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GABION STEPPED SPILLWAY: INTERACTIONS BETWEEN FREE-SURFACE, CAVITY AND SEEPAGE FLOWS

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Abstract: On a gabion stepped chute, the steps contribute to the dissipation of turbulent kinetic energy, free-surface aeration may be intense and there are complex interactions between the free-surface flow and seepage motion. Detailed measurements were conducted in a relatively large-size gabion stepped spillway model. Using a combination of high-speed movies and phase-detection probe measurements, the air-water flow properties in the step cavities and in the gabions were documented. Strong air-water exchanges between seepage and stepped cavity flows were observed. The data showed a complex bubbly seepage motion in the gabions, associated with a high level of interactions between seepage and free-surface flows, leading to a modification of the step cavity recirculation and lesser flow resistance.

Keywords: Air-water flow, gabion stepped spillways, seepage flow, overflow-seepage flow interactions, physical modelling.

INTRODUCTION

Stepped spillways have been used as flood release facilities for several centuries (Chanson 2001). The steps contribute to some dissipation of the turbulent kinetic energy, thus reducing or eliminating the need for a downstream stilling structure. Highly turbulent flows are experienced down a stepped chute (Rajaratnam 1990). For low- to medium-head stepped chutes, gabions may be a suitable construction material. The advantages include stability, low cost, flexibility, porosity and noise abatement (Agostini et al. 1987, Chanson 2001). Peyras et al. (1992) investigated the flow patterns and energy dissipation performances of gabion stepped weirs with 0.2 m step height. Wüthrich and Chanson (2014) compared the energy dissipation performances of flat impervious and gabion stepped chutes. Their findings showed lesser rates of energy dissipation on the gabion chute, which motivated the present investigation.

Herein the turbulent flow properties above a gabion stepped chute were investigated experimentally. The air-water flow was studied in the mainstream flow and step cavities, and within the gabions, using a combination of dual-tip phase-detection probe and high-speed video observations. It is the aim of this study to detail the interactions between air-water seepage and cavity flows, and to characterise the flow through the gabions.

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EXPERIMENTAL SETUP AND INSTRUMENTATION

Experiments were conducted at the University of Queensland in a gabion stepped chute, previously used by Wüthrich and Chanson (2014). The test section was 3 m long and 0.52 m wide, consisting of an impervious broad-crest followed by ten 0.1 m high, 0.2 m long gabion steps: the chute slope was $\theta = 26.6^\circ$ (1V:2H). Each gabion was 0.3 m long, 0.1 high and 0.52 m wide, filled with 14 mm sieved gravels, and the gabions overlapped (Fig. 1). The bulk density of dry gravels was 1.6 t/m^3 with a porosity about 0.35-0.4. The hydraulic conductivity of gabions ranged from 1.1×10^{-1} to 2.3×10^{-1} m/s. The discharge was recorded from the upstream head above crest. The air-water flow measurements were performed with a dual-tip phase-detection probe ($\varnothing = 0.25$ mm) in the free-surface flow and step cavities, with the probe sensors sampled at 20 kHz for 45 s. The translation of the probe in the normal direction was controlled by a fine adjustment traverse. Visual observations were made with high speed video recordings at speeds up to 1,000 fps.

The flow investigations were conducted for discharges per unit width up to $0.28 \text{ m}^2/\text{s}$, with a focus on the aerated transition and skimming flows: i.e., $d_c/h > 0.6$ where d_c is the critical flow depth ($d_c = (q^2/g)^{1/3}$), q is the discharge per unit width, g is the gravity acceleration and h is the vertical step height. Phase detection probe measurements were performed in the overflow including in the step cavities. Bubble trajectories in the gabions were tracked with the high-speed video camera. The tracking was performed using a manual frame by frame analysis to guarantee maximum reliability of the data.

FLOW PATTERNS

On the gabion stepped spillway, the water seeped through the gabion at very low discharges ($d_c/h < 0.2$) and no overflow was observed at the step edges. For $d_c/h > 0.2$, some overflow was observed above all the gabion steps. A nappe flow regime occurred for $0.2 < d_c/h < 0.5-0.6$. A transition flow was seen for $0.6 < d_c/h < 0.9$, characterised by large hydrodynamic instabilities and intense splashes in the overflow. For $d_c/h > 0.9$, a skimming flow was seen. The upstream flow was non-aerated. The inception of free-surface aeration was clearly marked. Downstream, the air entrainment process was highly three dimensional and complex.

The gabions were fully saturated for $d_c/h > 0.2$. Downstream of the inception point, a strong bubbly motion was observed inside all gabions as sketched in Figure 1. A large amount of air entered the gabion through the downstream half of the horizontal step face. The entrapped air flowed through the gabion as individual bubbles and groups of bubbles. Fast flowing bubbles exited the gabion through the next vertical step face (Fig. 1). Other bubbles flowed downwards before travelling back into the step cavity. 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 negative pressures on the upper part of vertical step faces, in a manner consistent with the pressure data of Sanchez-Juny et al. (2007). In the gabion material, bubble recirculation, breakup and coalescence took place. These processes were linked to the combination of constrictions between adjacent gravels as well as relatively large cavities between pebbles. The observations indicated 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.

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Energetic air-water interactions were observed between the seepage and free-surface flows, 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. 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 1. This has never been reported on smooth impervious steps.

AIR-WATER FLOW PROPERTIES

Downstream of the inception point of free-surface aeration, both free-surface, step cavity and seepage flows were highly aerated. 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). An example is shown in Figure 2a including both void fraction and bubble count rate data, where y is the distance normal to the pseudo-bottom (Fig. 1), C is the time-averaged void fraction, F is the bubble count rate and V_c is the critical flow velocity. Note that the void fraction and bubble count rate were not zero at the step edges ($y = 0$) because of the bubble contents in the gabions (Fig. 2a). In the step cavities beneath the pseudo bottom ($y < 0$), the void fraction data (Fig. 2b) presented a flat shape highlighting the clear water core sketched in Figure 1. Figures 2b and 2c present contour plots of void fraction and bubble count rate data, with x' and y' the horizontal and vertical coordinates respectively and l the step length: $l = 0.20$ m. The bubble count rate, defined as the number of water-to-air interface detected per unit time, gave new information on the interfacial flow structure. In the free-surface flow, the data showed a distinct bubble count rate maximum for local void fractions about 0.4-0.5. In the step cavity, visual observations and phase-detection probe data showed a lesser aeration (Fig. 2b & 2c). The interfacial velocity data in the free-surface flow presented some self-similar shape (Zhang and Chanson 2014). In the mainstream, the velocity profiles were close to a power law distribution for $y < Y_{90}$ where Y_{90} is the characteristic elevation where $C = 0.90$. At each step edge, the velocity was not zero at the step edge ($y = 0$) because of the bubble motion in the gabion boxes. Between step edges, the velocity data highlighted a developing shear region in the wake of the step edge (Fig 1).

The bubbly motion in the gabions was documented with high-speed movies. Typical results are presented in Figure 3, including the average bubble velocity vectors (Fig. 3a) and velocity fluctuations ($V_{75}-V_{25}$), defined as the difference between the third and first quartiles ($V_{75}-V_{25}$), with the symbol sizes proportional to the magnitudes of velocity fluctuations (Fig. 3c). The gabion data showed a high velocity motion in the upper outer corner of each gabion (Fig. 3a, top right): i.e., maximum mean bubble velocities in excess of 1 m/s and maximum instantaneous velocities up to 2 m/s. The findings were quantitatively consistent with the interfacial velocity data recorded at $y = 0$ at step edge. Elsewhere in the gabions, the bubble velocities were smaller, but the data showed large velocity fluctuation (Fig. 3b). Inside the gabions, the bubbles presented a variety of shapes and sizes. The characteristic bubble sizes were measured herein perpendicular to the bubble direction. The data indicated some skewed distribution with a preponderance of smaller bubble sizes and a mode about 0.6-0.9 mm (Fig. 4). The observations identified occasional occurrences of large bubbles (> 5

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mm), mostly inside cavities between large pebbles.

DISCUSSION

The flow resistance was estimated to characterise the combined form and friction losses above the gabion stepped spillway in the air-water flow. An equivalent Darcy-Weisbach friction factor was calculated based upon the measured air-water flow properties. The results yielded friction factors between 0.04 and 0.15 (mean value: 0.1). The data were comparable those of Wüthrich and Chanson (2014). Both gabion spillway data sets are compared to flat smooth stepped spillway data in Table 1, for the same chute slope ($\theta = 26.6^\circ$). The comparison showed a smaller flow resistance on gabion stepped spillways in transition and skimming flow regimes. The gabion stepped chute friction factor was on average half of that on smooth flat stepped spillways for same flow regime and slope. The finding was counter-intuitive, but likely linked to the effects of exchanges between seepage and recirculation flows. It is proposed that the lower flow resistance resulted from a combination of seepage outflow into the cavity and non-zero velocity at step edges. At each step edge, the overflow velocity was non zero ($V(y=0) > 0$), leading to lesser shear stress, compared to smooth flat stepped spillway flows. The gabion seepage outflow into the step cavities further acted as fluid injection into the separated cavity region reducing the form drag.

CONCLUSION

On a gabion stepped spillway, both the free-surface and seepage flow motions were investigated. Detailed air-water flow properties were recorded with a phase-detection probe in the free-surface and cavity flows, and a high-speed video camera in the gabions. Downstream of the inception point of free-surface aeration, the observations indicated a bubbly seepage motion through the gabions with complicated flow patterns and exchanges with the step cavity flow. While the free-surface overflow was highly aerated, the cavity recirculation was in contrast less aerated. Bubble tracking in the gabions showed large bubble velocities particularly next to the step edge. Large bubble velocity fluctuations were recorded throughout the gabions. The gabion stepped spillway friction factor was on average half of that on smooth flat stepped spillways for the same conditions. Altogether the interactions between seepage and free-surface flows were significant, leading to a complex cavity recirculation flow pattern and lesser flow resistance on gabion stepped chutes compared to smooth stepped chutes.

ACKNOWLEDGEMENTS

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NOTATION

C	void fraction;
d_c	critical flow depth (m);
F	bubble count rate (Hz);
f_e	air-water flow Darcy-Weisbach friction factor;
g	gravity acceleration (m/s^2);
h	vertical step height (m);
l	horizontal step length (m);
Q	water discharge (m^3/s);
q	water discharge per unit width (m^2/s);

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- R Reynolds number defined in terms of the hydraulic diameter;
- V interfacial velocity (m/s);
- V_c critical flow velocity (m/s);
- V_{25} first quartile of velocity data sample (m/s);
- V_{75} third quartile of velocity data sample (m/s);
- x longitudinal coordinate (m);
- x' horizontal coordinate (m);
- Y_{90} characteristic distance (m) where $C = 0.90$;
- y distance (m) normal to the pseudo-bottom formed by the step edges;
- y' vertical coordinate (m);
- θ angle between pseudo-bottom formed by the step edges and horizontal;
- ρ water density (kg/m^3);
- \emptyset diameter (m);

Subscript

- c critical flow conditions;
- 25 first quartile;
- 75 third quartile;
- 90 characteristic air-water flow property for $C = 0.90$.

Table 1 - Average air-water flow Darcy-Weisbach friction factor f_e on smooth flat and gabion stepped spillways for $\theta = 26.6^\circ$

Stepped configuration	f_e	
	Transition flow TRA	Skimming flow SK
Smooth flat steps	0.174	0.239
Gabion steps	0.080	0.119

Note: Gabion stepped data: Wüthrich and Chanson (2014), Present study; Smooth flat stepped data: Bung (2009), Felder and Chanson (2011), Guenther et al. (2013), Wüthrich and Chanson (2014)

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LIST OF CAPTIONS

Fig. 1 - Sketch of air-water flow patterns above a gabion stepped spillway: bubbly seepage motion, shown by arrows, and air-water free-surface flow above

Fig. 2 - Void fraction and bubble count rate above the gabion stepped chute including in step cavities

(a) Distributions of void fraction and bubble count rate in the free-surface flow: $d_c/h = 1.1$, $R = 4.5 \times 10^5$, step edge 10 - Comparison between void fraction data and theoretical model of Chanson and Toombes (2002)

(b) Void fraction contour plot in two consecutive step cavities, $d_c/h = 0.9$, $R = 3.4 \times 10^5$

(c) Dimensionless bubble count rate Fd_c/V_c contour plot in two consecutive step cavities, $d_c/h = 0.9$, $R = 3.4 \times 10^5$

Fig. 3 - Bubble velocity measurements in the gabions in skimming flow

(a) Average bubble velocity vectors at the gabion box 8, $d_c/h = 1.3$, $R = 5.8 \times 10^5$

(b) Bubble velocity fluctuations ($V_{75}-V_{25}$) in the gabion boxes 6 to 8, $d_c/h = 1.3$, $R = 5.8 \times 10^5$

Fig. 4 - Bubble size distribution in gabions

(a) Left: $d_c/h = 0.7$

(b) Right: $d_c/h = 1.3$

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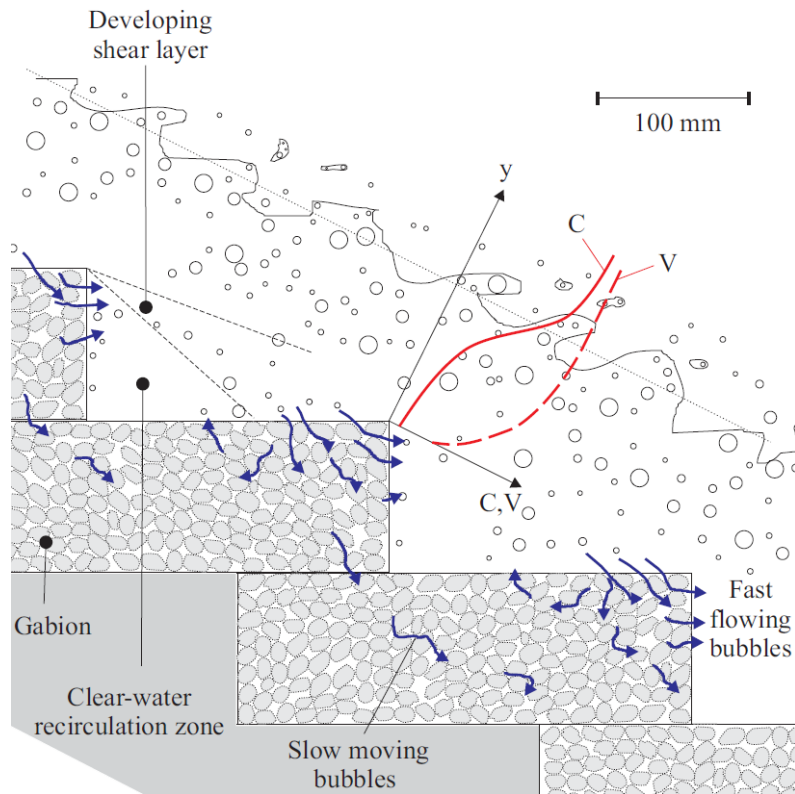
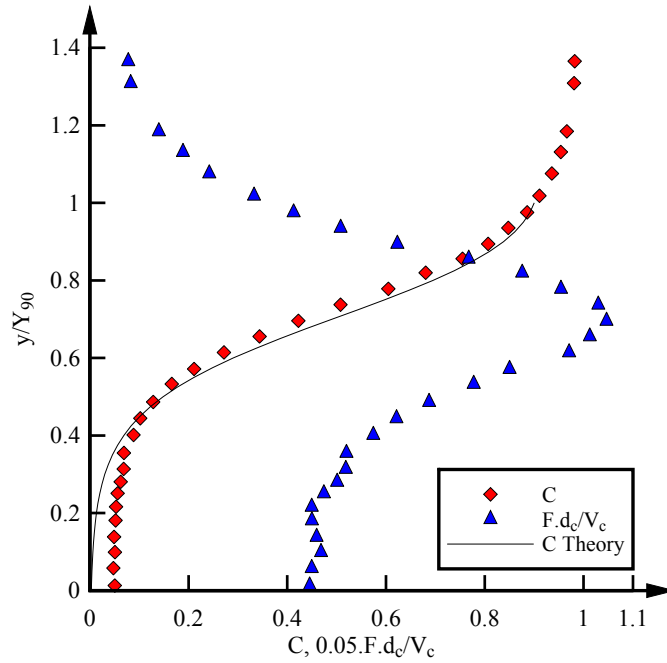
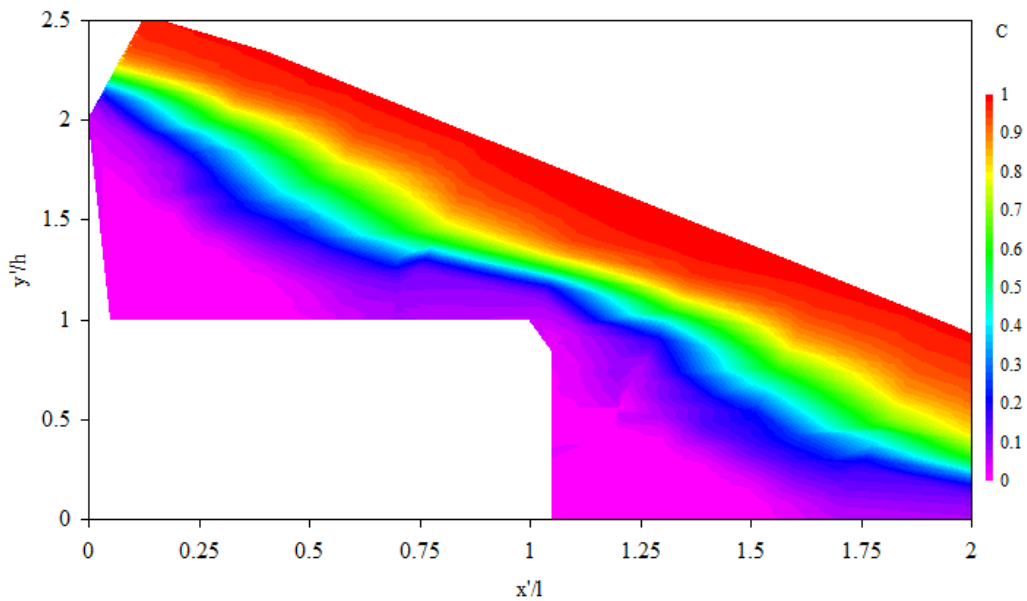


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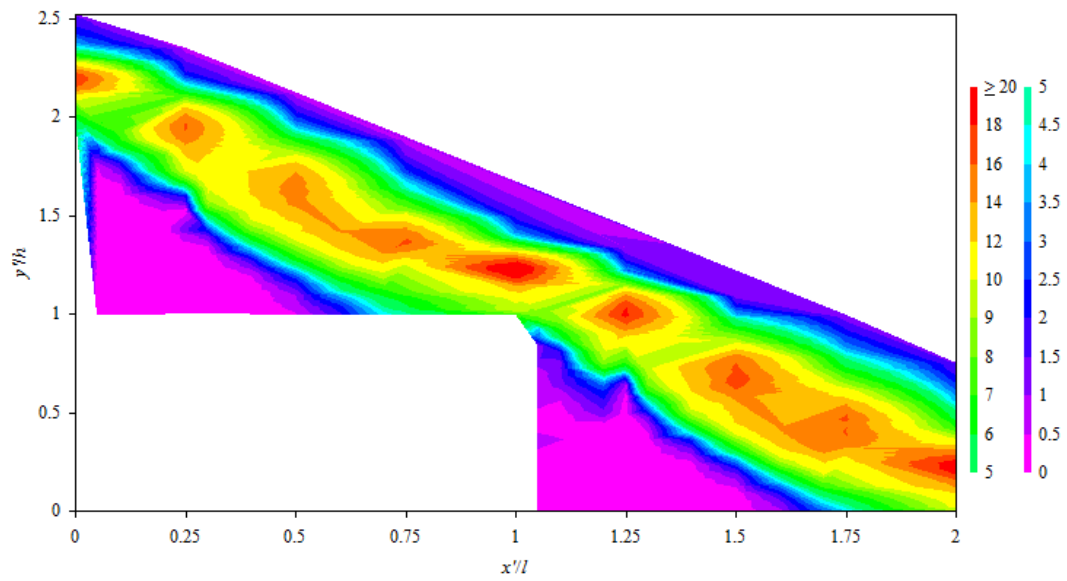


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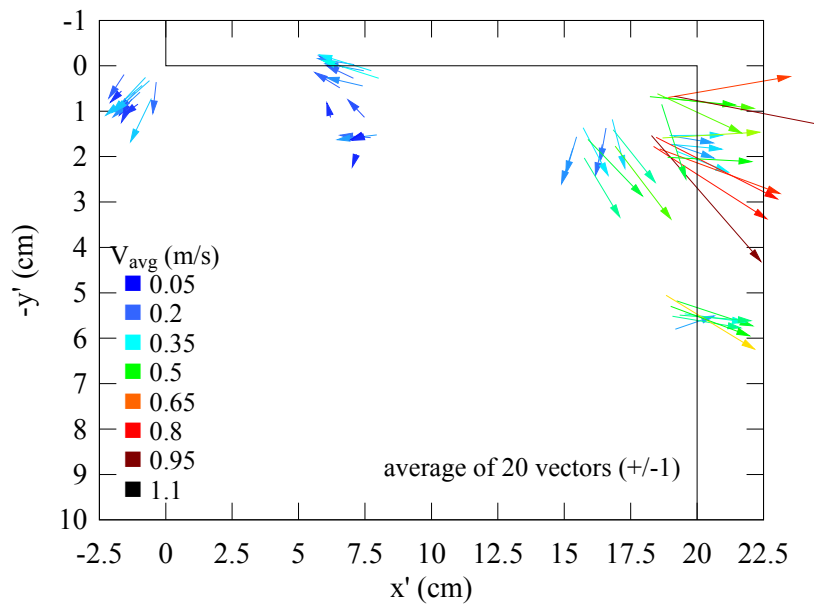
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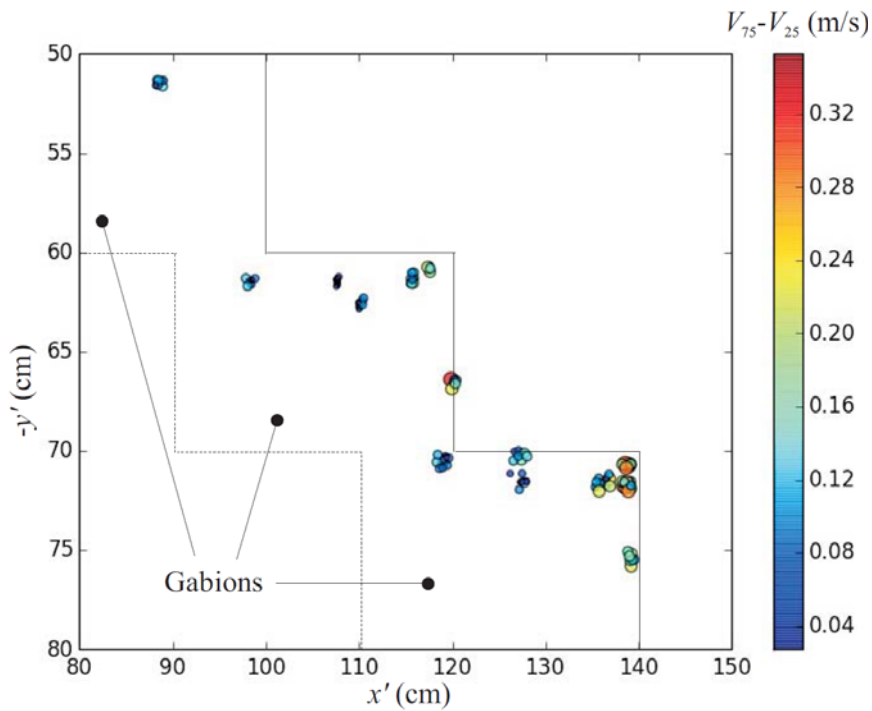
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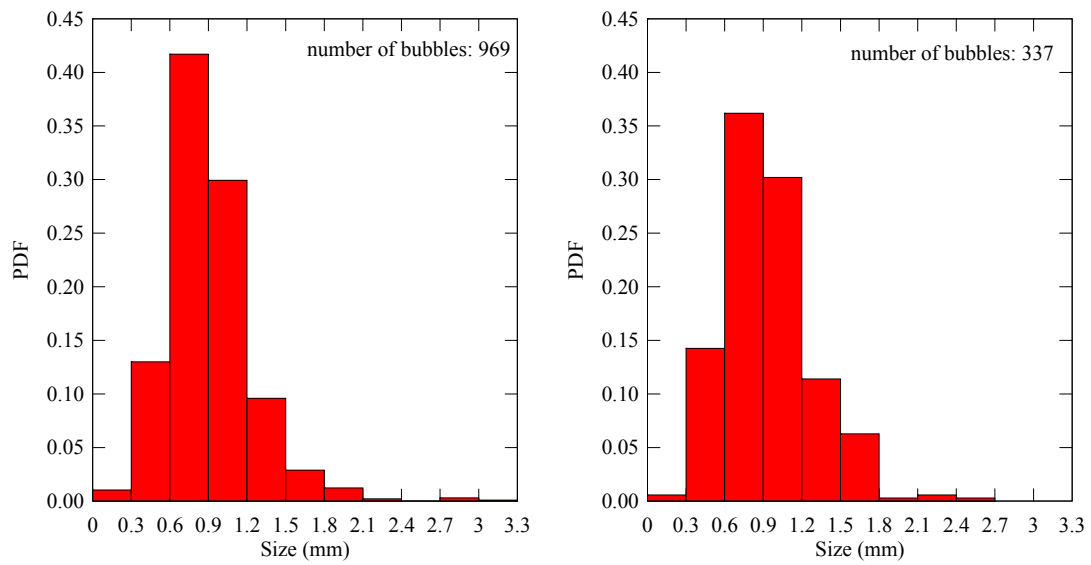


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