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Two-Phase Flow on a Gabion Stepped Spillway: Cavity and Seepage Air-Water Motion

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Abstract

On a stepped spillway, the steps contribute to some dissipation of the turbulent kinetic energy, while free-surface aeration can be very intense. The aim of this study is to investigate the two-phase flow properties on a gabion stepped spillway, including both free-surface and seepage flows, as well as the bubbly flow interactions at the gabion interface. Detailed measurements were conducted in a relatively large-size gabion stepped chute model. Using a combination of high-speed video movies and phase-detection probe measurements, the aeration processes in the step cavities and within the gabions were documented. The observations showed some very strong air-water interactions between seepage and step cavity flows. The results indicated a high level of interactions between two-phase seepage and cavity flows.

Introduction

In free-surface flows, interfacial aeration is caused by turbulence fluctuations acting next to the air-water interface. Through the pseudo-free-surface, air is continuously trapped and released in an uncontrolled manner. The aeration process involves both entrainment of gas bubbles and formation of liquid drops. The exact location of the free-surface becomes undetermined. The interactions between flowing waters and atmosphere may lead to strong air-water mixing, turbulence modulation and complex gas-liquid flow patterns. To date relatively few research studies considered strongly-turbulent flows associated with intense free-surface aeration (Rao and Kobus 1971, Chanson 1997,2013).

Highly turbulent flows are experienced down a stepped chute (Rajaratnam 1990, Chanson and Toombes 2002). At low flows, the cascading waters behave as a succession of free-falling nappes. For a range of intermediate flow rates, a transition flow regime takes place with a chaotic appearance with energetic droplet ejections. At larger flows, the water skims over the pseudo-bottom formed by the step edges (skimming flow regime). Intense recirculation is observed in the step cavity and the flow is highly aerated (Chamani and Rajaratnam 1999, Felder and Chanson 2011). For low- to medium-head stepped chutes, gabions may be a suitable construction material and the advantages of this type of construction include its stability, low cost, flexibility, porosity and noise abatement (Agostini et al. 1987, Boes and Schmid 2003) (Fig. 1). Peyras et al. (1991) investigated the flow patterns and energy dissipation performances of gabion stepped weirs with 0.2 m step height. Kells (1993) discussed the interactions between seepage and free-surface flows on a gabion weir.

Herein the two-phase turbulent flow properties above a gabion stepped spillway were investigated experimentally. The measurements were conducted in a large facility with a chute slope of 26° (1V:2H). The two-phase flow motion was studied in the mainstream flow, step cavities as well as within the gabion materials, using a combination of dual-tip phase-detection probe and high-speed video observations, for flow conditions corresponding to the transition and skimming flow regimes. It is the aim of this study to detail the interactions between air-water seepage and cavity flow motions.

Figure 1. Flow down a gabion stepped weir (Courtesy of Tony Marszalek).

Experimental Apparatus and Instrumentation

Experiments were conducted at the University of Queensland in a 0.52 m wide stepped chute, previously used by Wüthrich and Chanson (2014). The test section consisted of a broad-crest followed by 10 identical steps (h = 0.1 m) made of gabion boxes laid over a marine ply structure (Fig. 2). The gabions were 0.3 m long, 0.1 high and 0.52 m wide, made of 14 mm sieved gravels. The density of the dry gravel material was 1.6 tonnes/m^3 with a porosity of 0.35-0.4. The hydraulic conductivity of gabions were tested independently (Wüthrich and Chanson 2014). The results yielded a hydraulic conductivity from 1.1×10^{-1} to 2.3×10^{-1} m/s depending upon the data analysis method (linear and non-linear). Along the stepped chute, each step was 0.1 m high and 0.2 m long, corresponding to a chute slope: θ = 26.6º (Fig. 2).

The discharge was measured from the upstream head above crest using the calibration of Felder and Chanson (2012). Air-water flow properties were recorded using a dual-tip phase-detection probe (Ø = 0.25 mm) in the overflow. The probe sensors were aligned in the flow direction and excited by an air bubble detector (AS25240). The probe signal was scanned at 20 kHz per sensor for 45 s. The translation of the probe in the normal direction was controlled by a fine adjustment traverse connected to a Mitutoyo™ digimatic scale unit. Visual observations were based upon a combination of high shutter speed digital imagery (1/1,000-1/8,000 s) and high speed video recordings up to 1,000 fps using a Casio™ EX-ZR200 camera.

The two-phase flow investigations were conducted for flow rates ranging from 0.052 to 0.147 m^2/s, with a focus on the highly aerated transition and skimming flows. Phase detection probe measurements were performed both at the outer step edges and in the step cavities. Visual observations were conducted through the perspex sidewalls and bubble trajectories in the gabions were tracked with a high-speed video camera.

Figure 2. Skimming flow down the gabion stepped weir model - Flow conditions: $q = 0.147$ m^2/s, $d_c/h = 1.3$, $Re = 5.8 \times 10^5$.

Basic Observations

On the gabion stepped chute, four different overflow regimes were observed depending upon the dimensionless discharge d_c/h where d_c is the critical flow rate ($d_c = (q^2/g)^{1/3}$), q is the discharge per unit width, g is the gravity acceleration and h is the vertical step height. At very low discharges, the water flowed over the impervious crest and onto the upper surface of the first gabion box. The water seeped into the gabion material and no overflow was observed at the first step edge. The water discharge exited the gabions through the vertical face of the last gabion box. There was no overflow above the gabion boxes. In the gabions, the water table was clearly seen through the transparent sidewalls.

For $d_c/h > 0.2$, some overflow was observed above all the gabions. A nappe flow regime occurred for $d_c/h < 0.5$ to 0.6. The overflow occurred in the form of a succession of free falling nappes from one step edge to the next step. The cavity below the nappe was partially filled with a series of water jets seeping out of the upstream gabion's vertical face. A transition flow regime was observed for $0.6 < d_c/h < 0.9$. It was characterised by large hydrodynamic instabilities and intense splashes in the overflow. For the largest discharges ($d_c/h > 0.9$), a skimming flow was observed. At the upstream end of the chute, the flow was non-aerated. The inception of free-surface aeration was clearly marked. Downstream, intense free-surface aeration was observed and the air entrainment process was highly three dimensional and complex. In the step cavities, however, the aeration process differed from conventional stepped spillway structures (Matos 2001, Gonzalez and Chanson 2004). Figure 3 illustrates some bubbly motion inside the gabions and step cavities.

For $d_c/h > 0.2$, a substantial amount of air bubbles were entrained into the gabion materials. The gabions were fully saturated and the seepage was a bubbly two-phase flow motion. Figure 4 illustrates the two-phase flow pattern, including typical seepage bubble paths (blue arrows), for a skimming flow. Downstream of the inception point of free-surface aeration, a strong bubbly motion was observed in all gabions. A large amount of air entered the gabion through the downstream half of the horizontal step faces. The entrapped air flowed through the gabions as individual bubbles and groups of bubbles. Fast flowing bubbles were seen exiting the gabion material through the next vertical step face (Fig. 4). Other bubbles were observed to flow downwards before travelling back into the step cavities. More bubbles were entrained through the next gabion box. The bubbly seepage pattern and cavity flow motion suggested the existence of large positive pressures on the downstream end of horizontal step faces and subpressures on the upper part of vertical step faces. This would be consistent with pressure distributions recorded on impervious stepped spillway models (Sanchez-Juny et al. 2007).

In the gabions, some bubble recirculation, breakup and coalescence took place. These processes were linked to the combinations of constrictions between adjacent gravels as well as relatively large cavities between pebbles. A high-speed video study of bubbles inside the gabion materials showed a broad variety of bubble shapes, ranging from highly distorted and elongated shapes in regions of high shear to pseudo-ellipsoidal shapes in larger cavities.

Figure 3. Cavity and gabion aeration in skimming flow - Overflow direction from top left to bottom right - Note bubble motion on the gabion (shutter speed: 1/180s, flash).

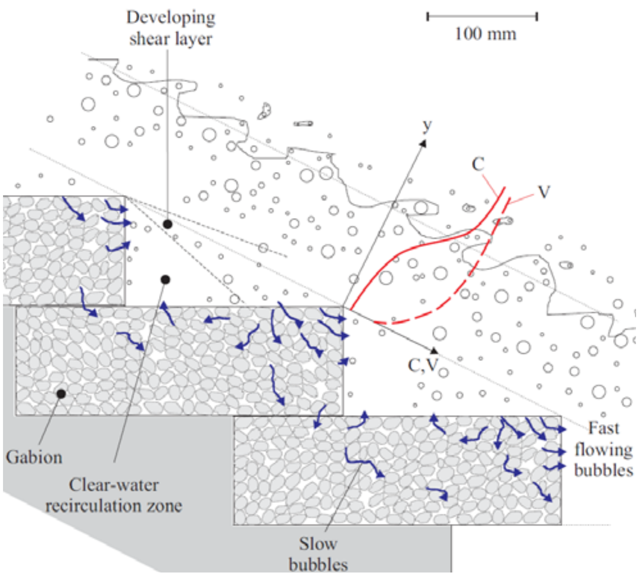


Figure 4. Sketch of two-phase skimming flow above gabion stepped spillway: bubbly seepage motion (blue arrows) and air-water free-surface overflow.

Cavity flow motion

The present observations highlighted a large amount of air-water interactions between the seepage and free-surface flows. The interactions were most energetic next to the gabion step surfaces and in the step cavity. The seepage appeared to modify the cavity recirculation pattern, compared to smooth impervious stepped chutes. Herein a vertical flux of air bubbles was observed close to the vertical step face. Most bubbles came out of the gabion materials and were entrained upwards in the cavity. In a third of the step cavity, a clear water core was seen as illustrated in

Figure 4. Such a similar clear water core was previously reported by Gonzalez et al. (2008) and Bung and Schlenkhoff (2010) for rough impervious steps, but it has never been observed in smooth impervious steps.

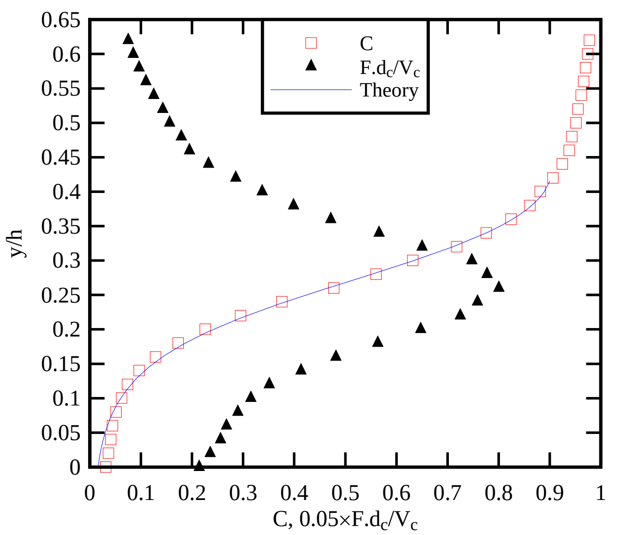
In skimming flows, the cavity recirculation motion was affected by a combination of interactions between seepage and free-surface flow, and step surface roughness. The effect of gabion seepage outflow into step cavities was documented in monophase flow, sometimes called ventilation (Naudascher and Rockwell 1994). The step surface roughness might also induce some turbulence manipulation, in a manner similar to riblets and d-type roughness in developing boundary layer (Djenidi and Antonia 1995).

Two-phase flow properties

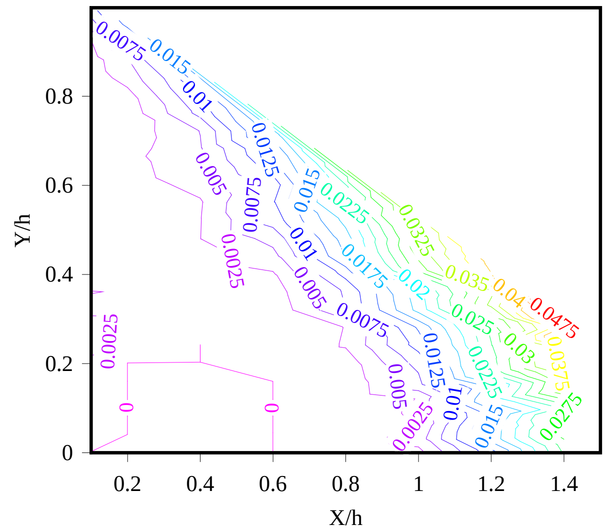
Free-surface flow

Downstream of the inception point of air entrainment, both the free-surface, step cavity and seepage flows were highly aerated (Fig. 3 & 4). At each step edge, the void fraction distributions in skimming free-surface flow presented an inverted S-shape, typical of skimming flows (Chanson and Toombes 2002) (Fig. 5). A typical example is shown in Figure 5 including both void fraction C and bubble count rate F data. Note in Figure 5A that the void fraction and bubble count rate were not zero at the pseudo-bottom formed by the step edges (y = 0) because of the bubble motion in the gabions. In the step cavities beneath the pseudo bottom (y < 0), the void fraction data (Fig. 5B) presented a flat shape highlighting the clear water core sketched in Figure 4. The bubble count rate, defined as the number of water-to-air interface detected per unit time, gave some information on the bubbly flow structure. In the free-surface flow, the data showed a distinct maximum for local void fractions about 0.4-0.5, as previously reported (Chanson and Toombes 2002, Felder and Chanson 2011). In the step cavity, both visual observations and phase-detection probe data showed a drastically lesser aeration, likely linked to the interactions between seepage and cavity flow.

The interfacial velocity and turbulence data in the free-surface flow presented some self-similar shapes (data not shown). The velocity profiles were close to a power law distribution, while the turbulence intensity data indicated a marked maximum for about C ~ 0.5. About the pseudo-bottom formed by the step edges, the velocity data highlighted a developing shear region in the wake of the step edge, as sketched in Figure 4.



(A) Dimensionless distributions of void fraction and bubble count rate at Step edge 7, d_c/h = 1.0, Re = 3.9×10^5



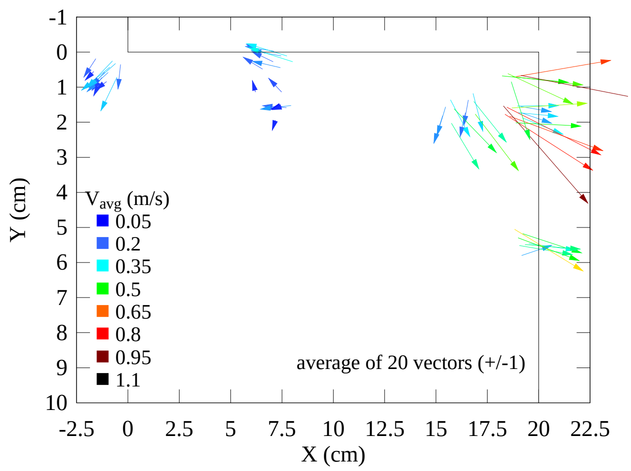
(B) Void fraction contour lines in step cavity 8-9, d_c/h = 1.3, Re = 5.8×10^5

Figure 5. Two-phase flow properties in the free-surface skimming flow.

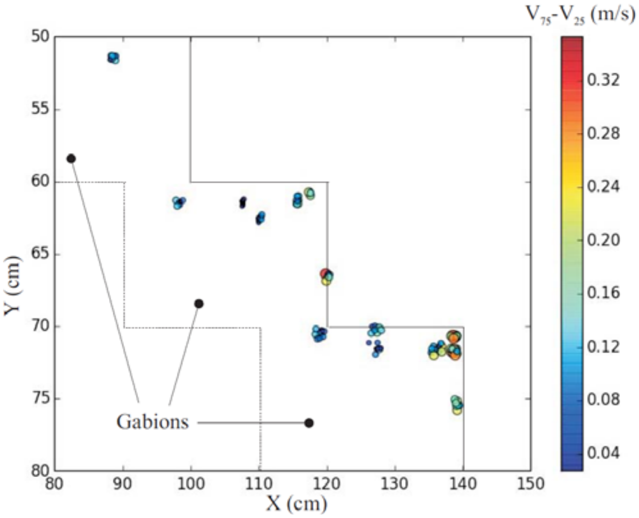
Seepage flow

High-speed movies were analysed to document the bubbly motion in the gabions. The outputs included the bubble trajectories, velocities and sizes. Typical results are presented in Figure 6, including the average bubble velocity vectors (Fig. 6A) and velocity fluctuations (V_{75}-V_{25}). In Figure 6, X and Y are the horizontal and vertical co-ordinates respectively. Herein the velocity fluctuations were quantified in terms of the difference between the first and third quartiles (V_{75}-V_{25}). For comparison, (V_{75}-V_{25}) would be equal to 1.3 times the standard deviation for a Gaussian distribution of the velocity data set around its mean.

The results showed a relatively high velocity motion in the upper, outer corner of the gabion (Fig. 6A, top right). Maximum mean bubble velocities in excess of 1 m/s were measured, with maximum instantaneous velocities up to 2 m/s in that region. Elsewhere the bubble velocities were smaller, but the data showed large velocity fluctuations in the gabions. The largest velocity fluctuations were recorded next to the outer step edge, with velocity fluctuations (V_{75}-V_{25}) up to 0.4 m/s (Fig. 6B). Yet significant bubble velocity fluctuations were recorded at all locations, including in regions of slow bubble motion.



(A) Average bubble velocity vectors at gabion box 8



(B) Bubble velocity fluctuations (V_{75}-V_{25}) in gabion boxes 6 to 8

Figure 6. Bubble velocity field in the gabions - $d_c/h = 1.3$, Re = 5.8×10^5.

Conclusion

The two-phase flow characteristics of a gabion stepped weir were investigated. Both the free-surface and seepage flow motions were highly aerated. The detailed flow properties were documented with a phase-detection probe in the overflow and a high-speed video camera in the gabion material. The observations highlighted a two-phase air-water seepage motion through the gabions with complicated flow patterns.

The quantitative measurements highlighted the strong aeration of the free-surface flow with void fractions ranging from non-zero values close to the gabion to unity above the free-surface. The cavity flow was in contrast drastically less aerated. Bubbly flow measurements in the gabions showed relatively large bubble velocities particularly next to the step edge. Large velocity fluctuations were also observed throughout the gabions. Altogether the interactions between seepage and free-surface flows were significant, leading to a complex cavity recirculation flow pattern.

Acknowledgments

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