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Investigating skimming flow conditions over stepped spillways using particle image velocimetry

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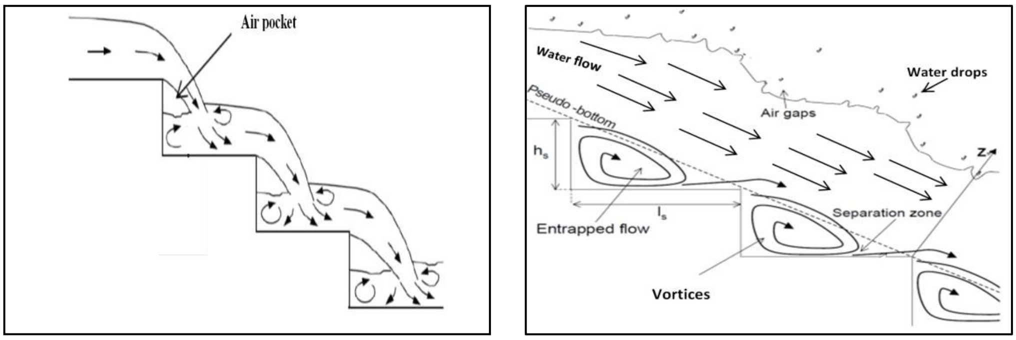
Abstract. Turbulent flow over stepped spillways can be considered the most significant flow that can cause severe problems at the downstream side, near the toe of the structure, such as sediment erosion which normally occurs due to the high amount of water energy. The presence of turbulent flow over the steps can cause cavitation damages due to pressure differences over the steps. The turbulent flow, which is induced at certain times of the year, especially during the flooding seasons, is examined experimentally and numerically in this study. Flow measurements were conducted using Particle Image Velocimetry (PIV) system in a hydraulic flume where the dam break condition is applied in order to achieve the skimming turbulent flow. Two cases of stepped spillways were tested, normal stepped spillways and gabion stepped spillways. For each case, measurements of the instantaneous turbulent velocity field were taken at different locations of the physical models of a slope of (1V:2H). A comparison has been conducted between the gabion and normal steps to assess the required time to attach skimming flow. The results indicated that the presence of the porous media could increase the required time to attach skimming flow.

1. Introduction

The essential purpose of hydraulic structures is to modify the natural behavior of the water body in rivers, lakes and seas by controlling its flow. This modification can lead to many economic benefits like generating the electric power and protecting the environment during the flooding seasons (flood control). Hydraulic structures can be divided into three types: water retaining structures, water conveying structures and special-purpose structures [1]. Dams are the archetypal water retaining structures. Dam construction is one of the earliest examples of civil engineering. Saving water from the rainy seasons in order to be used through the drought seasons represented the main aim of dam construction; however, ancient people have used dams for other objectives as well such as raising water levels for irrigation purposes and controlling flooding during the rainy season [2].

Dams can be classified according to their purpose. Some categories include irrigation, water supply, hydroelectric power generation, river regulation and flood control. Classification can also be based on the construction material, whether it is concrete, steel, earth embankment or masonry. Embankment dams are constructed by using the natural ground materials which are composed of fragmented particles, graded and compacted, in order to prevent flow through the dam body (i.e. seepage). André and Schleiss [3] claimed that about 40% of embankment dams around the world, not including China, with heights less than 30m, are damaged due to overtopping. All dams, especially embankment dams need structures

to discharge the overtopping flow during the flooding seasons to the downstream safely and effectively, which was the main reason to construct spillways. The high water energy along the spillway slope is considered as an important issue that needs to be controlled in order to reduce the scour at the downstream of the chutes.
Three different flow regimes can be identified in stepped spillways: nappe flow, transition flow and skimming flow (figure 1). Chanson [4] showed that these types of flow have a direct relationship with the amount of the discharge and the geometry of the steps. For example, for a given step geometry, the flow could be nappe flow if the discharge is low, it could be skimming flow if the discharge is high. Skimming flow can also be identified when the water flow appears as a coherent stream above the pseudo-bottom which forms by the external edge of the steps [5]. A transition flow can be achieved when the flow rate is higher than the maximum limit for the nappe flow and lower than the minimum limit for the skimming flow [6].



(a) (b)

Figure 1. Flow conditions: a) Nappe flow and b) Skimming flow.

The skimming flow regime can be divided essentially into two zones depending on the presence of air. In the first zone which is normally located on the early steps near the crest, the water has a smooth free surface (clear water) and also no air entrainment can be observed. Hence, it is called non-aerated zone. However, in the second zone, the water free surface has air entrainment and therefore the water flow becomes turbulent [3]. This zone is named as the aerated zone (figure 2). The point that separates the non-aerated zone (water zone) and the aerated zone (air-water zone) is called the inception point [3].

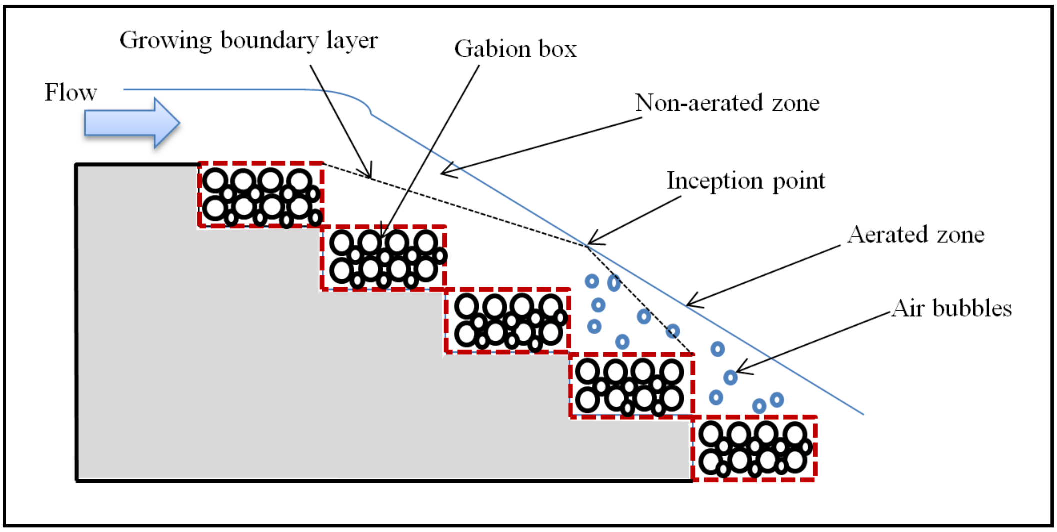


Figure 2. Skimming flow characteristics over gabion stepped spillways.

The primary goal of this study is to investigate the skimming flow over normal and gabion stepped spillways under dam break conditions experimentally. A comparison between the normal steps and the gabion steps will be conducted to assess the required time to achieve skimming flow. Moreover, Particle Image Velocimetry (PIV) is used to extract surface skin velocity maps from video images which allow measuring the velocity field. The experimental set-up which includes the procedure and instrumentation are both described in the first part of this paper. Then, comparisons between the required times to attach skimming flow are obtained in the second part. Then, the velocity distributions across the spillway steps are discussed. Finally, the paper closes with short and brief conclusions.

2. Physical modelling

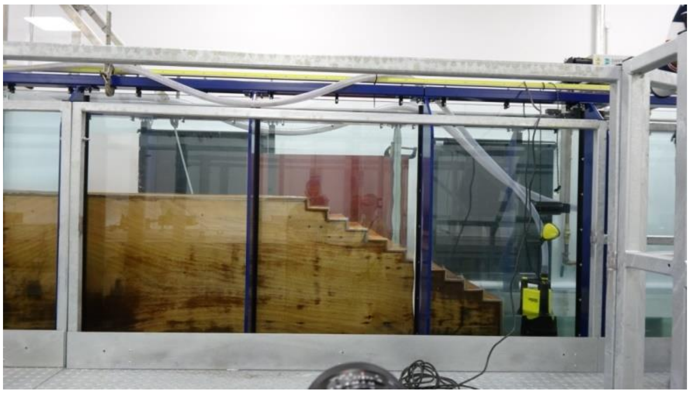
The experiments were conducted over a stepped spillway model in the Coastal Laboratory at Swansea University, UK. As a result of the experimental data lack in the non-aerated zone for stepped spillways, especially gabion stepped spillways, a physical model has been built to run some experiments. The model was installed inside a wave flume that has a paddle to produce different types of wave. The dimensions of the flume are 1.2m height, 0.8m width, and 30m length. The 'flume' is a wave tank and was never designed to be a hydraulic flume. However, it was adapted to simulate dam break problems and therefore dam break conditions were selected to run the experiments.

The stepped spillway model was positioned at 12.9m with 0.7m height and 1.5m length of broad-crested weir followed by ten identical steps with 0.05m height and 0.1m length thus the slope of the spillway is 1:2 (V:H). The eleventh step height was 0.2m in order to assure that the water flow will not submerge the last two steps when the gate lifted up as the downstream side of the flume is closed. In other words, when the water flow hits the downstream wall, it would come back towards the model. The model was constructed by using a ply marine wood. In order to increase the resistance of wood against water, the entire model was varnished (figure 3).

A guillotine-type mechanism was used to lift the gate; this was achieved by using a cylinder with an air compressor to lift the gate very fast. The gate was installed with a metal frame to increase the stability (figure 3). According to the dam break conditions, the time to open the gate should be very fast depending on the initial water depth at the upstream. The mechanism was designed to lift the gate up in less than 0.3s.

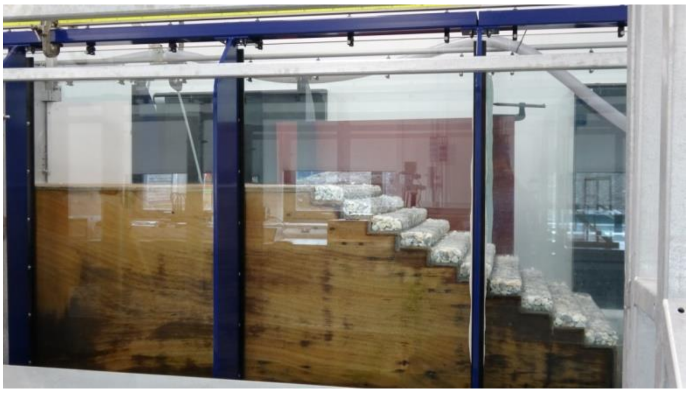
Two baffles were installed behind the gate to reduce the wakes and vortices over the spillway crest. These two baffles are connected to the frame of the guillotine gate which is already connected to the model. The connection between the parts of the whole system increased the stability of the model as well. Another two baffles were installed over the crest with 0.4m length to help reduce downstream wakes and vortices induced by the frame of the guillotine.

The experimental studies were divided into two stages: flow measurements over normal stepped spillways and flow measurements over gabion stepped spillways. The initial water depth in the first stage is fixed to be 0.4m above the crest elevation so that the volume of water in the upstream side above the crest is 4.128m^3. On the other hand, 0.35m was the initial water depth over the crest in the gabion test stage. The second stage of the experimental work tested the water flow over gabion stepped spillways by using PIV (Particle image velocimetry) measurements. Thus, the gabion steps were installed over the impermeable steps. Square mesh wires (chicken wire) with size of 13mm*13mm have been used to construct the cages into which gravel was loaded. The gravel particle size was ranged between 14-20mm in order to have reasonable space size among the particles to assess the impact of the porous media presence.



(a) Normal stepped spillway model

(b) Guillotine-type gate



(c) Gabion stepped spillways

(d) Front view of gabion steps

Figure 3. Experiment set-up.

2.1. Particle image velocimetry

Particle image velocimetry (PIV) has been used recently to investigate water characteristics under different conditions. PIV has the capability to measure flow parameters by mixing seeding particles such as polystyrene within water together with a laser light sheet (LLS). Flow parameters such as velocity can be calculated by following some patterns of particles by using a cross-correlation function between a pair of digital images in a narrow interrogation window [7]. Velocity vectors can be observed by PIV through tracing particles which are illuminated by planar laser light. The PIV system is comprised of dual cavity flash-pumped Nd-Yag lasers using a cylindrical lens (DualPower lasers), with a maximum energy output of 700 mJ and capability of providing various wavelengths range from the fundamental wave of 1064nm, and including 532, 355 and 266nm harmonics. Nd-Yag can provide light pulses of short duration like 4ns which can capture rapid movements typical of turbulent flow. A high sensitivity speed camera, CCD camera, of 2320×1726 pixel resolution has been used to capture frames. A Nikkor 50mm 2.8, together with a narrow bandwidth filter that passes the 532 nm light from the Nd-Yag laser, is mounted on the CCD camera. The camera and laser pulses are synchronised with an electronic sequencer, (figure 4).

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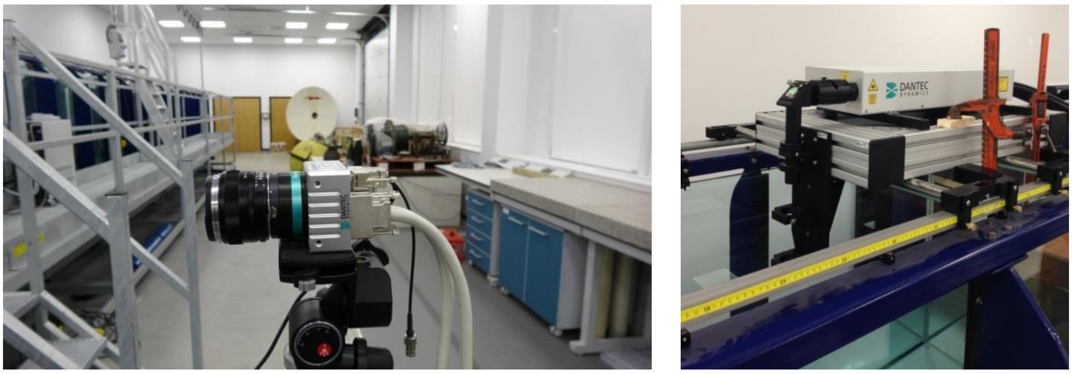


(a) (b)

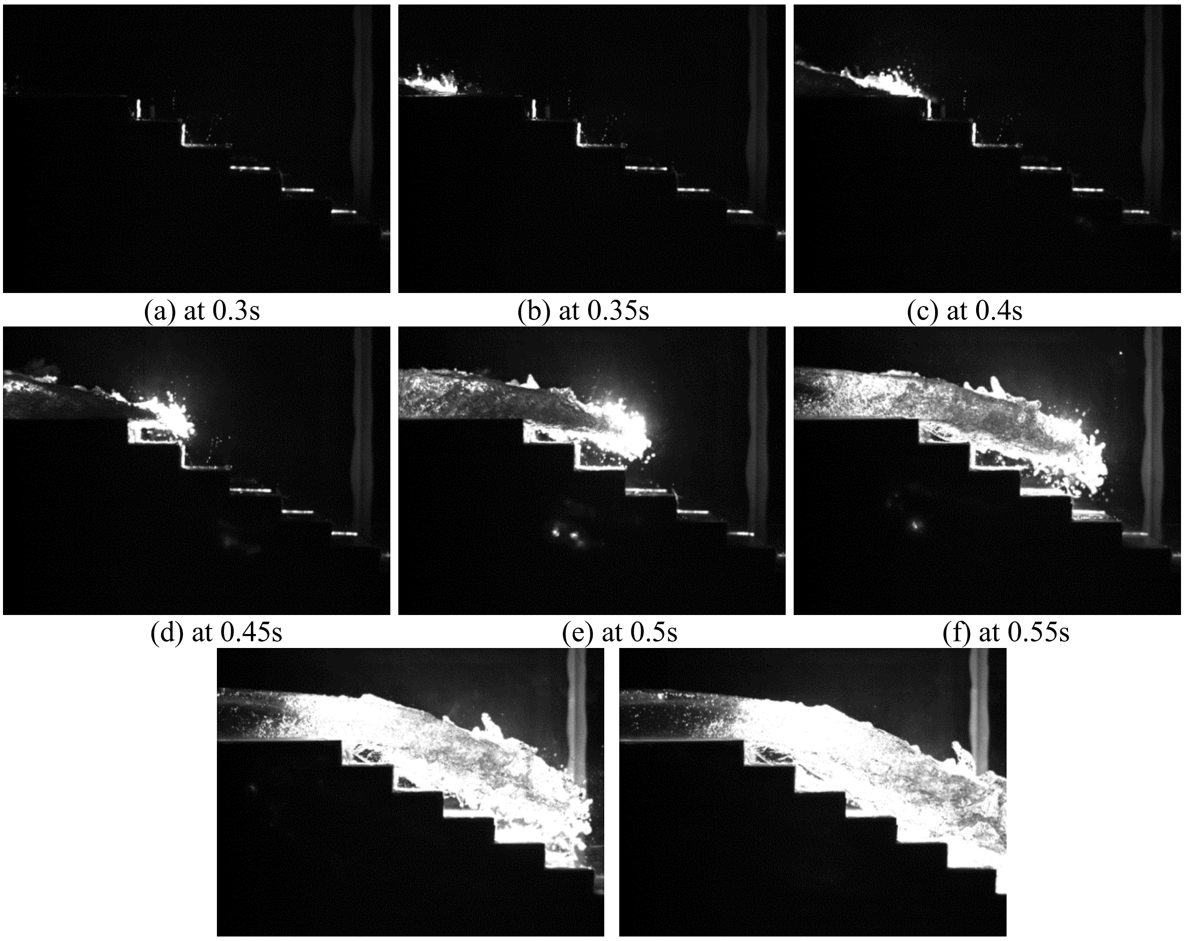
Figure 4. PIV equipment: a) CCD camera b) laser shutter.

3. PIV Measurements

PIV has become one of the most important techniques in hydro-sciences nowadays, for instance, PIV has been used to measure different types of flow such as mixing flow and open channel flow [7]. A high capacity computer has been used to check the connections between the laser and the camera and also to set the parameters like the time between two pulses and the trigger rate (number of images per second). The single frame mode has to be selected through the calibration process while the double frame mode should be selected for the acquisition.

The size of the PIV seeds which used in the experiments is 50**μ**s ceramic micro spheres. In order to get a maximum particle image displacement of eight pixels, the separation time between two lasers pulses should be between 200-250**μ**s. Trigger rate is the number of frames per second of the camera and it represents an important parameter that can affect the measurement accuracy. As the flow moves very fast over the steps, the trigger rate should be set carefully to be able to capture a good number of frames in each second so that particle movements can be captured unambiguously from the sequence of PIV images (figure 5). Different trigger rates have been tested in order to demonstrate the suitable rates for this study. For the normal stepped spillways, 20 frames per second was enough to capture the details of establishing skimming flow, However, 30 frames per second was selected in the gabion case due to the presence of flow through porous media.

It is important to mention that the PIV should be calibrated before running the experiments. Generally, the calibration process should be established once the position of the camera is changing. Hence, to conduct the calibration, an object with known dimensions should be located in front of the camera. As mentioned earlier, the single frame mode has to be selected before the acquisition. Then, after the acquisition and saving the snapshots, one snapshot should be selected to run the calibration. The real dimensions between two points, it could be the edges of the object, should be applied through the calibration window of the software. Once the calibration is done, the acquisition can be applied normally after selecting the double frame mode. After the acquisition and saving of data, results are analysed. To do this, a suitable tracking method and interrogation area within the full images must be defined. The size of the interrogation area is required in order to determine velocity vectors. Obviously, that could be significantly vital because the interrogation area size can change the values of the velocity vectors. Generally, selecting a small size for the interrogation area within the PIV post-processing analysis will lead to better results. However, if the interrogation area is too small then the accuracy of the velocity vectors may be degraded [7]. Therefore, selecting the correct size of the interrogation area is extremely important.



(a) at 0.3s (b) at 0.35s (c) at 0.4s
(d) at 0.45s (e) at 0.5s (f) at 0.55s
(g) at 0.6s (h) at 0.7s

Figure 5. Snapshots of flow over a normal stepped spillway at different time steps.

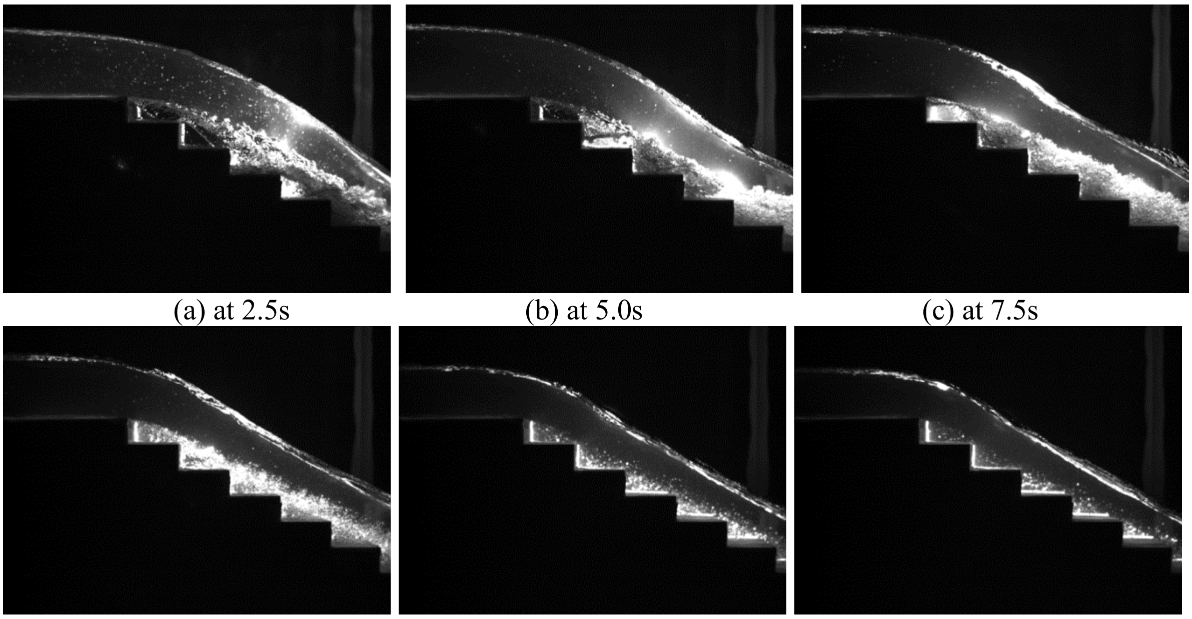
Post-processing was conducted using Dantec's DynamicStudio 2015a to obtain water particle velocities. Adaptive PIV technique was used to analyse the data. It can be defined as an automatic method for calculating velocity vectors based on particle images. It is adaptive because the velocity vector calculation adjusts the shape and the size of the individual interrogation areas depending on the seeding density (the amount of the seeds in one image) and flow gradients.
The Grid Step Size parameter has been used to control the number of interrogation areas and the spacing between their centres and can be determined as the number of pixels from one area to the next. It is important to mention that the adaptive PIV has the ability to change the size of the interrogation areas during the process of the analysis depending on the solution. However, the maximum and the minimum sizes need to be specified. The largest size of interrogation areas will be used in the first iteration and then with more iteration, the size will reduce until reach that size where the particle density is high enough to get the vectors.

4. Time to attach skimming flow

Skimming flow conditions over stepped spillways represents the most significant flow that causes different kind of problems over the steps such as cavitation damages in the non-aerated zone. Therefore, determining the required time to achieve it can be considered extremely important, in order to be used in the hydraulic design of stepped spillways under dam break conditions. The captured frames from the PIV camera are used to determine the required time to achieve the skimming flow.

The definition of the skimming flow was applied in this stage to determine the initial time accurately. Thus, that was the reason for waiting some time at certain stages of the experiment until the water fills all air pockets over steps. In figure 6a, it is clear that water has not filled the first two steps at that moment. However, after 6.25s, water starts to fill both of them gradually, and then they will be completely vanished at 8.75s as illustrated in figure 6d.

Some cloudy patches can be observed at the early stage of the skimming flow where some tiny air pockets reflect the laser light. Therefore, it is better to wait longer to assure that skimming flow conditions have established completely. Under skimming flow conditions, particles can be observed due to laser reflections (figure 6).



(a) at 2.5s (b) at 5.0s (c) at 7.5s

(d) at 8.75s (e) at 10s (f) at 10.5s

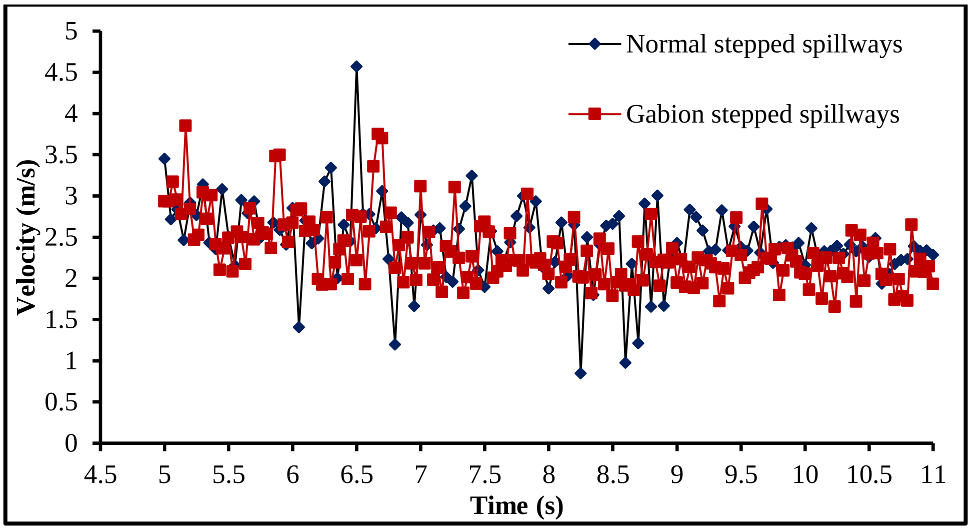
Figure 6. Snapshots showing flow developing over a normal stepped spillway.

For gabion stepped spillways, it can be concluded that the process to establish skimming flow is almost the same without gabions, however, gabion stepped spillways needs little more time to establish skimming flow as some of the water goes through the porous media (between the gravel); this is likely to be the reason for the delay in establishing skimming flow. It is worth mentioning that the required time to achieve the skimming flow in the gabion case was about 8s which is half a second more than the normal case if the same initial water depth is applied.

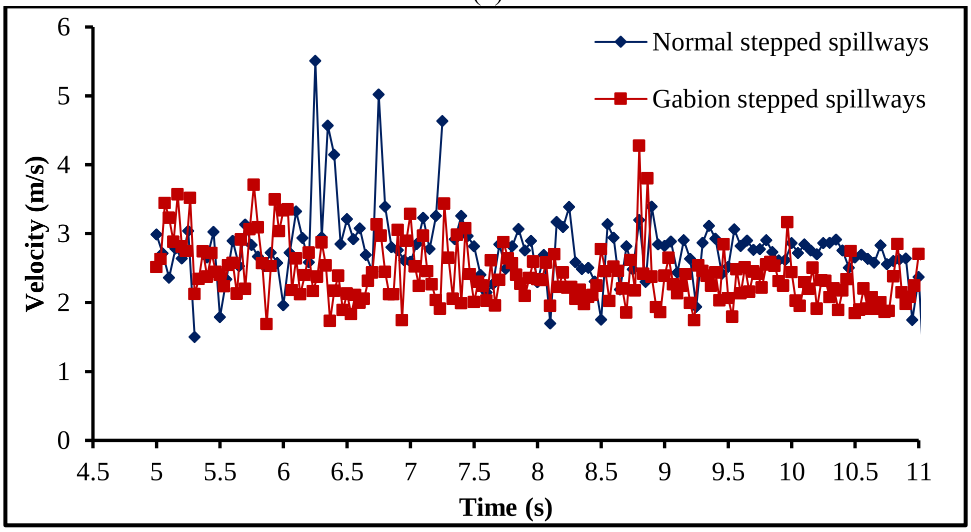
5. Velocity distributions over the non-aerated zone

Figure 7 shows the PIV results of the velocity over two types of stepped spillways. It is significantly crucial to test the velocity distributions over stepped spillways during the skimming flow. This is due to the velocity impact on the pressure distribution which is stated clearly in the Bernoulli's principle. It is identified from the previous research that any variation in the pressure over the steps can easily enhance the cavitation damages in the non-aerated zone. Consequently, a comparison for the velocity vectors has been conducted between the flow over the permeable and impermeable steps. In order to avoid discrepancies in the results which are observed in the aerated zone due to air entrainment, this study was carried out for the non-aerated zone.

It was noted that the main issue in the aerated zone is that air bubbles act as reflectors and that would make PIV images much nosier and more difficult to process. Thus, the flow velocity data of the experimental work was observed and measured over the steps in the non-aerated zone where no air entrainment is expected to be observed. Furthermore, the reason for having some spikes in the experimental results could be related also to the noise and that may come due to the reflection of the laser when it hits the turbulent flow. Generally, the level of the noise in the non-aerated zone was relatively small as can be seen in figure 7; and therefore acceptable results were able to be achieved. It is observed that the values of the velocity over normal stepped spillways are more than their corresponding values over the gabion stepped spillways (figure 7). This is an indication that the presence of the porous media (i.e gabion steps) can reduce the flow velocity over the steps as a result of the flow seep between the particles. It is important to highlight that the velocity values for both cases have been increased towards the downstream of the spillways as illustrated in figure 8. The maximum value of the velocity distribution might not be achieved near the flow free surface in the aerated zone. This is due to occurrence of the air bubbles which could slightly impact the cross section of the velocity distribution.

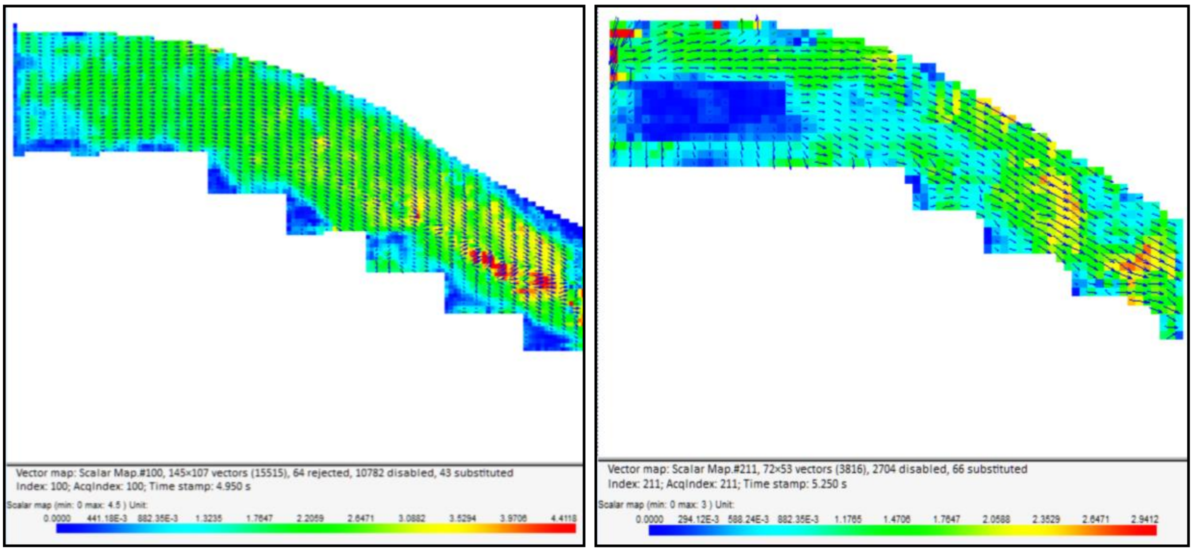


(a)



(b)

Figure 7. A comparison between the flow velocities over normal and gabion stepped spillways at the edge of (a) step 2 and (b) step 3.



(a) (b)

Figure 8. PIV scalar map with velocity vectors (m/s) over (a) normal stepped spillways at t=4.95s and (b) gabion stepped spillways at t=5.25s.

6. Conclusion

Particle image velocimetry measurements over permeable and impermeable steps of stepped spillways under skimming flow regime are investigated and described. The non-aerated flow zone which is close to the inception point of the spillway is tested as it is represented a critical region for evaluation of cavitation risk. Some significant differences were detected in the experimental investigation in terms of mean velocity between gabion and normal stepped spillways which could impact the turbulence characteristics like the Reynolds stresses. The results revealed that the time required to attach skimming flow in the gabion case is more than the normal case due to the presence of the porous media of the gabion. Accordingly, water flow needs some more time to seep between the particles in order to eliminate the air pockets inside the porous media completely, which do not exist in the normal case. The PIV measurements provide a vision about the flow features which deliver a better understanding of how the flow conditions developing over the steps.

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