Closure to "Simple Design Criterion for Residual Energy on Embankment Dam Stepped Spillways" by Stefan Felder and Hubert Chanson

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The authors thank the discussers for their comments and for providing further experimental data on embankment sloped stepped spillways. The authors would like to reiterate their difficulty in using the data from the discussers' original paper (Hunt et al. 2014). While the authors agree that the data in Hunt et al. (2014) allowed an identification of the aerated and nonaerated flow regions, the authors had (and still have) difficulties in extracting the dimensionless residual head H_{res}/d_c versus the dimensionless discharge d_c/h out of Hunt et al. (2014). The authors are grateful that the discussers provided their data in the discussion for a comparison with the proposed simple design guideline (Fig. 1).

Herein the discussers' data were analyzed and applied in the same way as the data summarized in the original design guidelines of the original paper. Based on the discussers' flow rate and chute slope data, only the residual head at the chute's downstream end was selected, i.e., one data point for each flow condition. For data to be considered, these had to be at least three step edges downstream of the inception point of air entrainment, and the comparison was applied to the following flow conditions: $1.06 \le d_c/h \le 4$ for $14.6° \le \theta \le 19°$ and $0.69 \le d_c/h \le 3.6$ for $\theta = 26.6°$. As seen in Fig. 1, the discussers' data fit very well with the analysis in the original paper within the range of all available residual head data. The data are also well within the range of the mean residual head for the corresponding chute slope and its standard deviation (dashed lines, Fig. 1). Overall, the data in the discussion confirm the simple design guidelines in the original paper for flat stepped spillways.

The authors would like to emphasize that their simple design guidelines in the original paper develop a more advanced approach to established criteria, presenting both mean value and standard deviation from all available air-water flow data at the downstream end of a stepped spillway and for a particular channel slope. The present design criterion accounts for all flow conditions for a range of discharges in both transition and skimming flow regimes and a wide range of chute slopes relevant to embankment dam spillways.

The discussers raised further aspects that the authors would like to correct and clarify:

- The majority of data used for the design criterion were skimming flow data, not transition flow experiments as hinted by the discussers. As reported by Felder and Chanson (2011), a transition flow regime for a stepped spillway with $\theta = 26.6°$ was observed for $d_c/h < 1$. For a stepped spillway with $\theta = 15.9°$, Gonzalez (2005) observed transition flows for $d_c/h \le 1.3$. As can be seen in Fig. 1, the large majority of data were observed in the more stable skimming flow regime.

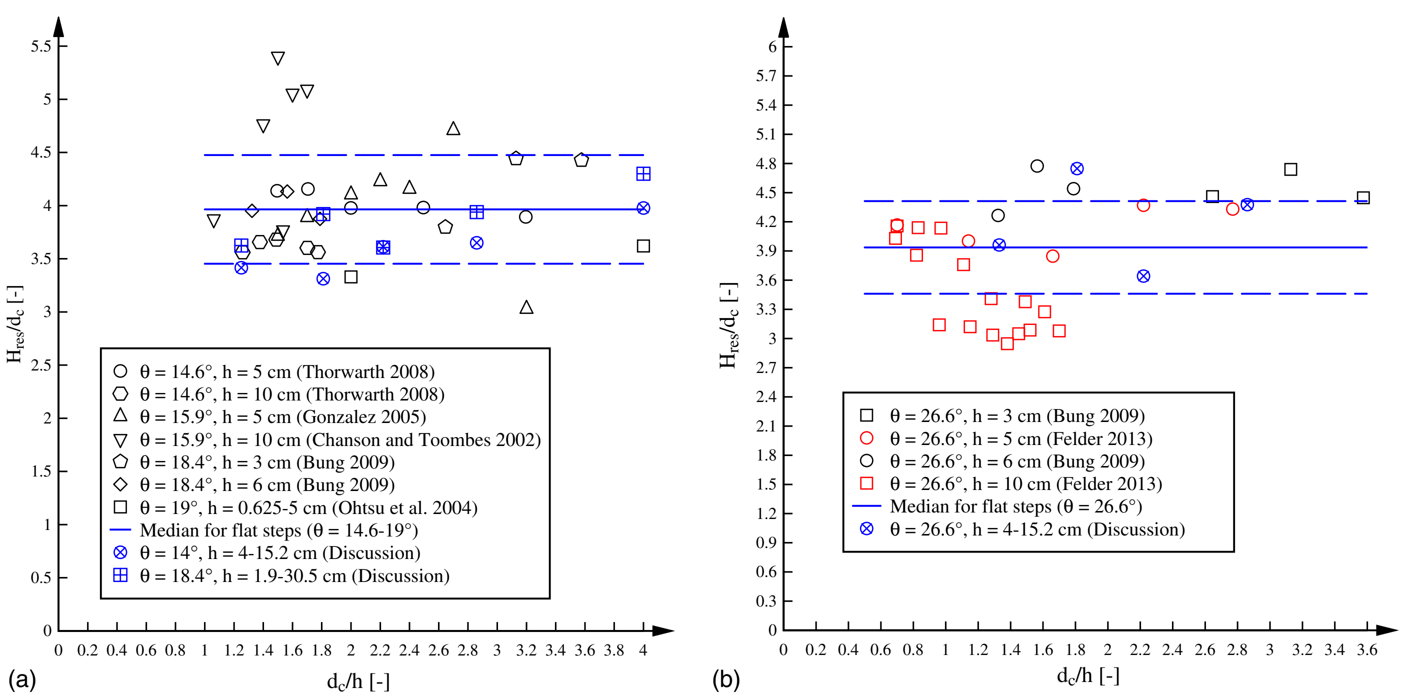

Fig. 1. Dimensionless residual energy at the downstream end of stepped spillways with flat uniform steps and with embankment dam slopes; comparison of data and design criterion from the original paper with data from the discussion; solid line = median values for design guidelines; dashed lines = standard deviation of data: (a) residual energy and median values for $14.6° \le \theta \le 19°$; (b) residual energy and median values for $\theta = 26.6°$

Moreover, the design criterion for slopes within $14.6° \leq \theta \leq 19°$ is only valid for skimming flows, as clearly explained in the original paper (e.g., Table 3).

- The discussers assert that it is important for the designer to know the flow regime for the stepped spillway design due to the more unstable transition flow regime. Indeed, the design must incorporate the design flow conditions as well as the transition flows. During the rising stage of a flood, the spillway outflow will always pass first through the nappe flow and later the more unstable transition flow regime before reaching a skimming flow regime. To the best of our knowledge, the proposed guideline in the original paper is the only guideline that incorporates both transition and skimming flow regimes. A sensitivity analysis by design engineers can be performed based on the provided mean values and the standard deviation.
- The discussers ascertain that there might be an effect of step height on the residual head. While the authors agree that there is a clear effect of scaling on the air-water flow properties (e.g., Felder and Chanson 2009), no effect of step height on the residual head was observed. Indeed, both the authors' and the discussers' data were collected for a range of step heights, presenting very consistent results in terms of residual head along the stepped spillway independently of step height. For completeness, the dimensionless properties of the inception point of free-surface aeration were also independent of the step heights.
- The discussers ask about the effects of chute slope on the residual head at the downstream end. The chute slope is indeed a key parameter of the authors' design guidelines, highlighting different mean values for different stepped spillway slopes (e.g., Fig. 1). The original paper confirmed a trend of an increase of residual head with increasing chute slope for $\theta \leq 19°$. For a chute slope of $\theta = 21.8°$ ($1V$:$2.5H$), the residual head was smallest within the range $14° \leq \theta \leq 26.6°$, suggesting an optimum embankment dam design for this slope. These observations were consistent with the observations of Ohtsu et al. (2004) and Gonzalez and Chanson (2006).
- The discussers questioned if the distance between the inception point of air entrainment and the downstream end of the spillway was long enough to be in the uniform (equilibrium) flow region. As shown in Fig. 5 of the orignal paper, the data used for the calculation of the residual head were obtained in a gradually varied flow region in which both mean void fraction and equivalent clear-water flow depth approached quasi-uniformity and hence the residual head was close to a uniform equilibrium value. On the contrary, some other air-water flow properties did not reach equilibrium, e.g., bubble count rate and air-water-specific interface area. Such gradually varied flow data sets (e.g., Toombes 2002; Gonzalez 2005; Felder 2013) are further directly relevant to small to moderately high dam projects, for which the downstream flow conditions are most unlikely to reach uniform equilibrium at moderate to large overflows.

The authors believe that their design criteria present a simple design alternative to existing design guidelines for stepped spillways with flat steps and without any tailwater influences. The authors thank the discussers for their data, which confirmed the authors' design guidelines, with a further data set of air-water flow experiments on stepped spillways with embankment dam slopes. The authors hope that the clarifications in this closure shall contribute to a better understanding and acceptance of their simple design approach.

References

Bung, D. B. (2009). "Zur selbstbelüfteten gerinneströmung auf kaskaden mit gemäßigter neigung." Ph.D. thesis, Bergische Universitaet Wuppertal, Wuppertal, Germany (in German).

Chanson, H., and Toombes, L. (2002). "Air-water flows down stepped chutes: Turbulence and flow structure observations." *Int. J. Multiphase Flow*, 28(11), 1737–1761.

Felder, S. (2013). "Air-water flow properties on stepped spillways for embankment dams: Aeration, energy dissipation and turbulence on uniform, non-uniform and pooled stepped chutes." Ph.D. thesis, School of Civil Engineering, Univ. of Queensland, Brisbane, Australia.

Felder, S., and Chanson, H. (2009). "Turbulence, dynamic similarity and scale effects in high-velocity free-surface flows above a stepped chute." *Exp. Fluids*, 47(1), 1–18.

Felder, S., and Chanson, H. (2011). "Energy dissipation down a stepped spillway with non-uniform step heights." *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000455, 1543–1548.

Gonzalez, C. A. (2005). "An experimental study of free-surface aeration on embankment stepped chutes." Ph.D. thesis, Dept. of Civil Engineering, Univ. of Queensland, Brisbane, Australia.

Gonzalez, C. A., and Chanson, H. (2006). "Flow characteristics of skimming flows in stepped channels." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2006)132:5(537), 537–539.

Hunt, S. L., Kadavy, K. C., and Hanson, G. J. (2014). "Simplistic design methods for moderate-sloped stepped chutes." *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000938, 04014062.

Ohtsu, I., Yasuda, Y., and Takahashi, M. (2004). "Flow characteristics of skimming flows in stepped channels." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2004)130:9(860), 860–869.

Thorwarth, J. (2008). "Hydraulics of pooled stepped spillways. Self-induced unsteady flow and energy dissipation." Ph.D. thesis, Univ. of Aachen, Aachen, Germany (in German).

Toombes, L. (2002). "Experimental study of air-water flow properties on low-gradient stepped cascades." Ph.D. thesis, Dept. of Civil Engineering, Univ. of Queensland, Brisbane, Australia.