Measurement of the free-surface elevation in a steady flow in complex topography using photogrammetry

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ABSTRACT: Experiments are widely used to obtain validation data for numerical models in well-controlled flow conditions. One difficulty when conducting experiments is the selection of appropriate measurement techniques. Most of the current techniques can only capture a small portion of the area of interest and some of them are also intrusive. This study uses photogrammetry to determine the water elevation in a wide area representing a scale model of the Dahan creek in Taiwan, without perturbing the flow. In this work, steady flows over a fixed bed (without sediment transport) are investigated. Based on the obtained results, the capabilities and limitations of the photogrammetry in capturing the flow features are discussed.

1 INTRODUCTION

Many numerical models have been developed for the simulation of flows in arbitrary bathymetries. To assess the capabilities of those models, the simulation results have to be compared to data obtained during experiments.

To measure water levels, different methods can be used such as resistive gauges that are slightly intrusive and provide only point measurements, or non-intrusive image capture through a side panel (e.g. Lauber and Hager 1998; Soares-Frazão 2007) or using a laser-sheet (e.g. Soares-Frazão *et al.* 2007; Rousseaux *et al*. 2016), which provide data along a given section. These techniques allow the measurement of a continuous flow profile along the considered axis. However, these are restricted to the possibility of having optical access to the area of interest in the flow. In cases of complex topographies, such an optical access is not always available.

Some attempts were made to apply particle detection to floating tracers in steady flows to reconstruct the free surface but this technique also presented serious drawbacks. For example, in Douxchamps *et al*. (2005), the authors used two alternative techniques to determine the free surface position: stereoscopic matching of particles on the free surface filmed by two cameras, and estimation of the free-surface elevation based on the horizontal velocity measured using a single camera. They obtained acceptable results but highlighted difficulties in both methods. The first method suffered from many errors due to the difficulty of identifying accurately the particles and positioning them in the vertical direction while the second required strong assumptions in order to use the Bernoulli equation to link the velocity to the elevation.

Aureli *et al*. (2011) used a light-absorption method to capture the water level during a dam-break on a flat bed. With the combination of a backlighting diffusing light and a colored solution, the authors could determine the water depths from recorded RGB values. The determination is possible because the absorption is a function of the wavelength and the water depth. The method showed promising results. However, it suffers the limitation of being valid only on a flat bed or a smoothly varying bed.

The research presented here uses photogrammetry to capture the whole water free-surface elevation.

According to Schenk (2005), photogrammetry is defined as the science of obtaining reliable information about the properties of surfaces and objects without physical contact with the objects, and of measuring and interpreting this information. The information is obtained by taking several overlapping pictures (stereopsis) issued from different viewpoints in order to reconstruct a 3D geometry. This method has the advantage of being both non-intrusive and able to capture a wide area. Those two characteristics are interesting for capturing water level while performing experiments, or in the field.

Photogrammetry is here applied to an experiment conducted at the National Taiwan University. The case considered is a scale model of the Dahan creek, located upstream of the Shihmen reservoir in the northern part of Taiwan. This creek is characterized by a complex topography, with a main channel and floodplains limited by cliffs and then higher terrain, and featuring abrupt changes in the cross-section shape (Figure 1).

The goal of this experiment is to assess the capabilities of this technique in capturing the water level for a flow in a completely arbitrary topography.

The paper is organized as follow: in section 2, the experiment and measurement technique are detailed. Then, results are presented and validated in section 3. Finally, conclusions about the capabilities of photogrammetry in the domain of experimental hydraulics are drawn. Several possibilities of improvement are also highlighted.

2 EXPERIMENTAL SETUP

The 1/2500 scaled model was constructed in fiberglass reinforced polyester (Figure 1). The topography was created from field measurements and maps. To obtain an accurate representation of the terrain, a mold was cut out of a block of Styrofoam by a Computer Numerical Controlled Styrofoam Cutter. As Styrofoam is not water tight and highly resistant, a layer of fiberglass-reinforced polyester was added on top of it.

Considering the important scale factor, a vertical / horizontal distortion of a factor 7 has been applied in order to obtain measurable water-depths in the model. The vertical scale is thus 7/2500. The final model, illustrated in Figure 1, is 12 m long and 2 m wide.

In order to reproduce the observed water depths taking into account the distortion factor applied, it is necessary to have an adapted high value of the Manning coefficient. This is not achievable with a channel in polyester. Therefore, a higher friction is created using small acrylic cubes placed on the riverbed. Their size (3 mm) and distribution were selected to reach the expected water depths without affecting too much the water surface, i.e. without creating a step-pool behavior. The 3 mm height in the model corresponds to approximately 1 m in the prototype; this is non-negligible but the increase of friction is important to reach the correct measured water depth.

Three different discharges are considered. The lower one corresponds to a flow restricted to the main channel with Q = 0.93 l/s, corresponding approximately to 16 000 m^3/s in the prototype. The largest one corresponds to the peak discharge that could be reasonably expected in case of a dam failure at the Shihmen Reservoir, with Q = 2.37 l/s, i.e. approximately 40 000 m^3/s in the prototype. The last one corresponds to intermediary conditions, with Q = 1.48 l/s, i.e. approximately 25 000 m^3/s in the prototype.

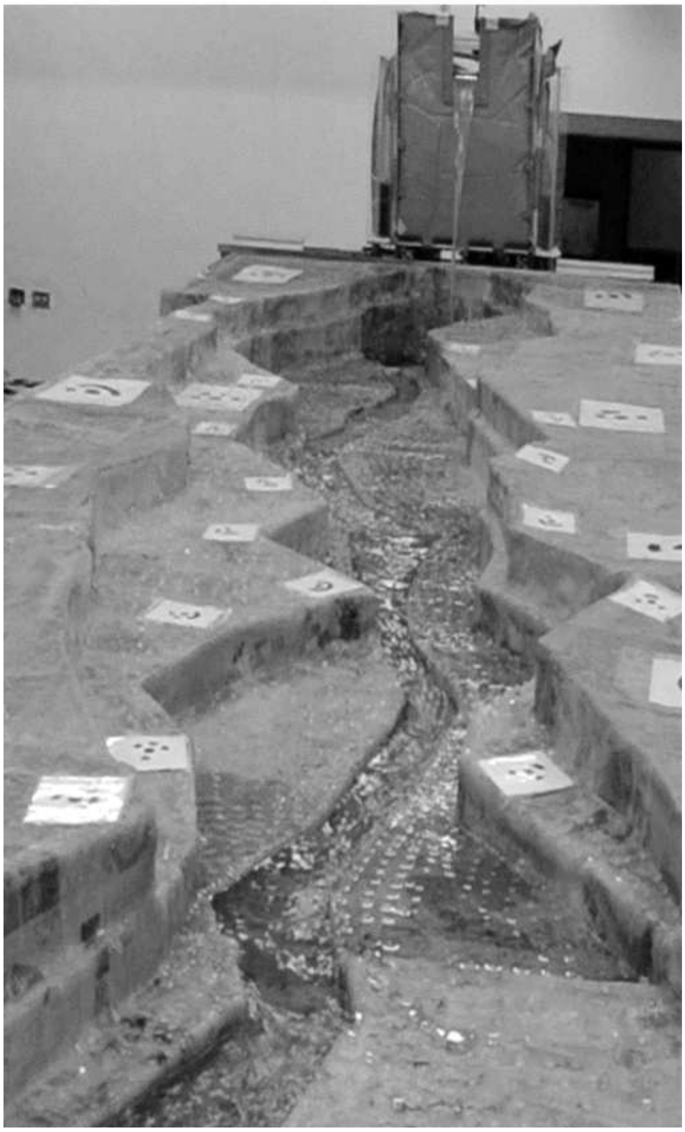

Figure 1. Experimental setup

To impose the discharge, a reservoir with a rotating door was built. Inside the reservoir, the water level was kept constant using a system of pumps. Thus, the inclination of the door could control the discharge exiting by overflow.

As can be seen in Figure 1, a waterfall is created at the exit of the reservoir. To diminish the energy of the flow there and prevent this waterfall to alter the behavior of the flow in the rest of the channel, a dissipation pool has been added at the upstream end of the model.

3 DATA ACQUISITION AND TREATMENT

The water free surface elevation was measured using photogrammetry. The technique is briefly recalled, and then its application to the present case is described.

3.1 *Photogrammetry for level measurements*

Photogrammetry is used to reconstruct the 3D water surface from aerial photographs.

First, photographs should be captured with enough overlap: a minimum of 60% is recommended (Ippoliti *et al.*, Figure 2). With this overlap, points on the domain are captured from different points of view and thus with different angles. These different angles will allow the correct positioning of the photographs

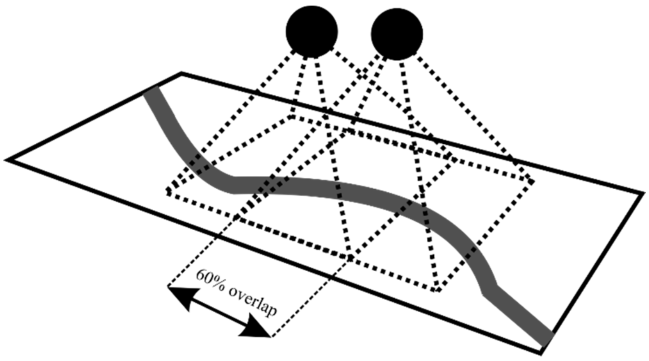

Figure 2. Sketch of the pictures capture

Then, the treatment starts by correcting the distortions of the camera (Figure 3); these optical distortions are created by the lens and can be corrected knowing the characteristics of the lens used.

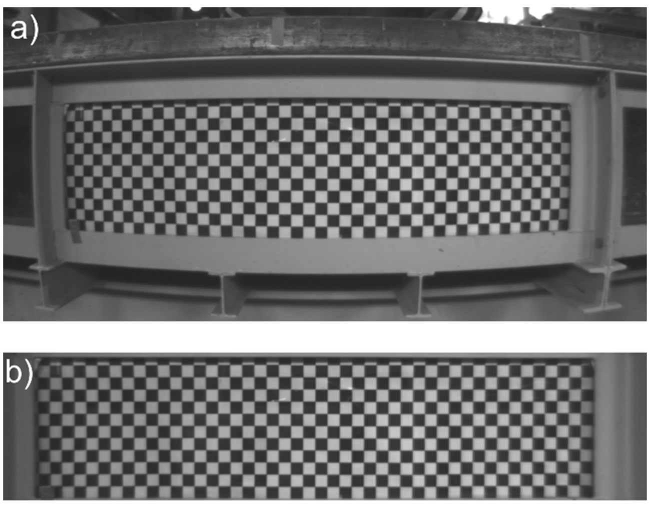

Figure 3. Distortion correction: original picture (a) and picture after correction (b)

After the correction, the second step of the treatment consists in a correct positioning and orientation of the pictures. It is determined using other pictures by matching identical points with a known position.

Finally, elevation data can be extracted from pixels information to create a cloud of points with known properties (e.g. coordinates of points, size…). In the third step of the treatment, a mesh is created by interpolation between the points. The mesh is scaled and oriented using information from the identified objects.

3.2 *Application to the Dahan creek model*

Several reference points have been placed to ensure recognition and scaling during data treatment (Figure 1). Their position has been determined using a total station (the accuracy of the total station is around 2 seconds in angle, 2 mm in distance). The positioning of these reference points is crucial and presents some difficulties. To ensure the correct positioning and orientation of the pictures in the second step of the treatment, a sufficient number of reference points should be captured in the entire set of pictures. In addition, these detected reference points should be distributed randomly to prevent any ambiguities in the picture positioning, which could happen if the reference points appear aligned on a picture. This constraint is enhanced by the fact that no reference point can be used if submerged.

To satisfy as much as possible these recommendations, 72 reference points have been placed on the channel, on the small plateaus, out of the reach of the flow and as close as possible to the main channel. The average distance between two consecutive reference points (on the same bank) is thus 0.2 m.

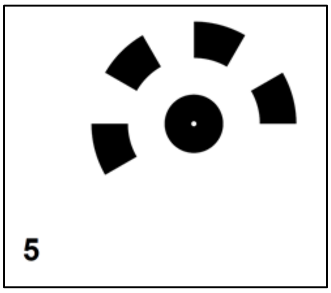

Figure 4: Example of reference points (12-bit circular)

Any type of reference points can be used. In this case, 12-bit circular reference points (Figure 4) have been used, because they can easily be recognized (position and number) by the software used in the pictures treatment.

The pictures were captured using four synchronized cameras (see Table 1). The synchronization was controlled by four independent flashes. It was necessary to use four flashes in order to obtain uniformly bright pictures and a recycling time low enough to be able to take many pictures in a short time. To synchronize correctly the pictures, the room was kept completely dark and the cameras were set in long exposure mode. That way, the flash ensures that all the pictures are taken at exactly the same time. The area covered by one set of pictures is approximately 2 by 2 meters. The set of cameras is thus moved twelve times to cover the complete domain with enough overlap. This is relatively easy for steady flows, as the water surface is considered stable.

Table 1. Cameras used in the experiments.

Camera Type	Lens focal length
Nikon D3	24 mm
Nikon D200	18 mm
Nikon D7000	18 mm
Nikon D7000	18 mm

Before starting the experiment, pictures of the dry bed have been taken to obtain a reference situation to extract water depths. Then, the flow measurement process was realized in three consecutive stages illustrated in Figure 5: (1) capture of pictures (Figure 5a), (2) treatment of the pictures to obtain the free surface (Figure 5b), (3) validation and further treatments of the results, in order to extract the water depths (Figure 5c). These stages are described below.

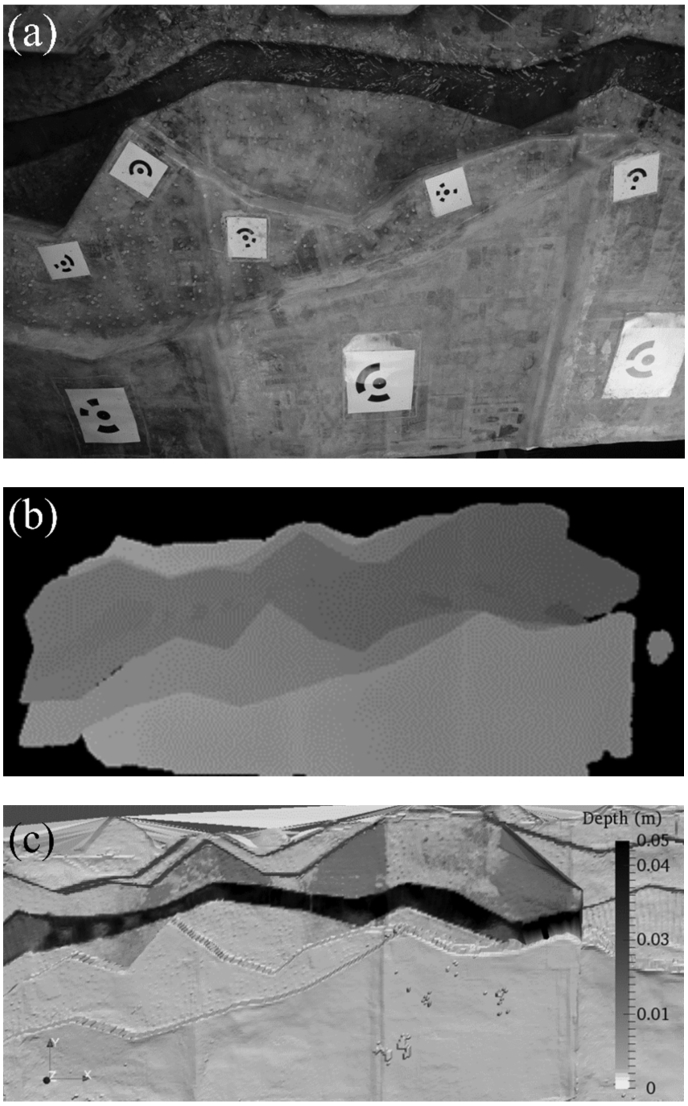

Figure 5: Complete process to obtain results: (a) Sets of four pictures taken on the flume (only one is represented here), (b) Determination of the level using the commercial software Photoscan, and (c) Final treatment of the data and extraction of the water depth

In the first stage, in order to obtain good quality pictures, the free-surface detection was improved by adding blue dye to the water in order to make it an opaque surface. In addition, for each steady flow case and for each camera position, ten sets of pictures were taken to obtain an average water level. Figure 5a shows such a picture, where eight reference points can be identified, and the water surface can be identified as a darker area.

In a second stage (Figure 5b), the sets of pictures are treated using the commercial software Agisoft Photoscan. This software, first, corrects the pictures considering the lens deformation and positions them in the global system of coordinates. This step uses recognizable features in the photographs such as the reference points or points with enough texture.

The last treatment in the process is to assemble the meshes created with Photoscan. To obtain the steady water level, the values given by each of the ten meshes corresponding to the ten sets of pictures are time averaged. The results are thus smoothen and depend less on local errors or fluctuations. Finally, the bed level mesh, obtained from the dry-bed pictures, is subtracted from the water level mesh to provide the water depth in the whole domain (Figure 5c).

4 RESULTS AND DISCUSSIONS

To assess the accuracy of the complete process, two cross-sections S1 and S2 have been measured manually using a point-gauge (Figure 6). Both the water level and the bed level were measured, for a discharge of 2.37 l/s. In addition, the experiment was repeated twice with the same discharge (i.e. 10 pictures for each position of the camera, for each of the two experiments), as well as the treatment with the two sets of pictures to verify the good reproducibility of the experiment.

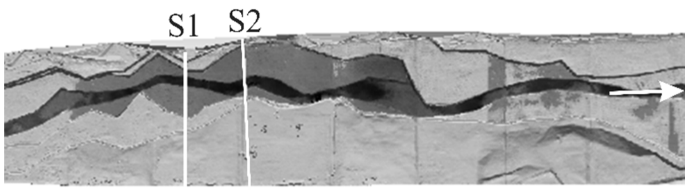

Figure 6: Location of the cross-sections S1 and S2 used for the verification of the photogrammetry measurements. (Direction of the flow indicated by an arrow)

Then, the bed level, water level and water-depths obtained by the photogrammetry measurements for these two cross-sections were compared to the manual measurements (Figures 7 and 8).

The results in the main channel, where the water is the deepest, show a good agreement and reproducibility. However, low water depths on the flood plains are not correctly captured and feature more variations from one test to the other. This problem could be caused by a lack of texture or a too important transparency of the water. A consequence of an excessive transparency is that a limit within the water column is detected instead of the water surface, yielding an incorrect value for the water level.

Furthermore, water depths lower than 3 mm will not be correctly represented, as there would be some interference with the acrylic blocks placed to increase the friction. These blocks would also have an impact on the flow pattern with low water depth; this should be kept in mind if the results from the experiment should be compared to numerical simulations.

To study the averaging process of the different water level meshes, Figure 9 shows the envelope of the water depth for the first section. The envelope is defined with the limits: Mean ± Standard deviation.

Figure 10 illustrates the results obtained for different discharges (0.93 l/s, 1.48 l/s and 2.37 l/s). The water depth is represented using a gray scale, the deepest water being the darkest.

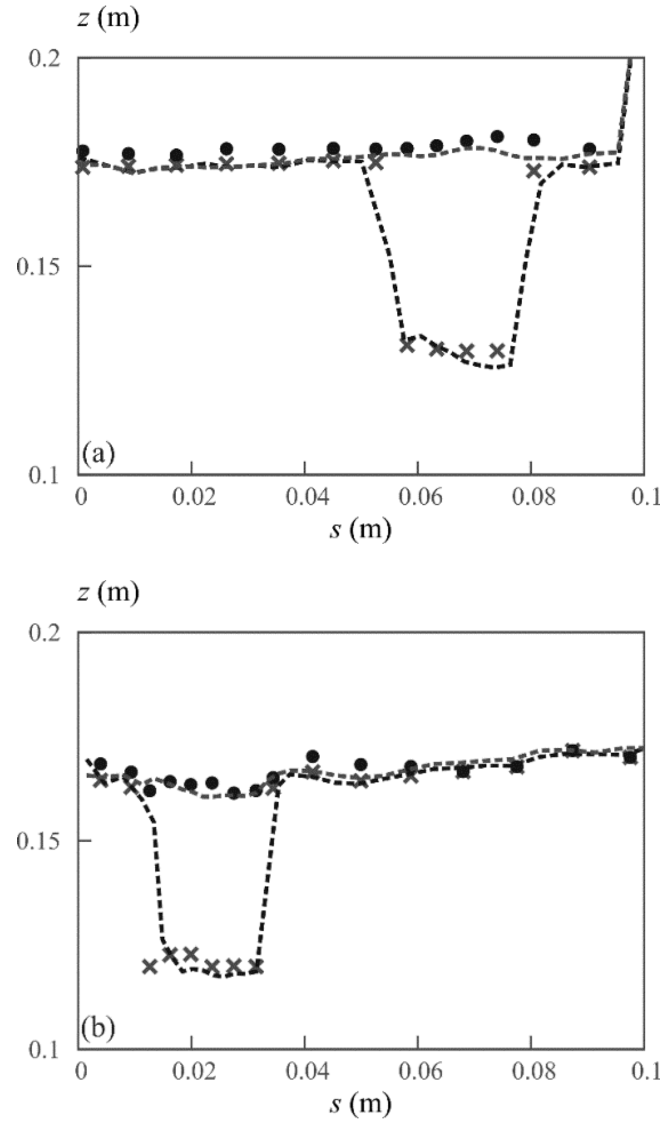

Figure 7: Comparison of the bed and water levels obtained by photogrammetry (lines) and measured manually (crosses and dots) for (a) cross-section S1, (b) cross-section S2

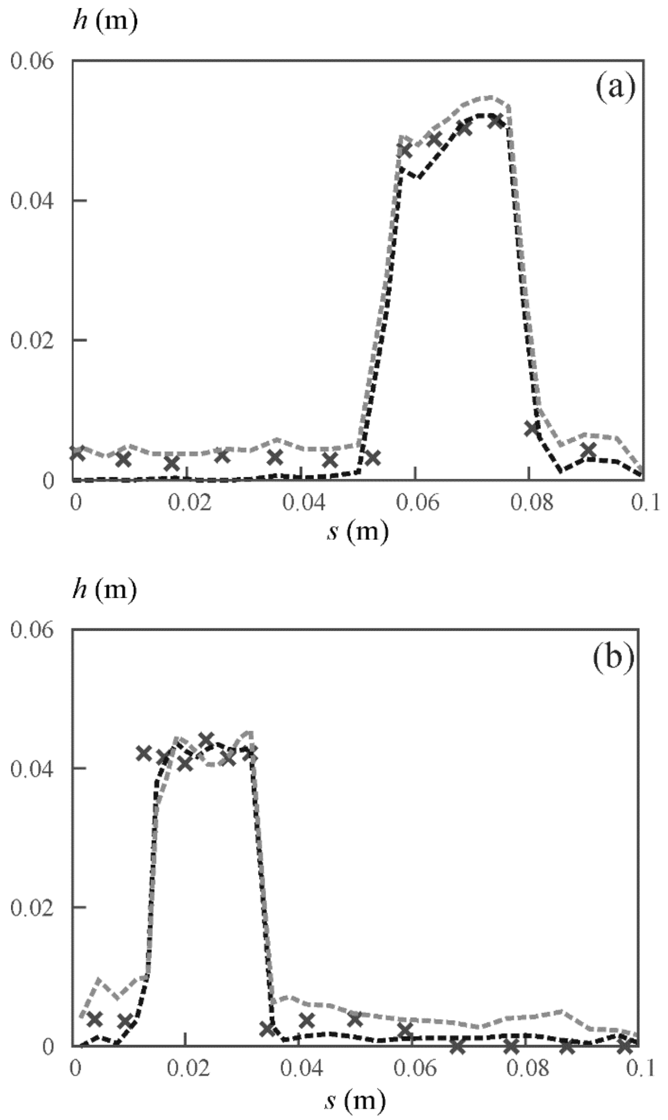

Figure 8: Comparisons of the water depth obtained by photogrammetry for the two repeated experiments (lines) and measured with point-measurements (crosses) for (a) cross-section S1, (b) cross-section S2

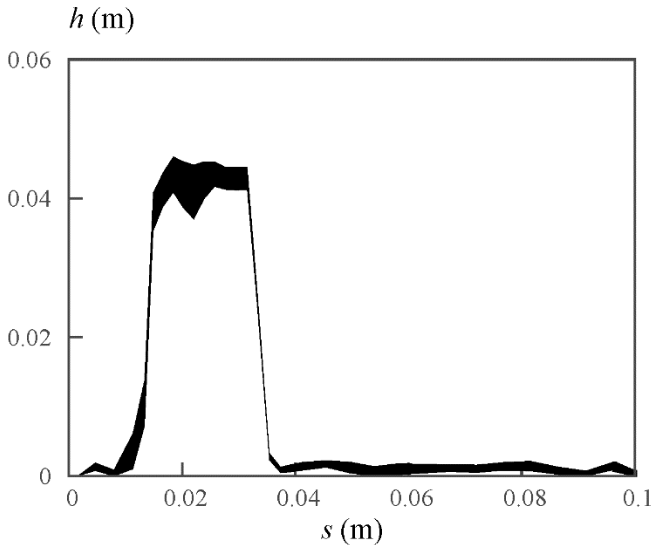

Figure 9: Envelope obtained for the second section. The envelope is constructed using Mean ± Standard deviation of the 10 meshes

The results generally agree well qualitatively with what was observed during the experiment. However, as observed before (Figures 7 and 8), problems in the flood plains are present for the discharge of 1.48 l/s (Figure 10b, indicated by the black arrow) where there seems to be water coming from nowhere, not linked to the rest of the flow.

As can be expected, the water depth increases with the discharge. In the first case, water is restricted to the main channel. In the second case, water starts to appear on the flood plain. Finally, for the last two cases corresponding to the repeated experiment, with the largest discharges, water floods a large area on the flood plains.

The measurement technique was able to capture the hydraulic jump (darkest colors) at the narrowing part of the channel, as observed during the experiments.

5 CONCLUSIONS AND FUTURE WORK

The use of photogrammetry to capture water level in experiments conducted in a scale model of the Dahan creek has been presented.

Photogrammetry is able to provide accurate results even though it showed some difficulties with low water depth despite the use of dye. A way to solve this problem might be to increase the concentration of dye in water or to use other ways to add texture to the flow. This could be done adding particles or an oil film on the water; the solution should be selected to have the least impact on the flow.

Future work will focus on the improving of shallow water recognition. The use of photogrammetry to capture transient flows should also be investigated. This technique could help a lot in these experiments by allowing the capture of a wide area of the flow in one run. This would reduce the number run needed to characterize the whole domain.

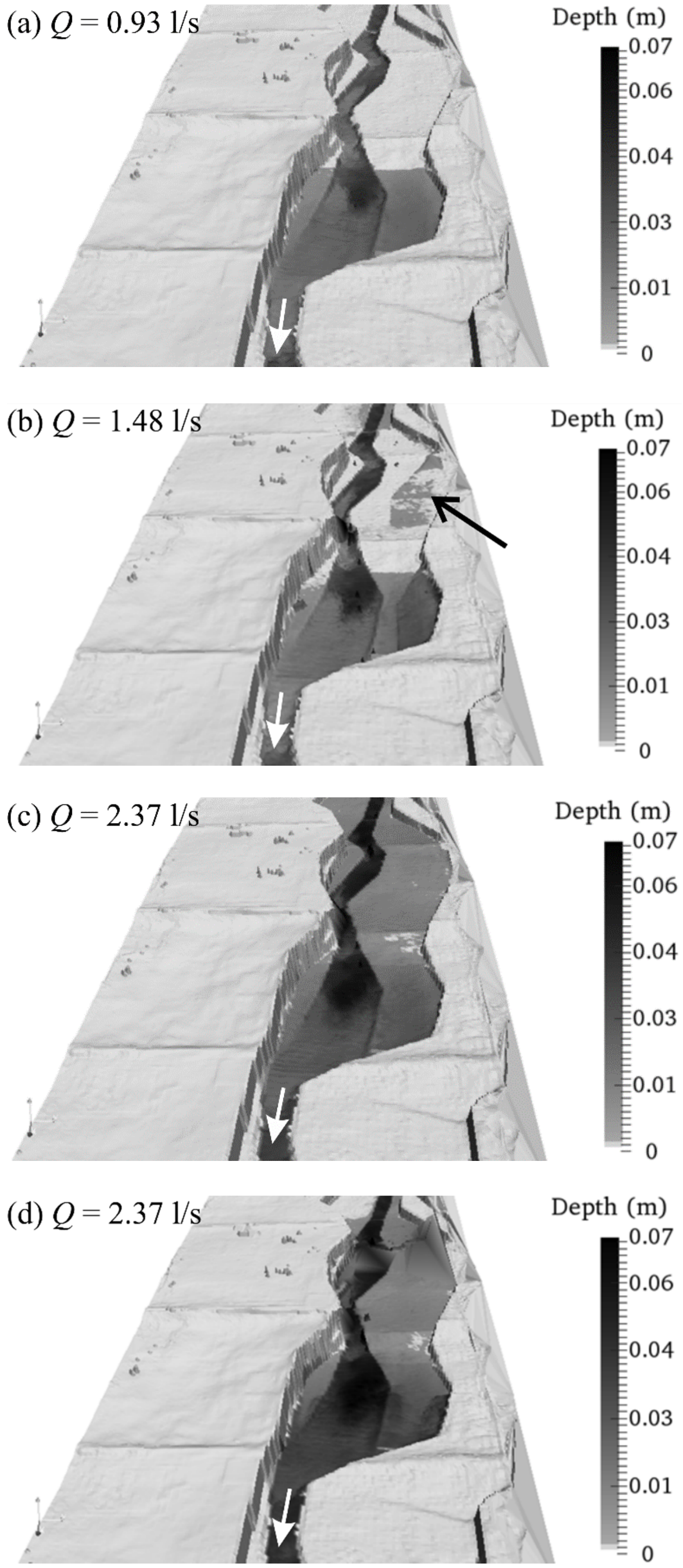

Figure10: Water depths results for tests with a discharge of (a) 0.93 l/s, (b) 1.48 l/s, (c-d) 2.37 l/s. The direction of the flow is indicated by the white arrow

However, several challenges would need to be faced in order to use photogrammetry in transient flows.

First, the time elapsed between two consecutive pictures is controlled by the flashes used. In this experiment, the use of four independent flashes, with independent power supplies, allowed to take a set of pictures every second, but not faster without losing quality. This poses a limitation to the type of transient flows that could be captured. Real dam break or transient flows in arbitrary topographies would, currently, be out of reach (with the technique used in this paper).

Second, in order to reconstruct the complete domain from different data set, it would be necessary to have pictures taken at the same time but in different positions. This would need a complete automatized system to control the beginning of the test (e.g. the starting of the pumps, or, in this case, the opening of the door) and the capture of the pictures. Another solution would be to increase the number of cameras. However, this is not the most practical solution as, for example, 48 pictures were necessary to represent the full domain in the experiments presented here. To improve the results, as in the steady state, every set of pictures should be duplicated to be able to determine an average water level. This increase the importance of a well-timed experiment. This is not as important in the case of a steady flow as it can be assumed that the water level does not change when moving the cameras set.

Finally, photogrammetry could be applied to monitor the morphological evolution in flows over movable beds by, for example, projecting a grid on the bed surface (Frank and Hager, 2015)

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