Closure to "Aeration, Flow Instabilities, and Residual Energy on Pooled Stepped Spillways of Embankment Dams" by Stefan Felder and Hubert Chanson

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The authors thank the discussers for their comments. The pooled stepped design is a variation of the classical design with flat steps that may be useful for increased aeration and energy dissipation. Due to the observed instabilities for intermediate flow rates, a safe operation might not be possible and the flat stepped design is preferable. Practical applications for the pooled design could be linked with fish passage or for flood water discharge (e.g., Sorpe dam, Germany). Further modifications of the pooled design introducing pool wall porosity reduce flow instability (Felder and Chanson 2014). The discussers raise some interesting points upon which the authors would like to comment.

The authors share the discussers' concern for scale effects in air-water flows on stepped spillways. Felder and Chanson (2009) conducted a detailed study of scale effects in air-water flows on a stepped spillway with $\theta = 21.8°$, comprising a wide range of air-water flow properties. While the criterion of Reynolds numbers $\mathsf{R} > 10^5$ (Boes and Hager 2003) may be valid in terms of void fraction and interfacial velocity, recent studies (Chanson 2009; Felder and Chanson 2009) highlighted that the notion of scale effects must be defined in terms of some specific set of two-phase air-water characteristics, and some aerated flow properties are more affected by scale effects than others, even in large-size facilities. The selection of the criteria to assess scale effects is critical and any mention of scale effects must be associated with a list of tested parameters (Chanson 2009; Chanson and Chachereau 2013). This is well-known in monophase flows (Schultz and Flack 2013). Furthermore, Chanson (2013) argued that prototype air-water flow experiments are needed to validate the model experiments because of the limiting Reynolds numbers in laboratory conditions. Since the same fluids (air and water) are used in model and prototype, dimensional considerations showed that the Morton number is a constant (Wood 1991; Chanson 2009). Thus the limitations relevant for air-water two-phase flows using the Froude similitude may be expressed either in terms of Reynolds or Weber number. Considering only one limitation, the other is implicitly also respected (Pfister and Chanson 2012). As stated in the original paper, the measurements of the air-water flow properties in Felder and Chanson (2013) were conducted for $0.073 \leq q_w \leq 0.25\ \mathrm{m^2/s}$ for $\theta = 26.6°$ and $0.054 \leq q_w \leq 0.234\ \mathrm{m^2/s}$ for $\theta = 8.9°$, which corresponded to Reynolds numbers of $2.9 \times 10^5 \leq \mathsf{R} \leq 9.9 \times 10^5$ for $\theta = 26.6°$ and $2.2 \times 10^5 \leq \mathsf{R} \leq 9.3 \times 10^5$ for $\theta = 8.9°$, which might be 1 to 3 orders of magnitude smaller than prototype Reynolds numbers, but fulfill the simplistic criterion of Boes and Hager (2003) for void fraction and velocity.

A wider range of flow rates were used for the observation of the air-water flow patterns and for the inception points of air entrainment only: $0.004 \leq q_w \leq 0.267\ \mathrm{m^2/s}$, $1.5 \times 10^4 \leq \mathsf{R} \leq 1.1 \times 10^6$ for $\theta = 26.6°$, and $0.004 \leq q_w \leq 0.234$, $3.4 \times 10^4 \leq \mathsf{R} \leq 9.3 \times 10^5$ for $\theta = 8.9°$. As pointed out by the discussers, the present and previous observations of inception point locations were in good agreement and close to the various empirical equations. The significance of the authors' findings is the close agreement of flat and pooled stepped observations showing little influence of the pooled weir on the location of onset of free-surface aeration for both channel slopes.

The discussers discussed the issue of the channel width. While the authors agree that the channel width might have effects upon the clear-water flow region upstream of the inception point of air

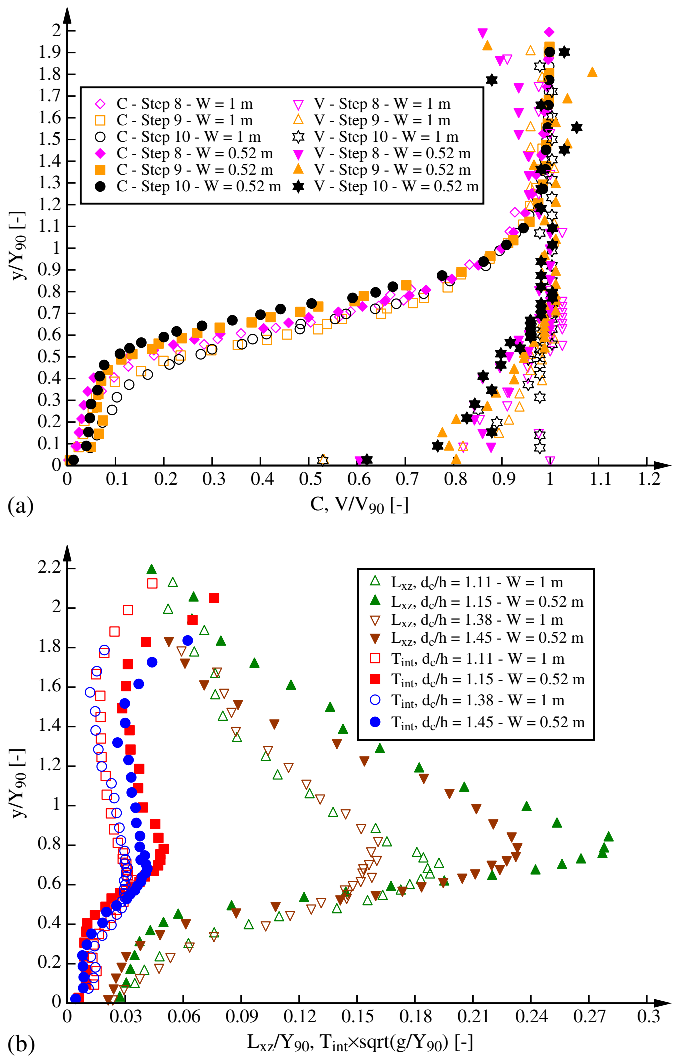

Fig. 1. Comparison of air-water flow properties on two stepped spillways with same channel slope $\theta = 26.6°$, same step height $h = 0.1$ m and different channel widths $W = 1$ and 0.52 m: (a) comparison of void fraction and interfacial velocity: Spillway $W = 1$ m: $d_c/h = 1.28$, $q_w = 0.143\ \mathrm{m^2/s}$, $\mathsf{R} = 5.7 \times 10^5$; Spillway $W = 0.52$ m: $d_c/h = 1.29$, $q_w = 0.144\ \mathrm{m^2/s}$, $\mathsf{R} = 5.7 \times 10^5$; (b) comparison of integral turbulent time T_{int} and length L_{xz} scales for different skimming flow rates at step edge 10

entrainment, the influence of the channel width in air-water flows is limited. Felder (2013) conducted experiments on two flat stepped spillway facilities with $\theta = 26.6°$, step heights of 0.1 m and two channel widths $W = 0.52$ and 1 m. The flow patterns and the inception point positions were not affected by the channel widths. A relatively close agreement in terms of void fraction and interfacial velocity was observed [Fig. 1(a)]. The bubble count rates and the turbulence levels were also similar. The comparison of the integral turbulent scales for the two spillways showed however some differences. The dimensionless integral turbulent time and length scales, i.e., the sizes of the large transverse eddies in the two-phase flows, were about 20–30% larger in the intermediate and spray regions on the spillway with $W = 0.52$ m [Fig. 1(b)]. The differences might be linked with the upstream inflow conditions on the different stepped facilities, but the channel widths of the two stepped spillways might have also an effect. Further tests are required.

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