.

AIR-WATER FLOW PROPERTIES ON THE SLOPE CHANGE REGION

2.1. Definitions

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

$$C_{mean} = \frac{\int_0^{Y_{90}} C dy}{Y_{90}} \quad (1)$$

where y is measured perpendicular to the pseudo-bottom formed by the step edges and Y_{90} is the depth where the air concentration is 90 %.

2.2. Air concentration distribution

Various air concentration profiles were acquired in skimming flow upstream and downstream of the slope change, as presented in Figure 3. The air concentration distribution varies significantly along the slope change region. Four main sub-regions may be identified: **sub-region I**, characterized by a decrease in the local air concentration (for identical distance to the pseudo-bottom) within the flow when approaching the slope change cross-section (Figure 3a), **sub-region II**, characterized by a sharp increase in the air concentration within the flow near the slope change cross-section, reaching maximum values shortly downstream (Figure 3b); **sub-region III**, where the air concentration decreases rapidly again and approaches to values close to uniform flow condition for the second slope (Figure 3c); and **sub-region IV**, where the air concentration continues to exhibit a decreasing trend, eventually approaching an almost constant value, hence leading to similar air concentration profiles (Figure 3d).

In the reaches not affected by the slope change, namely, steps -9 to -3 (Figure 3a) and +12 to +15 (Figure 3d), the air concentration distribution exhibits a S-shape profile, similarly as obtained in other experimental studies for constant chute slope under uniform flow condition, as well as well described by the advection-diffusion model for the air bubbles (e.g., Chanson, 1997; Chanson and Toombes, 2002).

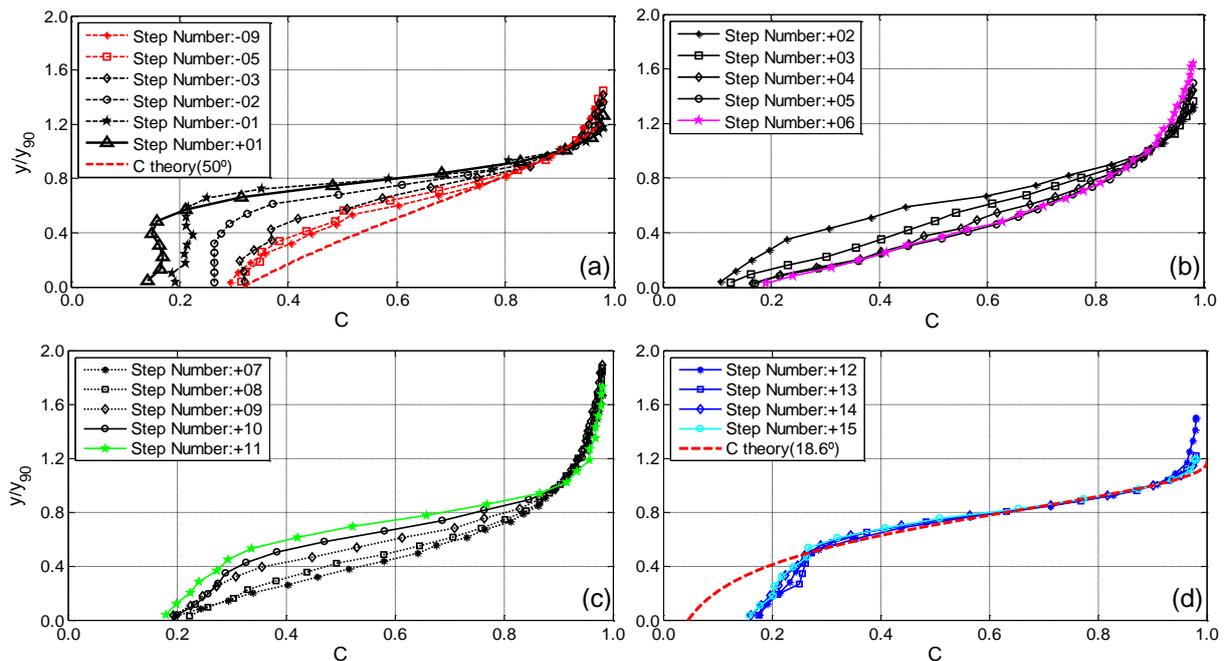


Figure 3 - Air concentration distribution upstream, downstream and along the slope change region (“-” and “+” signs represent the steps upstream and downstream of the slope change region, respectively (step numbers as per Figure 2): (a) sub-region I; (b) sub-region II; (c) sub-region III; (d) sub-region IV): $d/h=4.6$. “C theory” was obtained from Chanson (1997), for uniform flow on a similar sloping chute, assuming C_{mean} equal to 0.6 and 0.3 for 50° and 18.6° slopes, respectively.

2.3. Mean air concentration and characteristic flow depth

The development of the mean air concentration along the chute (obtained from Eq. (1)) is plotted in Figure 4, where x is the streamwise coordinate from the jetbox. A comparison of the experimental data against empirical formulae developed for estimating the mean air concentration in uniform flow on 50° and 18.6 ° sloping chutes, either stepped (e.g., Boes, 2000, Takahashi and Ohtsu, 2012) or smooth

(e.g., Wood, 1991, Hager, 1991, Chanson 1997, Matos, 1999) indicates that flow conditions not substantially dissimilar from quasi-uniform flow were observed at far upstream ($x/h \sim 52$) and far downstream ($x/h \sim 101$) of the slope change cross-section, where C_{mean} approaches 0.6 and 0.3, respectively. The influence of the slope change on the mean air concentration is noticeable slightly upstream of the slope change cross-section, where C_{mean} decreases considerably, which is judged to be due to the flow curvature and higher pressures near the pseudo-bottom, in such short region.

As one can see from Figure 5, the streamwise distribution of the characteristic flow depth normalized by the critical depth (Y_{90}/d_c) follows a similar overall trend as that obtained for the mean air concentration, except in the vicinity of the slope change cross-section.

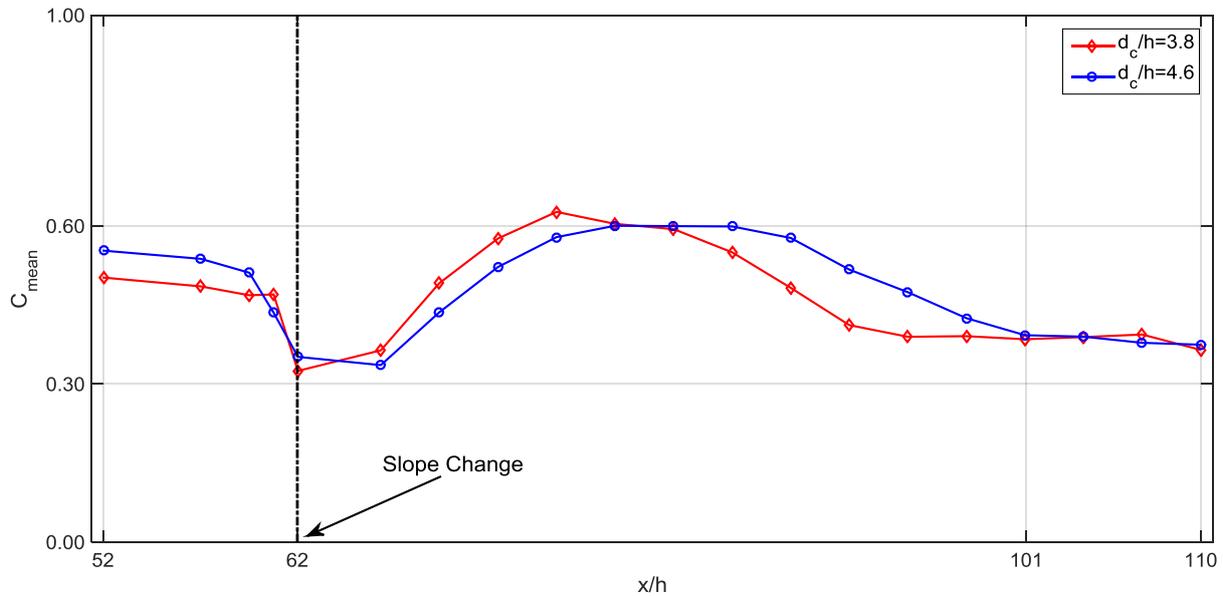


Figure 4 – Streamwise development of the mean air concentration for two unit discharges of $0.35 \text{ m}^2/\text{s}$ ($d_c/h=3.8$) and $0.46 \text{ m}^2/\text{s}$ ($d_c/h = 4.6$).

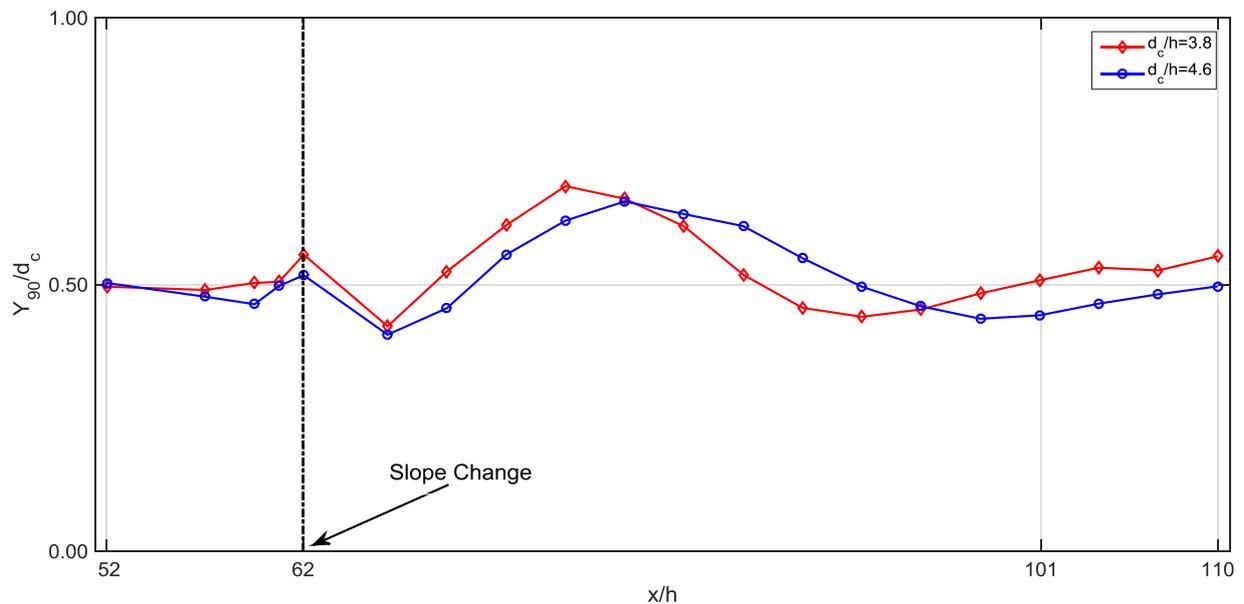


Figure 5 – Streamwise development of the normalized characteristic depth, for two unit discharges of $0.35 \text{ m}^2/\text{s}$ ($d_c/h=3.8$) and $0.46 \text{ m}^2/\text{s}$ ($d_c/h = 4.6$).

In Figure 6, the mean air concentration normalized by the uniform mean air concentration values for 50° and 18.6° chute slopes (after Boes, 2000, and Takahashi and Ohtsu, 2012, respectively) is plotted as a function of the normalized distance x_{oc}/L_i . Therein the experimental data of x_{oc} and L_i are estimated after modifying the origin for an uncontrolled ogee crest, following an approach similar to that applied by Boes and Hager (2003b) where $L_i = (5.9d_c^{6/5})/(\sin\phi^{7/5}h^{1/5})$. The difference between the calculated L_i from an uncontrolled ogee crest and the observed inception point length from the jet-box has been used to estimate the distance from an uncontrolled ogee crest (x_{oc}). The application of Pfister and Hager (2011) formula is also included in Figure 6, strengthening the conclusion that quasi-uniform flow condition was attained on the upstream chute ($C_{mean}/C_{mean u} \sim 1$).

The sub-regions previously referred in section 3.2 apply to the mean air concentration, including a decrease in the mean air concentration when approaching the slope change cross-section, followed by its sharp increase, eventually reaching a peak, and decreasing further downstream, approaching a practically constant value (Figures 4 and 6). However, uniform flow conditions were likely not reached in the 18.6° chute, because the mean air concentration is larger than those corresponding to the uniform flow for an identical slope on stepped (e.g., Takahashi and Ohtsu, 2012) or smooth spillway chutes (Figure 4), $C_{mean u} \sim 0.3$.

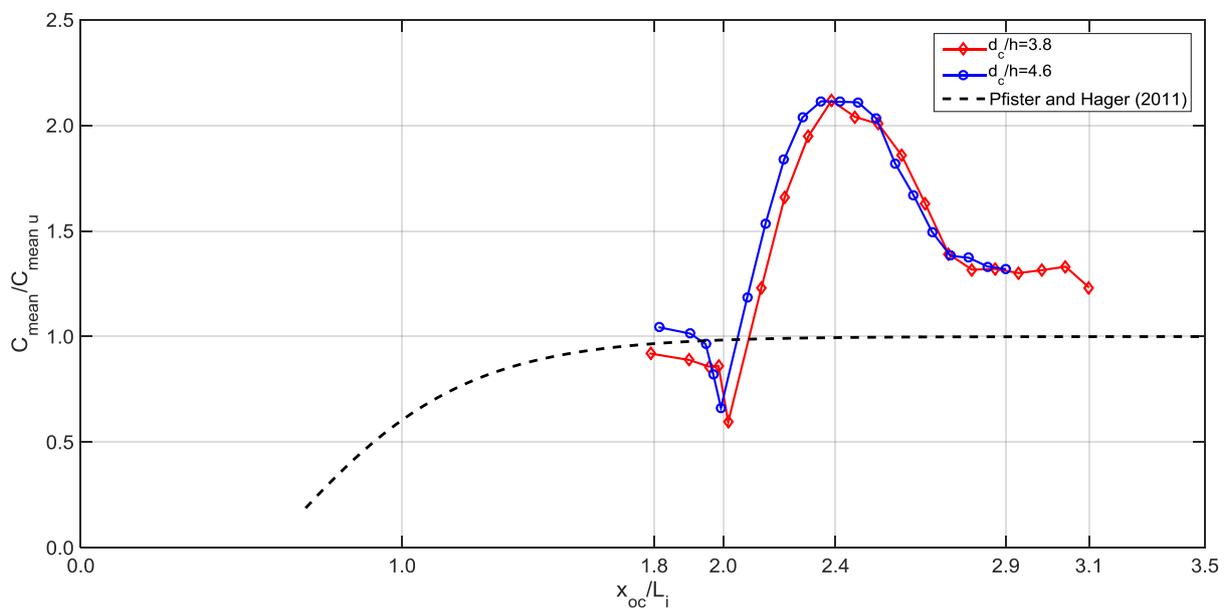


Figure 6 – Streamwise development of the mean air concentration ratio for two unit discharges of 0.35 m^2/s ($d_o/h=3.8$) and 0.46 m^2/s ($d_o/h = 4.6$). The experimental data is normalized by $C_{mean u}$, upstream and downstream of the slope change (after Boes, 2000, and Takahashi and Ohtsu, 2012, respectively). At the slope change, $x_{oc}/L_i \sim 2$ for both discharges.

3. CONCLUSION

The effect of a 50° to 18.6° abrupt slope change on the air entrainment on stepped chutes was analysed from data gathered on an experimental facility assembled at the Laboratory of Hydraulic Constructions (LCH) of EPFL. Measurements of air concentration profiles were conducted and the extracted data are discussed.

The results demonstrate that abrupt slope changes on stepped chutes have a major effect on the air entrainment and flow bulking in the vicinity of the respective transition region. Four main sub-regions were identified, with a decrease in the air concentration when approaching the slope change cross-section, followed by its sharp increase immediately downstream, reaching a peak, and decreasing further downstream towards an almost constant value. The peak mean air concentration as observed downstream of the slope change cross-section may be considerably larger than that corresponding to the uniform flow condition for the upstream chute, whereas the minimum mean air concentration

downstream of the slope change is larger than that estimated for uniform flow on a similar sloping chute, possibly due to the limited length of the chute.

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