E-proceedings of the 36th IAHR World Congress
28 June – 3 July, 2015, The Hague, the Netherlands

SCALE EFFECTS IN HIGH-VELOCITY AIR-WATER FLOWS ON A STEPPED SPILLWAY

STEFAN FELDER[(1)] &HUBERT CHANSON[(2)]

[(1)] *Water Research Laboratory, School of Civil and Environmental Engineering, UNSW Australia, Manly Vale, Australia, s.felder@unsw.edu.au*

[(2)] *The University of Queensland, School of Civil Engineering, Brisbane, Australia, h.chanson@uq.edu.au*

ABSTRACT

A comparative analysis of air-water flow properties was performed between two geometrically scaled stepped spillway models with step height of 5 and 10 cm respectively. The experiments were conducted in the same large size facility with chute slope of 26.6° and with the same phase-detection intrusive measurement devices. A full range of macro- and micro-scopic air-water flow properties was tested for Froude and Reynolds similitudes. Significant scale effects were found in transition and skimming flows. The present finding stressed that the notion of scale effects must be defined in terms of explicit set of air-water flow property(ies). Some air-water flow parameter are more affected by scale effects than others, even in large-size facilities. On one hand, the void fraction and flow bulking are not much sensitive to scale effects. On another hand, the data analyses confirmed scale effects in terms of bubble count rate, turbulence properties and air bubble and water droplet chord sizes, while the present investigation highlighted also scale effects in terms of further air-water flow properties including particle clustering, inter-particle arrival times as well as auto- and cross-correlation functions and time scales respectively. For all air-water flow properties, a close agreement was found between transition and skimming flow outcomes. The findings highlighted that a scaling of the air-water flow properties is rarely possible and measurements at a prototype scale are needed to identify the limitations of scaled air-water flow experiments.

Keywords: *Air-water flows, physical modelling, scale effects, air-water flow properties, stepped spillway*

1. INTRODUCTION

Stepped spillways are a common type of hydraulic structure designed to discharge waters safely in case of a flood event as well as used as low-head hydraulic structure in urban or riverine environments (Chanson 2001). The steps are advantageous because they increase the energy dissipation performance along the staircase chute and reduce the size of the downstream stilling basin. An additional benefit of the macro-roughness step elements is the position of the inception point of free-surface aeration which is occurs much earlier compared to smooth chutes resulting in a reduction of cavitation risks and an increased re-aeration of the flows. Downstream of the inception point, the air-water flows are complex and various three dimensional processes take place including momentum exchanges between different flow regions within the flow as well as interactions between the flow and the free-surface (Figure 1A).

Due to its complexity, the numerical modelling of aerated stepped chute flows is currently not possible and experiments at laboratory scale are typically conducted to investigate flow performances and design optimisation. These experiments are performed with a geometric scaling ratio trying to reproduce the air-water flows which would occur at prototype scale in the laboratory. A true dynamic similarity of the model scale flows is not possible unless working at prototype-scale and scale effects must be considered. In particular the scaling of air-water flows is difficult and scale effects have been reported in a variety of air-water flows in hydraulic engineering applications (Kobus 1984).

Recently Heller (2011) provided a literature overview about the scaling criteria and physical modelling approaches to minimize scale effects in hydraulic engineering. While the guideline provides some advice, the suggestions in terms of air-water flows scaling were crude, restricted to void fraction and interfacial velocity. Using these parameters Boes (2000) provided earlier guideline of maximal scaling proportion of 1:10 for stepped spillway flows based upon a Froude similitude. In air-water flows both viscous and gravity forces and important and further dimensionless parameters must be addressed. The Morton number was acknowledged as the dimensionless number which links the Weber and Reynolds numbers in air-water flows if the same liquids are used in the scaled models (Kobus, 1984; Wood, 1991; Pfister and Chanson, 2012). The general need for large size facilities in physical modelling of air-water flows and the limitations were emphasized recently by Chanson (2013) and Pfister and Chanson (2014). Indeed the results of recent experimental investigations emphasised that the selection of the criteria to assess scale affects is critical (Chanson, 2009; Chanson and Chachereau, 2013; Schulz and Flack, 2013). These results showed that some parameters, such as bubble sizes and turbulent scales, are likely to be affected by scale effects, even in relatively large-size laboratory models (e.g. 2:1 to 3:1). No scale effect is only observed at full scale using the same fluids in prototype and model.

In the past few years, several studies of air-water flow properties have pointed out that the scaling of air-water flows to a prototype is not possible using Froude or Reynolds similitudes. In particular the scaling of bubble chord sizes, turbulence levels and scales and number of entrained air bubbles is impossible in free-surface air-water flows. These studies comprised aerated flows in hydraulic jumps (Chanson, 2009; Chanson and Chachereau, 2013) and air-water flows on stepped spillways (Chanson and Gonzalez, 2005; Felder and Chanson, 2009; Felder, 2013). The present investigation adds to these findings by analysing the full range of macro- and microscopic air-water flow properties in terms of scale effects for a wide range of discharges in transition and skimming flows. Herein the present results provide a clearer guidance regarding which air-water flow properties may be affected by scale effects in both Froude and Reynolds similitudes.

2. Physical modelling and experimental configurations

A large number of parameters are relevant to describe the dynamic flow processes in the high-velocity turbulent air-water flows including the fluid properties, physical constants, flow conditions and stepped spillway geometry. A dimensionless analysis can identify the relationship between air-water flow properties and the relevant parameters (Eq. [1]). In stepped spillway flows both Reynolds and Froude numbers are relevant dimensionless numbers for a dynamic similarity. Therefore a true dynamic similarity between model and prototype cannot be achieved because it is impossible to satisfy simultaneously Froude and Reynolds similarities. Just one of these two parameters can be equal in model and prototype and a detailed testing of the limitations of both Froude and Reynolds similitudes is necessary.

Equation [1] shows a simplified relationship between air-water flow properties and physical constants for a skimming flow on a stepped spillway:

$$C, \frac{V}{\sqrt{g \times d_c}}, \frac{u'}{V}, T_{int} \times \sqrt{\frac{g}{d_c}}, \frac{L_{xz}}{d_c}, \frac{d_{ab}}{d_c}, ... = F\left(\frac{x}{d_c}, \frac{y}{d_c}, \frac{d_c}{h}, Re\right) \quad [1]$$

where C is the local void fraction, V is the local velocity, g is the gravity acceleration, d_c is the critical flow depth, u' is a characteristic turbulent velocity, T_{int} is a turbulent time scale, L_{xz} is a turbulent length scale, d_{ab} is a characteristic size of entrained bubbles, x and y are the coordinates in the flow direction and perpendicular to the flow measured from the step edges, h is the step height and Re is the Reynolds number defined in terms of the hydraulic diameter. The term d_c/h is the dimensionless discharge and proportional to a Froude number defined in terms of the step height since:

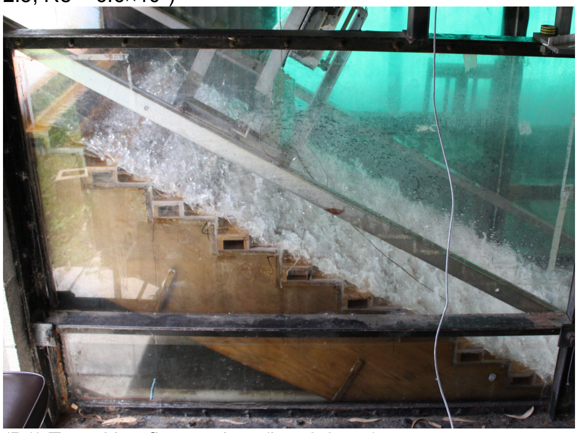
$$\frac{d_c}{h} = \sqrt[3]{\frac{q_w^2}{g \times h^3}} \propto Fr^{2/3} \quad [2]$$

In the present study, both Froude and Reynolds similitudes were tested for geometrically scaled stepped spillway models with a scaling ratio of 1:2. One stepped spillway model had step heights of h = 5 cm and the scaled version comprised 10 steps with height h = 10 cm. Both stepped configurations were installed in the same test section with channel slope of 26.6°, channel width of 1 m and identical inflow conditions. For a wide range of discharges in both transition and skimming flows, air-water flow experiments were conducted with dual-tip phase detection intrusive probes. Based upon the different resistivity of air and water, the two identical sensors provided an instantaneous air-water Voltage signal. The sensors were separated in flow direction by a distance of Δx = 7.2 mm and sampled simultaneously for 45 seconds with 20 kHz. The resulting raw signal was analysed based upon a single-threshold technique and correlation analyses to provide the full range of air-water flow properties (Felder 2013).

Tables 1 and 2 summarise the experimental flow conditions for the investigation of scale effects comprising a range of flow rates and Reynolds numbers in both transition and skimming flow regimes. For the two step heights, the tables include information regarding the dimensionless discharge d_c/h and the dimensional discharge per unit width q_w as well as the corresponding Reynolds number defined in terms of the hydraulic diameter (Table 1 and 2). Further information comprises the measured step edges for the respective flow conditions downstream of the inception point of air entrainment also provided. Please note that the comparison of scale effects was always conducted at the same distance downstream of the inception point of air entrainment and at least three step edges downstream of the rapidly varied flow at the inception point. Tables 1 and 2 include also information regarding the flow regimes, i.e. skimming flows (SK) and transition flows (TRA).

The skimming flow regime is characterised by relatively stable three-dimensional air-water flow motions with strong recirculation movements within the step cavities and an undefined air-water free-surface with a large amount of ejected water droplets (Figure 1). The transition flow regime is characterised by small flow instationarities comprising some instable cavity recirculation and ejection processes and water droplet ejection of several step heights (Figure 1B2). Figure 1B illustrates typical flow patterns for the two flow regimes investigated in the present study. The visual inspection of the flow patterns for the two scaled models did not show any differences in air-water flow motions for the respective flow regime. The inclusion of both transition and skimming flow regimes in the present study allowed for the testing of a wider range of flow conditions enabling the possibility to apply the scaling guidelines developed in this study to further air-water free-surface flows.

(A) Skimming flow on the Hinze dam stepped spillway (Gold Coast, Australia) in January 2013 (θ = 51.3°, h = 1.2 m, q_w = 17 m^2/s, d_c/h = 2.5, Re = 6.6×10^7)



(B1) Transition flow regime (h = 0.05 m)

(B2) Skimming flow regime (h = 0.10 m)

(B) Laboratory investigations (θ = 26.6°)

Figure 1.Air-water flow patterns on stepped spillways

Table 1. Experimental flow conditions for comparison of air-water flow properties in air-water flows on a stepped spillway (θ = 26.6°) based upon Froude similitude

Step height: h = 10 cm						Step height: h = 5 cm					
d_c/h [-]	q_w [m^2/s]	Re [-]	Flow regime	Step edge	Incep. point	d_c/h [-]	q_w [m^2/s]	Re [-]	Flow regime	Step edge	Incep. point
0.69	0.056	2.2×10^5	TRA	4–10	3 to 4	0.7	0.020	8.1×10^4	TRA	4–10	4
1.11	0.116	4.6×10^5	SK	6–10	6	1.14	0.042	1.7×10^5	SK	6–10	6 to 7
1.61	0.202	8.0×10^5	SK	9+10	9 to 10	1.66	0.075	3.0×10^5	SK	8–10	8 to 9

Table 2. Experimental flow conditions for comparison of air-water flow properties in air-water flows on a stepped spillway (θ = 26.6°) based upon Reynolds similitude

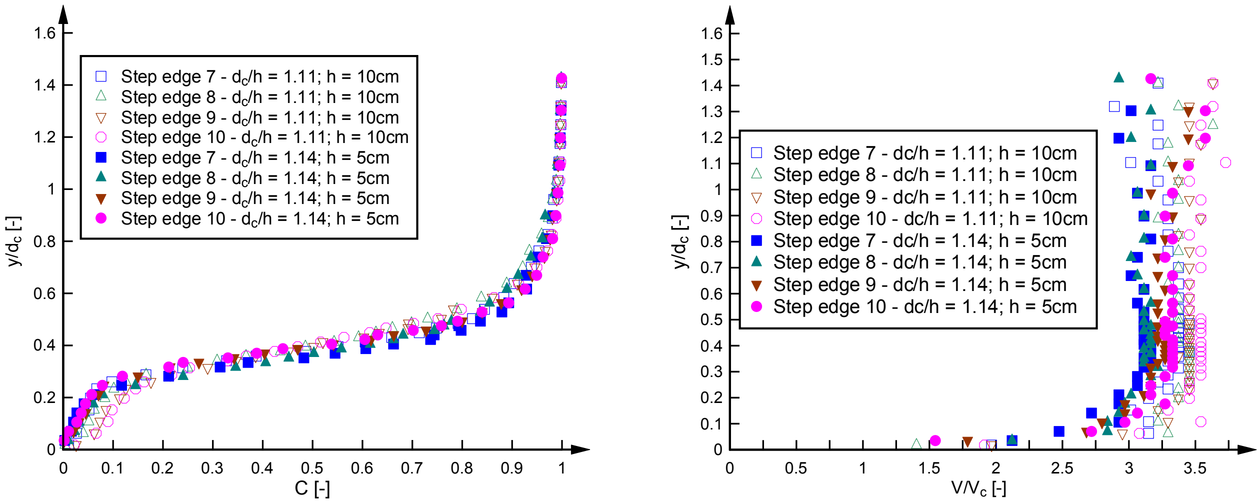
Step height: h = 10 cm						Step height: h = 5 cm					
d_c/h [-]	q_w [m^2/s]	Re [-]	Flow regime	Step edge	Incep. point	d_c/h [-]	q_w [m^2/s]	Re [-]	Flow regime	Step edge	Incep. point
0.83	0.075	3.0×10^5	TRA	4–10	4	1.66	0.075	3.0×10^5	SK	8–14	8 to 9
1.11	0.116	4.6×10^5	SK	6–10	6	2.22	0.116	4.6×10^5	SK	12–16	12
1.38	0.161	6.4×10^5	SK	7–10	7 to 8	2.77	0.161	6.4×10^5	SK	18–20	18
1.61	0.202	8.0×10^5	SK	9+10	9 to 10	3.3	0.210	8.3×10^5	SK	20	20

3. Scale effects in air-water flows

A large number of air-water flow properties were analysed in terms of scale effects comprising a range of standard air-water flow parameters such as void fraction C, bubble count rate F, interfacial velocity V and air bubble and water droplet chord sizes. Furthermore advanced air-water flow properties were included in the analysis including the turbulence intensity Tu, the integral turbulent time and length scales T_{int} and L_{xz} and for the first time, the auto- and cross-correlation functions and the corresponding auto- and cross-correlation integral time scales as well as a range of cluster properties and the inter-particle arrival time analysis. Not all parameters are shown in this manuscript, but a large range of parameters is presented for the Froude similitude for both transition and skimming flows. The results for the comparative analysis based upon the Reynolds similitude are not presented in detail, but the key findings are discussed. The full-range of results of investigated air-water flow properties is available in Felder (2013).

3.1 Froude similitude

A large number of air-water flow properties are presented in this section focusing on the comparative analysis of the two-scaled stepped spillways for the flow conditions summarized in Table 1. A typical parameter is the void fraction which showed good agreement between the geometrically scaled stepped spillways (Figure 2A). In Figure 2A, the agreement is visible for a typical skimming flow discharge for several consecutive step edges illustrated as the dimensionless distance perpendicular to the main flow direction y/d_c. The void fraction was properly scaled in a Froude similitude. The findings were consistent with observations of void fractions on geometrically scaled stepped spillways with slopes of 3.4° and 15.9° (Chanson and Gonzalez, 2005), on a stepped spillway with θ = 21.8° (Felder and Chanson, 2009) and for three different step heights on slopes of 30° and 50° (Boes, 2000). Figure 2B illustrates typical dimensionless distributions of interfacial velocity V/V_c for several consecutive step edges in a skimming flow. The interfacial velocity is a time-averaged air-water velocity and V_c is the critical flow velocity. The dimensionless interfacial velocity distributions showed little difference which was consistent with previous studies (Boes, 2000; Chanson and Gonzalez, 2005; Felder and Chanson, 2009). The interfacial velocity was properly scaled with a Froude similitude. For both void fraction and interfacial velocity distributions, similar results were also observed for the transition flow regime.



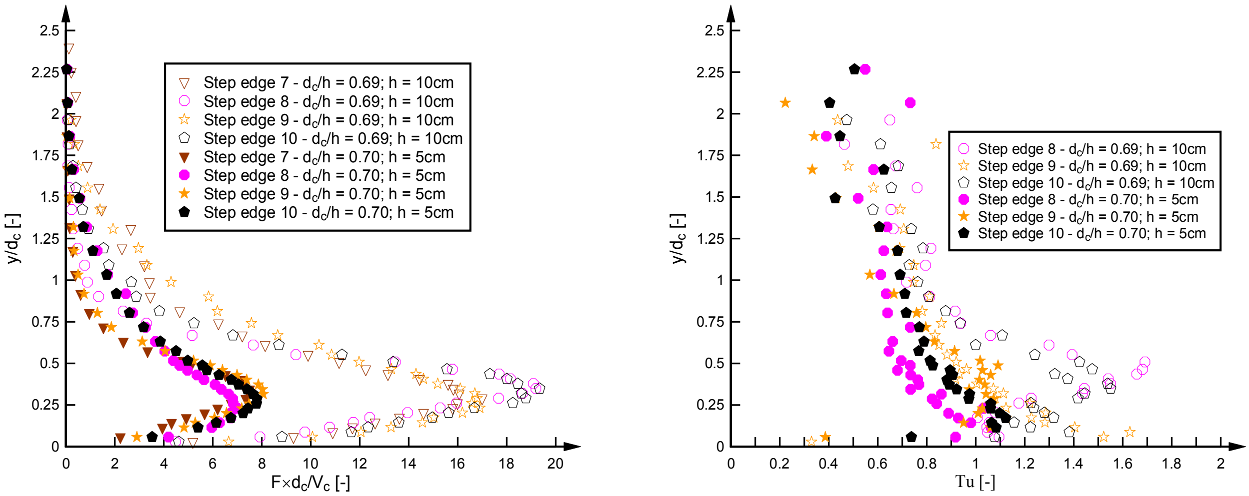
(A) Void fraction distributions

(B) Dimensionless interfacial velocity distributions

Figure 2. Comparison of air-water flow properties on two spillways with geometric scaling ratio of 1:2; Froude similitude; skimming flow regime: h = 10 cm, d_c/h = 1.11, q_w = 0.116 m^2/s, Re = 4.6 × 10^5; h = 5 cm, d_c/h = 1.14, q_w = 0.042 m^2/s, Re = 1.7 × 10^5

The bubble count rate represents the number of changes of water-to-air and air-to-water interfaces within the flows and characterizes the air-water activity levels of the flows. Typically the largest bubble count rates were observed in the intermediate flow region where 0.3 < C < 0.7 indicating strong energetic interactions between air and water faces in the bulk of the flow. For all experiments, the dimensionless bubble count rate distributions showed significant differences (Figure 3A) for both transition and skimming flows (Figure 3A). For the smallest step heights, the dimensionless bubble count rates were typically half the size of the complementing bubble frequencies for the larger step heights. The Froude similitude did not scale the number of entrained air bubbles accurately and the air-water mass transfer might be affected (Toombes and Chanson, 2005). A closely related parameter is the specific interfacial area a defined as the air-water interface area per unit volume of air and water. Herein large scale effects were also observed in terms of the specific interfacial area highlighting that the air-water mass transfer cannot be properly scaled with a Froude similitude. Please note that the scale effects of specific interfacial area are not shown in this manuscript. The finding of scale effects in terms of bubble count rate was consistent with the observations by Chanson and Gonzalez (2005) and Felder and Chanson (2009) in their stepped spillway experiments.

Good agreement of the present investigation with these previous studies was also found in terms of the turbulence intensities Tu. The turbulence intensities in air-water flows are not based upon velocity fluctuations as in mono-phase flows, but on the shape of the cross-correlation functions representing the deviation from the Gaussian distribution. The comparison of turbulence intensities for the two models showed scale effects with consistently larger turbulence levels for the larger step heights (Figure 3B). The differences were about 20 to 40% in both transition and skimming flows. Chanson and Gonzalez (2005) stated that lesser turbulence intensities for smaller models must imply a lesser rate of energy dissipation. The observation of smaller turbulence levels with lesser number of entrained air bubbles for the smallest step height is consistent with a dimensionless linear relationship between bubble count rate and turbulence intensities on stepped spillways (Felder and Chanson, 2011).



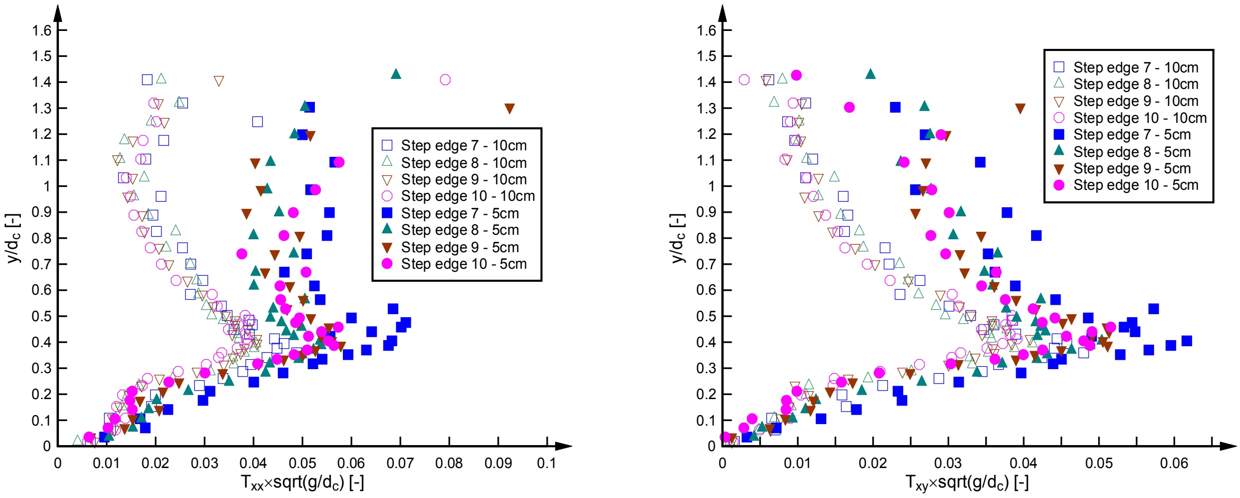
(A) Dimensionless bubble count rate distributions

(B) Turbulence intensity distributions

Figure 3. Comparison of air-water flow properties on two spillways with geometric scaling ratio of 1:2; Froude similitude; transition flow regime: h = 10 cm, d_c/h = 0.69, q_w = 0.056 m^2/s, Re =2.2 × 10^5; h = 5 cm, d_c/h = 0.7, q_w = 0.02 m^2/s, Re = 8.1 × 10^4

For the leading tip of the double-tip conductivity probe, an auto-correlation of the signal was performed providing auto-correlation distributions and after integration, the auto-correlation time scales of the air-water flows. Similarly, the cross-correlation analysis of the two simultaneously sampled sensors provided the cross-correlation functions and the corresponding cross-correlation time scales. All auto- and cross-correlation flow properties exhibited small scale effects. For both auto- and cross-correlation functions, slight differences were observed between the two stepped spillway configurations. It appeared that the stepped spillway with 10 cm step height had larger auto- and cross-correlation values in the bubbly flow region. In the intermediate flow region, little difference between the curves existed, but in the spray region, the auto- and cross-correlation functions of the smaller step height appeared slightly larger. The maximum cross-correlation coefficient was observed at different locations for the two stepped spillway configurations. Please note that no correlation functions are presented in this manuscript; they can be found in Felder (2013).

Figure 4 illustrates typical auto- and cross-correlation time scales for a typical skimming flow discharge. The comparative analysis of the dimensionless correlation integral time scales showed slightly larger time scales for the smallest step height (Figure 4). The differences were seen for the entire air-water flow column. Stronger scatter was observed for the transition flow data. The differences in auto- and cross-correlation time scale distributions were consistent with observations of the auto- and cross-correlation functions. It appeared that a scaling of the time scales to prototype scale was not possible using a Froude similitude. The finding indicates differences of air-water flow interactions on the microscopic scale and highlights the importance to base the scaling of air-water flows not just on rough parameters of void fraction and velocity.



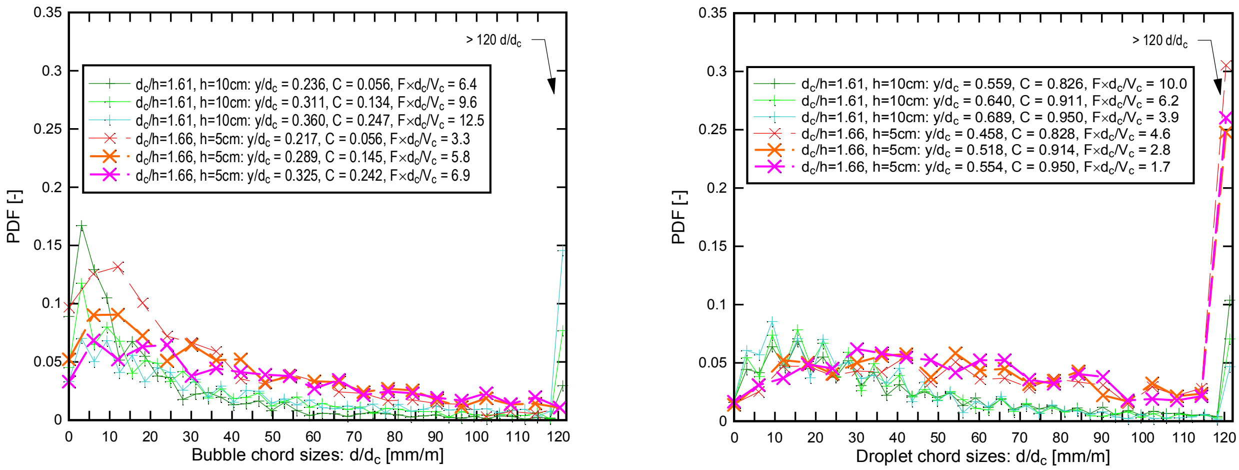
(A) Dimensionless auto-correlation time scale distributions

(B) Dimensionless cross-correlation time scale distributions

Figure 4. Comparison of air-water flow properties on two spillways with geometric scaling ratio of 1:2; Froude similitude; skimming flow regime: h = 10 cm, d_c/h = 1.11, q_w = 0.116 m^2/s, Re = 4.6 × 10^5; h = 5 cm, d_c/h = 1.14, q_w = 0.042 m^2/s, Re = 1.7 × 10^5

The comparative analyses of the two geometrically scaled models investigated in great detail potential scale effects in terms of microscopic air-water flow properties including the chord time distributions, the clustered properties and the inter-particle arrival times. This analysis provided a very detailed picture of the difficulty to scale the microscopic air-water flow interactions accurately and to extrapolate the particle characteristics to prototype scale.

A typical microscopic property are the particle chord sizes which are calculated based upon the time of the air and water phases and hence a characteristic size of the air bubbles and water droplets. In Figure 5, comparisons between the dimensionless air bubble chord sizes (Figure 5A) and between the water droplet chord sizes (Figure 5B) are illustrated. The comparison of the dimensionless chord distributions showed strong differences both in dimensionless air bubble and water droplet chord sizes. For all experimental data in transition and skimming flows, the results showed a greater number of smaller chord sizes for the largest step heights and a greater number of larger chord sizes for the smallest step heights. The Froude similitude did not scale the chord sizes properly. The observations were consistent with experimental results by Chanson and Gonzalez (2005) and Felder and Chanson (2009) and with statements of Kobus (1984) expressed that scaling of entrained air bubble sizes is nearly impossible. Experiments based on a Weber similitude might scale the bubble sizes better, but the gravity and viscous forces are more important than the surface tension in physical modelling of stepped spillways.



(A) Dimensionless air bubble chord sizes

(B) Dimensionless water droplet chord sizes

Figure 5. Comparison of air-water flow properties on two spillways with geometric scaling ratio of 1:2; Froude similitude; skimming flow regime: h = 10 cm, $d_c/h = 1.61$, $q_w = 0.202$ m^2/s, Re = 8.0×10^5; h = 5 cm, $d_c/h = 1.66$, $q_w = 0.075$ m^2/s, Re = 3.0×10^5

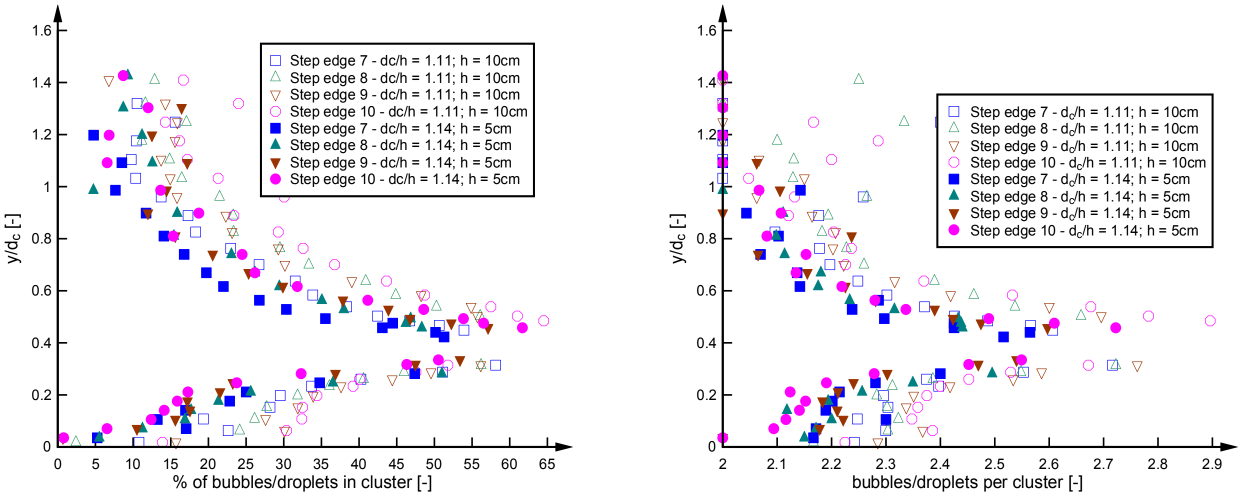
Another type of microscopic air-water flow property is the particle grouping or cluster characteristics providing detailed information about the streamwise structure of the two-phase flow (Heinlein and Fritsching, 2006). Cluster analyses were performed for all experiments based upon the near-wake criterion in which particles were considered as travelling in a cluster if the length scale between successive air bubble or water droplets chords was smaller than the size of the leading bubble/droplet chord (Gualtieri and Chanson 2010). The cluster analyses encompassed a wide range of parameters including the percentage of bubbles/droplets in clusters, the number of clusters per second, the average number of particles per cluster and the average clustered chord sizes.

The comparative analyses of the clustered properties for the two step heights highlighted scale effects for both transition and skimming flows. A larger percentage of bubbles/droplets in clusters for the largest step height were observed (Figure 6A). In Figure 6A, the percentage of bubbles/droplets in clusters is illustrated as a function of the dimensionless height above step edge. Similarly, a larger number of bubbles/droplets per cluster was observed for the largest step heights (Figure 6B).

Further cluster properties showed the same trend (Figure 7). The dimensionless number of clusters per second of the larger step height configuration was about double the number of the smaller step heights throughout the cross-section (Figure 7A). Differences between the two step height configurations were also seen in terms of the clustered bubble/droplet chord sizes. The dimensionless chord sizes for the smallest step height were larger compared to the largest step height (Figure 7B). This finding was consistent with the larger dimensionless chord sizes reported in the PDF distributions of air bubble and water droplet chord sizes (Figure 5).

Overall, the investigations of the cluster properties for the two stepped spillways with geometrically scaled step heights showed the existence of scale effects for several parameters. The findings indicated that the air-water flow properties on a microscopic scale were not properly scaled by a Froude similitude. An extrapolation of the results to a prototype scale is not possible.

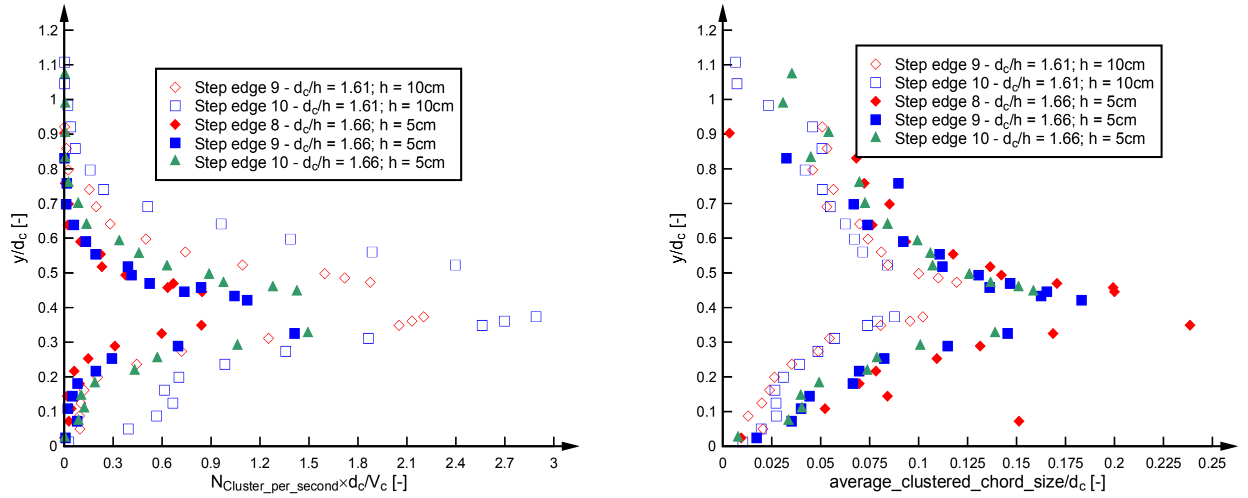
Potential scale effects in terms of the inter-particle arrival times were also investigated. The inter-particle arrival time provided information about the randomness of the travelling particles (Edward and Marx, 1995; Heinlein and Fritsching, 2006; Chanson, 2008). Herein, the particles are split into classes of particle chord sizes for which a similar behavior may be expected (Edward and Marx, 1995). For each class, the PDF of the inter-particle arrival time between successive bubbles/droplets was calculated and compared between the two step height configurations.



(A) Percentage of particles in clusters

(B) Number of particles per cluster

Figure 6. Comparison of air-water flow properties on two spillways with geometric scaling ratio of 1:2; Froude similitude; skimming flow regime: h = 10 cm, d_c/h = 1.11, q_w = 0.116 m^2/s, Re = 4.6 × 10^5; h = 5 cm, d_c/h = 1.14, q_w = 0.042 m^2/s, Re = 1.7 × 10^5



(A) Dimensionless number of clusters per second

(B) Dimensionless average clustered chord sizes

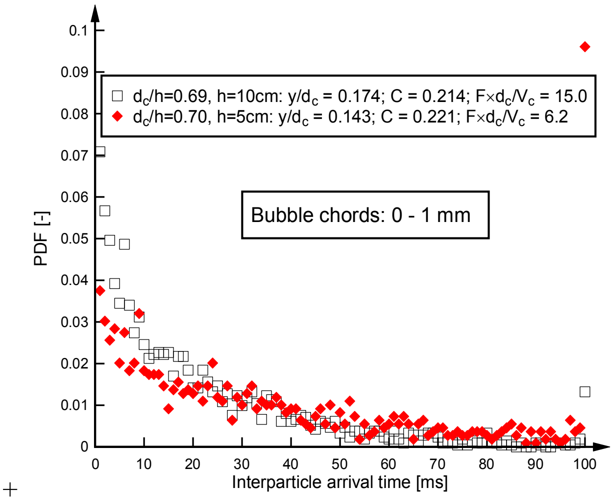
Figure 7. Comparison of air-water flow properties on two spillways with geometric scaling ratio of 1:2; Froude similitude; skimming flow regime: h = 10 cm, d_c/h = 1.61, q_w = 0.202 m^2/s, Re = 8.0 × 10^5; h = 5 cm, d_c/h = 1.66, q_w = 0.075 m^2/s, Re = 3.0 × 10^5

Typical results of inter-particle arrival times for the configurations with 5 and 10 cm high steps are shown in Figure 8 in dimensionless terms for classes of air bubble chord and water droplet sizes respectively. For all experiments and for both air bubbles and water droplet chords, smaller dimensionless inter-particle arrival times were more likely for the larger step heights, while larger dimensionless inter-particle arrival times appeared more often for the configuration with smaller step heights. Interestingly the differences between the two step heights decreased with increasing chord size classes. The comparative analysis indicated that the inter-particle arrival times between air bubbles and water droplets cannot be scaled properly with a Froude similitude.

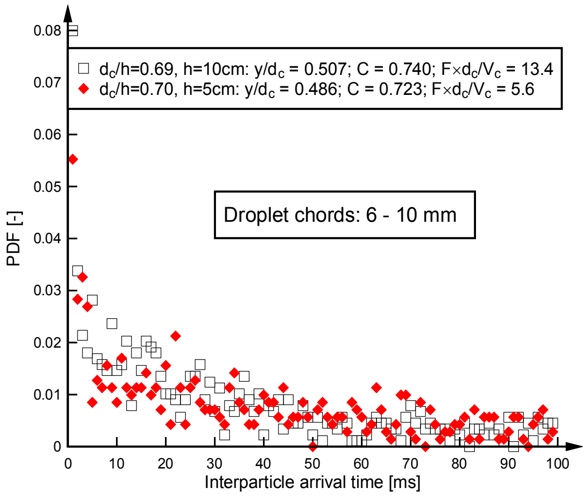
3.2 Reynolds similitude

A broad range of air-water flow properties were also investigated for the two step heights based upon a Reynolds similitude, i.e. the Reynolds numbers were identical in both stepped configurations. The comparative analyses comprised a range of flow conditions in both transition and skimming flows (Table 2). For all experiments, the investigated air-water flow properties included the void fraction, the bubble count rate, the interfacial velocity, the turbulence intensity, the maximum cross-correlation values, the auto- and cross-correlation time scales, the integral turbulent time and length scales, the advection length scale and the air bubble and water droplet chord sizes. For the void fraction and for the dimensionless interfacial velocity, only small differences were visible between the two different step heights. It seemed possible to extrapolate both void fraction and velocity distributions to a prototype scale.

Scale effects were observed in terms of the dimensionless bubble count rate with bubble frequencies for the larger step height about twice the size of the smaller step height. Similarly the turbulence intensities showed differences with turbulence levels about 30-60% lager for the larger step heights. Scale effects were also observed in terms of the auto- and cross-correlation time scales larger time scales for the larger step heights. Furthermore, the PDF of dimensionless bubble and droplet chord sizes showed also scale effects with comparatively smaller chord sizes for the largest step heights. Further details about the investigated parameters and the results can be found in Felder (2013). Overall, the present results confirmed significant scale effects for a Reynolds similitude which highlights the difficulty to scale the air-water flow properties accurately.



(A) Dimensionless inter-particle arrival time of air bubble chords



(B) Dimensionless inter-particle arrival time of water droplet chords

Figure 8. Comparison of air-water flow properties on two spillways with geometric scaling ratio of 1:2; Froude similitude; transition flow regime: h = 10 cm, d_c/h = 0.69, q_w = 0.056 m^2/s, Re =2.2 × 10^5; h = 5 cm, d_c/h = 0.7, q_w = 0.02 m^2/s, Re = 8.1 × 10^4

4. DISCUSSION

In the present study a wide range of air-water flow properties was tested for Froude and Reynolds similitudes and significant scale effects were found in terms of a broad range of parameters. While some key outcomes were presented in the present study, not all scale effects were presented. Table 3 summarises the tested macro- and microscopic air-water flow properties affected by scale effects. The results highlighted that a proper scaling of the air-water flows on geometrically scaled stepped spillways is not possible using either the Froude or Reynolds similitudes. It is believed that the stepped spillway investigation provides some clear guidance for possible scale effects in further air-water flows with violent entrainment process through the free-surface including hydraulic jumps, ski jumps, drop structures as well as for breaking waves. The findings of several systematic experimental studies including the present one demonstrated that the notion of scale effects must be defined in terms of very specific set of air-water flow property(ies), and (b) some aerated flow properties are more affected by scale effects than others, even in large-size facilities.

However, self-similar relationships were found which allowed a characterisation of the air-water flows independent of the physical scale (Table 3). While similar findings were previously by Chanson and Carosi (2007) and Felder and Chanson (2009), the present study encompassed a much broader data set for stepped spillways with slopes of 8.9, 15.9, 21.8 and 26.6° and for a wide range of flow conditions in transition and skimming flow regimes. The concept of self-similarity might be also applicable for other types of aerated flows and might be an important concept to progress the numerical modelling of complex aerated flows. Felder (2013) listed a number of self-similar equations which described the air-water flow properties independent of step height and channel slope. Herein the concept of self-similarity seems a powerful tool, prototype scale experiments are needed to confirm the self-similar relationships and to validate the laboratory studies of the past and present.

Table 3. Summary of scale effects for Froude and Reynolds similitudes in high-velocity free-surface flows on a geometrically scaled stepped spillway (θ = 26.6°).

AIR-WATER FLOW PROPERTY	SCALE EFFECTS IN FROUDE SIMILITUDE	SCALE EFFECTS IN REYNOLDS SIMILITUDE
Void fraction	No scale effects	No scale effects
Bubble count rate	**Scale effects**	**Scale effects**
Interfacial velocity	No scale effects	Small scale effects
Turbulence intensity	**Scale effects**	**Scale effects**
Interfacial aeration	**Scale effects**	**Scale effects**
Auto-correlation function	Small scale effects	not investigated
Cross-correlation function	Small scale effects	not investigated
Maximum cross-correlation coefficient	No scale effects	not investigated
Auto-correlation time scale	Small scale effects	Small scale effects
Cross-correlation time scale	Small scale effects	Small scale effects
Integral turbulent length scales	**Scale effects**	Small scale effects
Integral turbulent time scales	**Scale effects**	Small scale effects
Advection turbulent length scale	Small scale effects	Small scale effects
Air bubble chord sizes	**Scale effects**	**Scale effects**
Water droplet chord sizes	**Scale effects**	**Scale effects**
Clustered properties	**Scale effects for several parameters**	not investigated
Inter-particle arrival time	**Scale effects**	not investigated

5. CONCLUSION

An experimental investigation of scale effects in air-water flows was conducted on two geometrically scaled stepped spillway models with a scaling ratio of 1:2 and channel slope of 26.6°. For a wide range of discharges in both transition and skimming flow regimes, a systematic comparison of a broad range of air-water flow properties was conducted for Froude and Reynolds similitudes. The comparative analyses confirmed that a scaling of void fraction and time-averaged interfacial velocities is possible for both types of similitude. However several further parameters were not properly scaled including the bubble count rate, turbulence intensities and correlation time scales. The present investigation identified further that the microscopic air-water flow properties comprising particle chord sizes, particle clustered properties and inter-particle arrival time could not be accurately scaled. The present study provides clear guidelines of air-water flow properties which may experience scale effects. Considering the broad range of flow conditions in the present study, these guidelines may be also applicable to further air-water flows.

The present finding emphasised explicitly that any notion of scale effects must be defined explicitly in terms of specific set of air-water flow property(ies) as illustrated in Table 3. Some air-water flow parameter more affected by scale effects than others, even in large-size facilities. On one hand, the void fraction and flow bulking is much less sensitive to scale effects. On another hand, bubble sizes and interfacial area, hence mass transfer rate, are very prone to scale effects. In general a detailed study of air-water flow properties at the prototype scale is needed to further confirm scaling guidelines in air-water flows.

6. ACKNOWLEDGEMENTS

The financial support of the Australian Research Council (Grant DP120100481) is acknowledged.

REFERENCES

Barenblatt G.I. (1996). *Scaling, Self-Similarity, and Intermediate Asymptotics.* Cambridge University Press, 386 pp.

Boes R.M. (2000). Scale effects in modelling two-phase stepped spillway flow. *Proc. of the international workshop on hydraulics of stepped spillways*, Balkema, 53-60.

Chanson H., and Carosi G. (2007). Turbulent time and length scale measurements in high-velocity open channel flows. *Experiments in Fluids*, 42 (3), 385-401.

Chanson H. (2001). *The Hydraulics of Stepped Chutes and Spillways*. Balkema, Lisse, 418 pp.

Chanson H. (2008). Advective Diffusion of Air Bubbles in Turbulent Water Flows. in *Fluid Mechanics of Environmental Interfaces*. Gualtieri and Mihailovic Editors, Taylor & Francis, Leiden, Chapter 7, pp. 163-196.

Chanson H. (2009). Turbulent air-water flows in hydraulic structures: Dynamic similarity and scale effects. *Environmental Fluid Mechanics*, 9(2), 125-142.

Chanson, H. (2013). Hydraulics of Aerated Flows: Qui Pro Quo? *Journal of Hydraulic Research*, IAHR, Invited Vision paper, Vol. 51, No. 3, pp. 223-243 (DOI: 10.1080/00221686.2013.795917).

Chanson H., and Chachereau Y. (2013). Scale effects affecting two-phase flow properties in hydraulic jump with small inflow Froude number. *Experimental Thermal and Fluid Science*, 45. 234-242.

Chanson H., and Gonzalez C.A. (2005). Physical modelling and scale effects of air-water flows on stepped spillways. *Journal of Zhejiang University SCIENCE*, 6A (3), 243-250.

Edward C.F., and Marx K.D. (1995). Multipoint Statistical Structure of the Ideal Spray, Part II: Evaluating Steadiness using the Interparticle Time Distribution. *Atomic & Sprays*, 5, 435-455.

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, The University 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. *Experiments in Fluids*, 47 (1), 1-18.

Felder S., and Chanson, H. (2011). Air-Water Flow Properties in Step Cavity down a Stepped Chute. *International Journal of Multiphase Flow*, 37(7), 732-745.

Gualtieri C., and Chanson H. (2010). Effect of Froude number on bubble clustering in a hydraulic jump. *Journal of Hydraulic Research*, 48(4), 504-508.

Heinlein J., and Fritsching U. (2006). Droplet clustering in sprays. *Experiments in Fluids*, 40(3), 464-472.

Heller V. (2011). Scale effects in physical hydraulic engineering models, *Journal of Hydraulic Research*, 49(3), 293-306.

Kobus H. (1984). Local Air Entrainment and Detrainment. *Proc. Symp. on Scale Effects in Modelling Hydraulic Structures*, IAHR, Esslingen, Germany.

Pfister, M., and Chanson (2012). Scale Effects in Physical Hydraulic Engineering Models. Discussion. *Journal of Hydraulic Research*, IAHR, Vol. 50, No. 2, pp. 244-246 (DOI 10.1080/00221686.2012.654672).

Pfister M., and Chanson H. (2014). Two-Phase Air-Water Flows: Scale Effects in Physical Modeling. *Journal of Hydrodynamics*, 26(2), 291-298.

Schultz ,M.P., and Flack, K.A. (2013). Reynolds-number scaling of turbulent channel flow. *Physics of Fluids*, 25, Paper 025104, 13 pages (DOI: 10.1063/1.4791606).

Toombes L., and Chanson H. (2005). Air-Water Mass Transfer on a Stepped Waterway. *Journal of Environmental Engineering, ASCE*, 131(10), 1377-1386.

Wood, I.R. (1991). *Air Entrainment in Free-Surface Flows*. IAHR Hydraulic Structures Design Manual No. 4, Hydraulic Design Considerations, Balkema Publ., Rotterdam, The Netherlands, 149 pages.