

MEASUREMENT OF THE FREE-SURFACE ELEVATION FOR FLOWS IN COMPLEX TOPOGRAPHY USING PHOTOGRAMMETRY

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ABSTRACT

Predicting the flow in rivers is an important concern regarding potential damages induced by floods. Numerical models, if they can be used as predicting tool, need to be tested to assess their reliability. This can be done by comparing their results to field measurements or experimental data. However, such comparisons are often not easy to interpret since the differences can come from a multitude of causes. Therefore, it is preferred to use well-documented experimental data obtained in a well-controlled environment. As regards water level measurements, several methods exist. Gauges provide information on a small area (point measurement method). Other techniques (imagery based analysis) such as filming through a side panel provide the water level along the considered axis but require an optical access to the area which is not always possible. This paper investigates the use of photogrammetry to measure the water level. Photogrammetry is a non-intrusive method allowing for the capture of the water level over a large area in one run of the experiment. However, its application still presents numerous challenges. The work presented here compares the results obtained using photogrammetry to other more classical measurement methods on the case of a steady flow in an arbitrary topography built in concrete. The results show good agreement between both measurement techniques and highlight the capabilities of using photogrammetry in the laboratory.

1. INTRODUCTION

Modeling flow in arbitrary topographies is an important issue in fluvial hydraulics. Indeed, in order to prevent damages and life losses during floods events or natural disasters, mitigation strategies are implemented based on the results of numerical simulations that are used as predictive tools. The accuracy and the reliability of the results provided by the simulations can be assessed using field or experimental data. However, field data are not always easy to obtain and to interpret. Differences between data and simulation results can come from several different sources. The characterization of the surrounding topography is often partial and the bathymetry is not always described in detail all along the river. The flow conditions are also difficult to define since monitoring on the field is usually achieved using only few level gauge and a rating curve for the discharge. In some cases, only scarce rainfall measurements can be used to build the inflow hydrograph. Moreover, it is really exceptional when data sets include a characterization of the studied river reach before, during and after significant event (Lapointe 1998, Capart *et al.* 2007).

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Most of the time, assumptions have to be made to complete the data set in order to perform simulations, which can constitute an obstacle to assess the performances of numerical model. The use of experimental data thus appears as a more reliable approach as the key parameters (bathymetry, inflow and downstream boundary condition) can be much more controlled and reproduced in order to increase the accuracy and reliability of the experimental dataset produced. However, acquisition of high-quality data however remains a challenge in numerous cases, especially in arbitrary topographies or under severe transient flow conditions.

Several methods exist to measure water levels in the laboratory. Two categories of methods can be defined. The first, *point measurement methods*, using e.g. resistive gauges or ultrasonic probes, provide reliable information but only at one single location. Also, depending on the type of gauges used, the measurements can be intrusive and perturb the flow. With such point measurement methods, in order to characterize the whole free-surface, the measurements have to be repeated many times with different positions of the devices, or a large number of devices have to be used. The second category, *imagery based analysis*, has the advantage of being non-intrusive but requires an optical access to the flow area. Images can be acquired laterally, through the transparent walls of the flume (e.g. Soares-Frazão 2007), or for any section using a laser-sheet illumination to observe the intersection between the plane of the laser-sheet and the flow (e.g. Soares-Frazão et al., 2007). However, these methods are generally in flumes with rectangular cross-sections, and not on arbitrary topographies.

The present work considers more complex flows, under steady and transient flow conditions, with an arbitrary bathymetry closer to field conditions. Therefore, a dedicated flume was designed, reproducing an arbitrary topography over a length of 8.8 m and with an average width of 1.2 m for the valley. To measure the free-surface elevation over the whole flow area, recent developments based on photogrammetry, and particularly on the *Structure from Motion* (SfM) method are used.

The SfM has a wide range of applications in several research fields, e.g. architecture, archeology, medicine, geography, and certainly in geosciences (Westbody, 2012). The development and affordability of good-quality numerical cameras and computing facilities enlarge the perspectives and enable the photogrammetry to become an essential acquisition tool in numerous researches (Schenk 2005, Kalantari and Kasser 2008). If the traditional photogrammetry required high skilled users and specific devices, the SfM, based on algorithms developed by Lowe (2004) and promoted by Snavely *et al.* (2008), can be performed easily using a wide range of basic images obtained with simple devices. Using fixed points that can be identified on each image, a three-dimensional positioning of the elements in the images can be obtained. This technique begins to be widely used to measure local topography or morphology evolution on the field. The cameras can be fixed at known positions, yielding the ground based technique, or placed on a moving device whose position is recorded. Considering the recent development of Unmanned Aerial Vehicles (UAV), UAV-based applications allow affordable field data collection (Westbody, 2012).

Previous researches have already attempted to capture the free-surface elevation using imagery-based techniques. Douchamps et al. (2005) applied stereoscopic particle detection using two cameras to identify floating tracers in steady flows and to reconstruct the three-dimensional free surface position. They obtained acceptable results but highlighted difficulties since the method suffered from many errors due to the difficulty of identifying accurately the particles and positioning them in the vertical direction. Frank and Hager (2016) used a grid-projection technique in a flow consisting of a mixture of water and TiO_2 , yielding an opaque flowing mixture with the same density as water. The technique was successfully applied to the evolution of a breach in a sand-dike. However, this technique requires costly equipment and very special lightning conditions. SfM method was applied by Franzini et al. (2016) to a steady flow in a scale model of an existing river in Taiwan. The results appeared promising but the accuracy of the measurements in low-flow areas was not sufficient.

In this work, the SfM technique is applied to the newly designed experimental set-up to obtain measurements of the free-surface elevation, both under steady and unsteady flow conditions, trying to overcome the limitations identified by Franzini et al. (2016). The results of the SfM are compared to conventional measurement techniques for steady flow conditions, and the applicability to unsteady flows is discussed.

2. DESCRIPTION OF THE SETUP AND OF THE MEASUREMENT TECHNIQUE

2.1 Experimental setup

The scaled-model is placed in an existing rectangular channel with a useful area of approximately 8.80×1.20 m, and a depth of about 0.25 m. The inlet flow is controlled by a pump that can discharge up to 30 l/s and the downstream boundary is controlled by a lift gate over the whole channel width. An arbitrary topography based on cross-sections surveyed in a Haitian river (ref) and adapted to the channel dimensions has been designed to create the present complex bathymetry.

The model was built in light concrete guided by wood sections patterns (Figure 1a). The model is divided in twelve modules ($0.80 \times 1.18 \times 0.25$) containing five wooden sections each (Figure 1b). These modules are filled with a light concrete mix to allow easy handling (Figure 1c). The modules are then installed in the channel (Figure 1d) and a cover layer is poured directly on the set-up to link the modules and to obtain a smoother texture, but still with a sufficient roughness (Figure 1e). This method has the double advantages that it can be applied without too many infrastructures and that any module can be extracted and replaced to create a new bathymetry, which was made possible by an appropriate design of the first and last sections of each module.

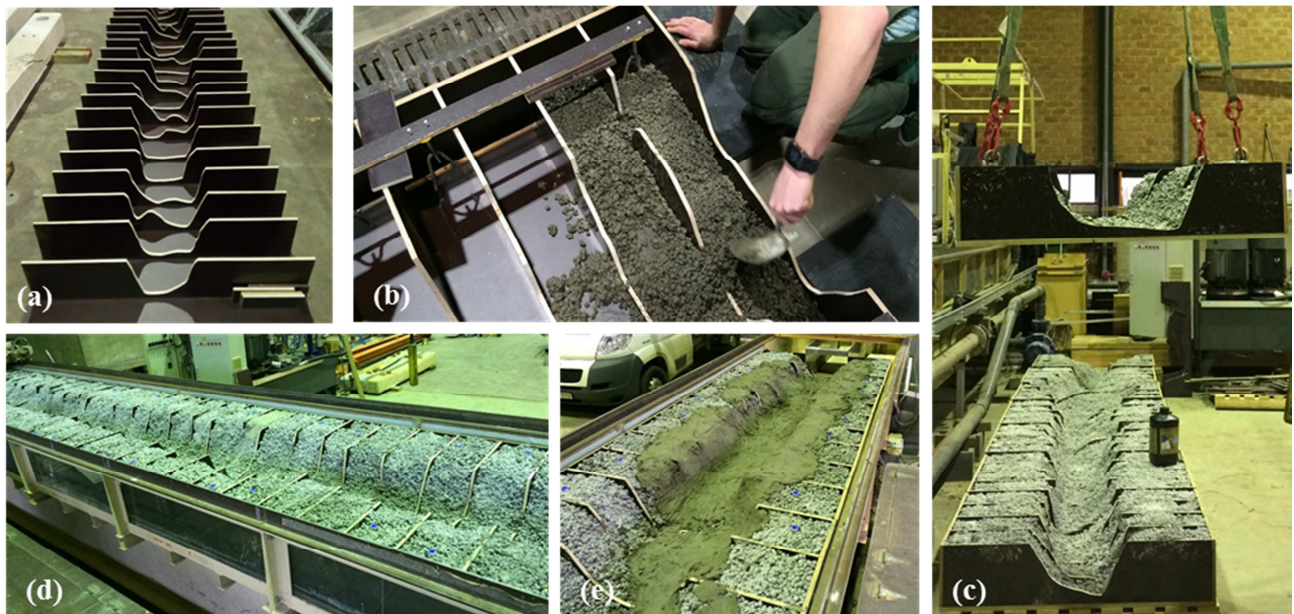


Figure 1: (a) alignment of wood cross-sections to build the channel casing (b) pouring concret of a module (c) lifting of a module to place it in the channel (d) positioning of modules along the channel (e) application of the cover layer to aggregate the module and make a continuous surface

Then, 66 reference points (RP) are placed all over the model (Figure 2d) to enable the positioning of the 3D reconstructed model from the filmed images. These RPs are 12-bit circular reference patterns that can be easily recognized (position and number) by the software used in the image treatment. A survey of these RP is done with a total station in a local 3-D coordinates system to allow the positioning of the experimental set-up with a high precision. The accuracy of the total station is about 2 seconds in angle, corresponding to 2 mm in horizontal distance.

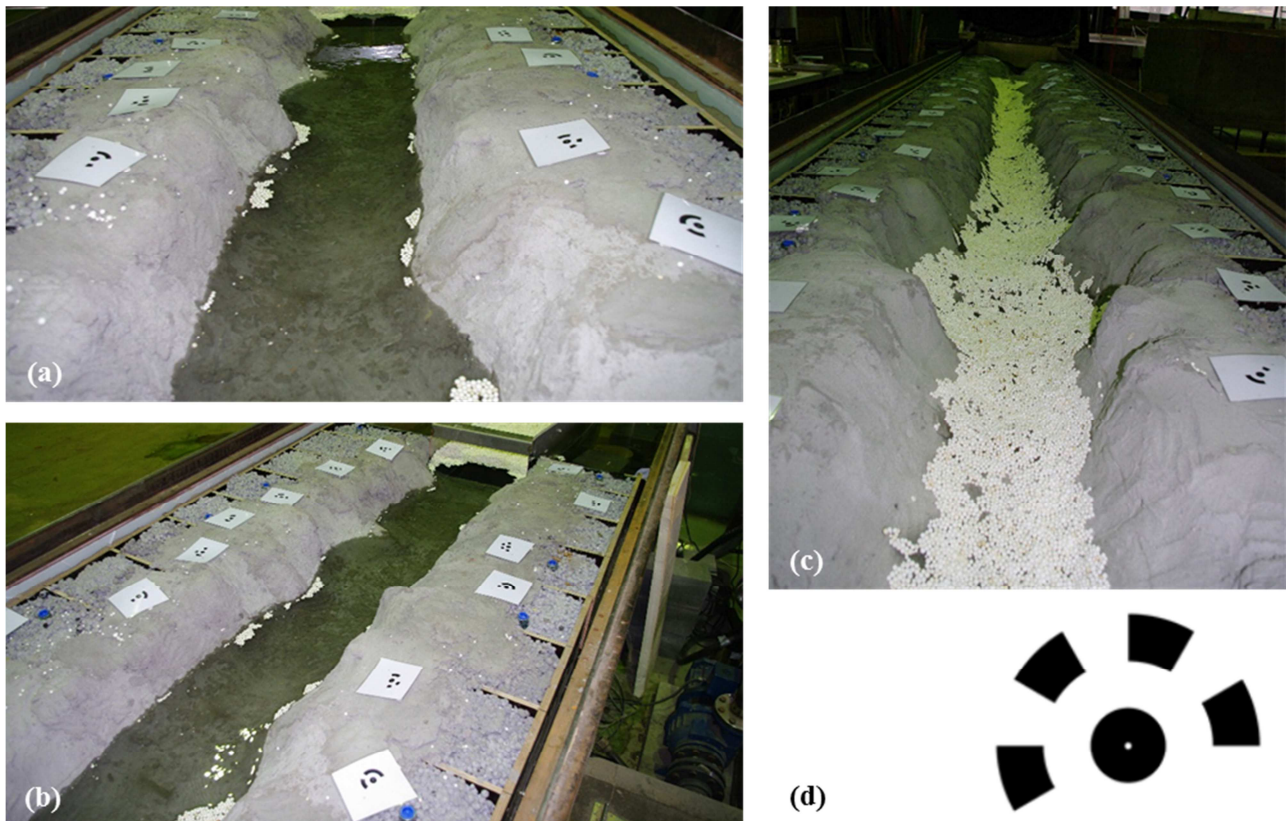


Figure 2: (a-b) views of the experimental set-up under water (c) view of the experimental set-up after an experiment conducted with white foam balls (d) Reference point example

2.2 Structure from Motion

In classical photogrammetry, overlapped photos of the same scene are used to reconstruct a three-dimensional object, knowing the position of the camera. The SfM differs from this approach since no information concerning the camera position, orientation and the scene geometry are necessary to run the process. These parameters are solved simultaneously through the automatic identification of common *features points* on numerous couples of images. Therefore, a large number of images are required.

Basically the SfM needs multiple views of a same object from several different positions. From a set of images, common features points are identified with an invariant description vector, the most used algorithm for this task being the Scale Invariant Feature Transformed algorithm (SIFT) developed by Lowe (2004). Feature points are thus identified on a range of pictures in order to establish spatial relationships between the original images locations and orientations in an arbitrary 3-D coordinates system. This reconstruction process is done by a “bundle adjustment” solving the camera position and orientation. This bundle adjustment consists in calculating a position and an orientation for each camera from a couple of photo, through the features points identified. Doing this for all couples of images available, these positions and orientations are further adjusted, in order to refine the calculated positions and orientations. At the end of this step, a sparse point cloud (Figure 3a) is produced. These sparse points represent the feature points identified in the coordinates system and are associated with a color that allows for a first visual appearance of the reconstructed scene.

At this time of the process, the user can identify on the pictures the different reference points (RP) disseminated on the model. These RP allow for positioning the point cloud previously created in a known 3-D coordinates system. In addition, these RP can be seen as additional feature points for which the exact position is known with high precision. The bundle adjustment can be relaunched and the process is then

optimized according to the importance given to the RP in comparison with the other feature points identified during the first phase of the process (SIFT).

Once the sparse point cloud is obtained, the SfM intensifies the results with Multi View Stereo techniques (Fukurawa and Ponce, 2010). Working on couples of photos previously linked, this step compares each pixel of the photos. It is consequently usual to work with compressed images as the computing time can become huge (Bemis et al. 2014). The final result is a dense point cloud (Figure 3b) with a higher resolution (according to the required refinement), and without most of outliers present in the sparse point cloud (James and Robson, 2012). As previously, each point can be colored, providing a visual appearance allowing a good representation of the scene.

From this points cloud, it is now possible to extract information about the scene such as elevation of each point of the area, orthophotoplans and digital elevation model (DEM). The accuracy that can be achieved with this technique has already been demonstrated in previous researches. The challenge in the present work is to apply the SfM also to the recognition of the free-surface elevation, the main difficulty being the transparency of water. Indeed, if the river bed can be seen on the images, the elevation of this river bed will be identified instead of the free surface, or an elevation between the bed and the free-surface.

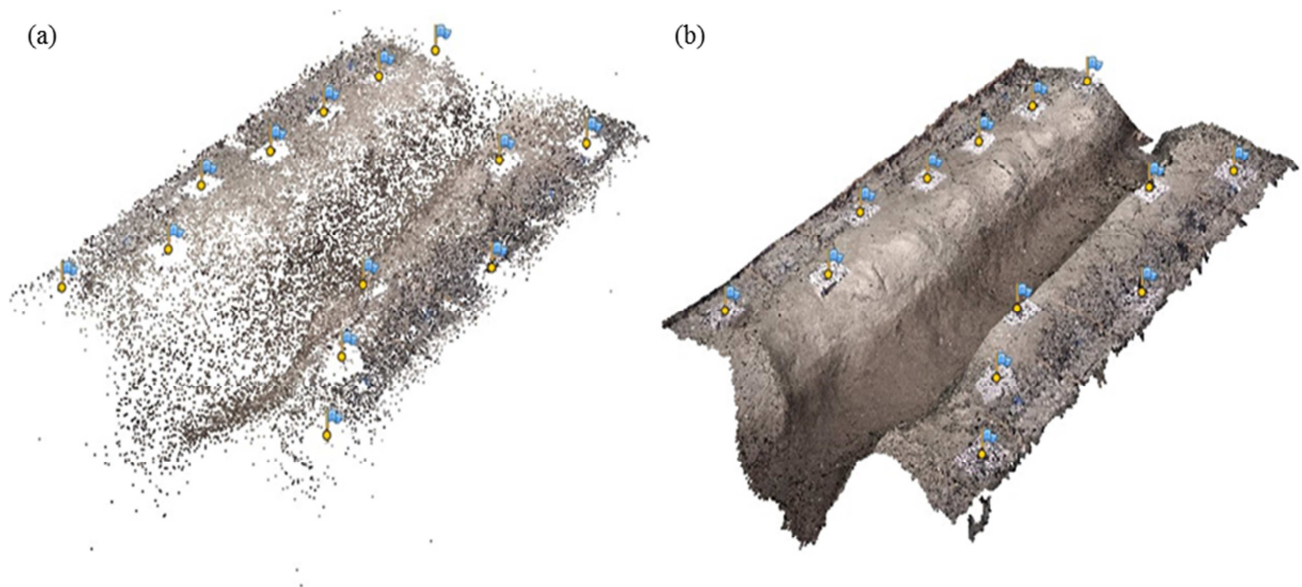


Figure 3: (a) Sparse point cloud with flagged reference point. (b) Dense point cloud with flagged reference point.

2.3 Data acquisition

2.3.1 Imaging system

As explained before, the SfM can be applied as a low-cost method, using simple cameras. Here, data acquisition is performed using a GoPro Hero 4 Silver camera. In photo mode, the GoPro Hero 4 Silver has a fixed focal length of 2.98 mm, a photographic sensor of 6.17 x 4.55 mm and provides 4000 × 3000 pixels photos (12 MPix). However, photos made by a GoPro present a huge distortion due to the wide-angle lens. These deformations can be correct by the software used to apply the SfM, which is the commercial package *Photoscan* (Fonstad et al., 2013).

The camera is fixed on a travelling structure above the channel, with different possible positions and orientations (Figure 4a) to obtain different angles of view. In order to obtain uniform lightning, the flume is covered by a dark chamber fixed on the travelling structure (Figure 4b). A typical image obtained during the experiment is shown in Figure 4c.

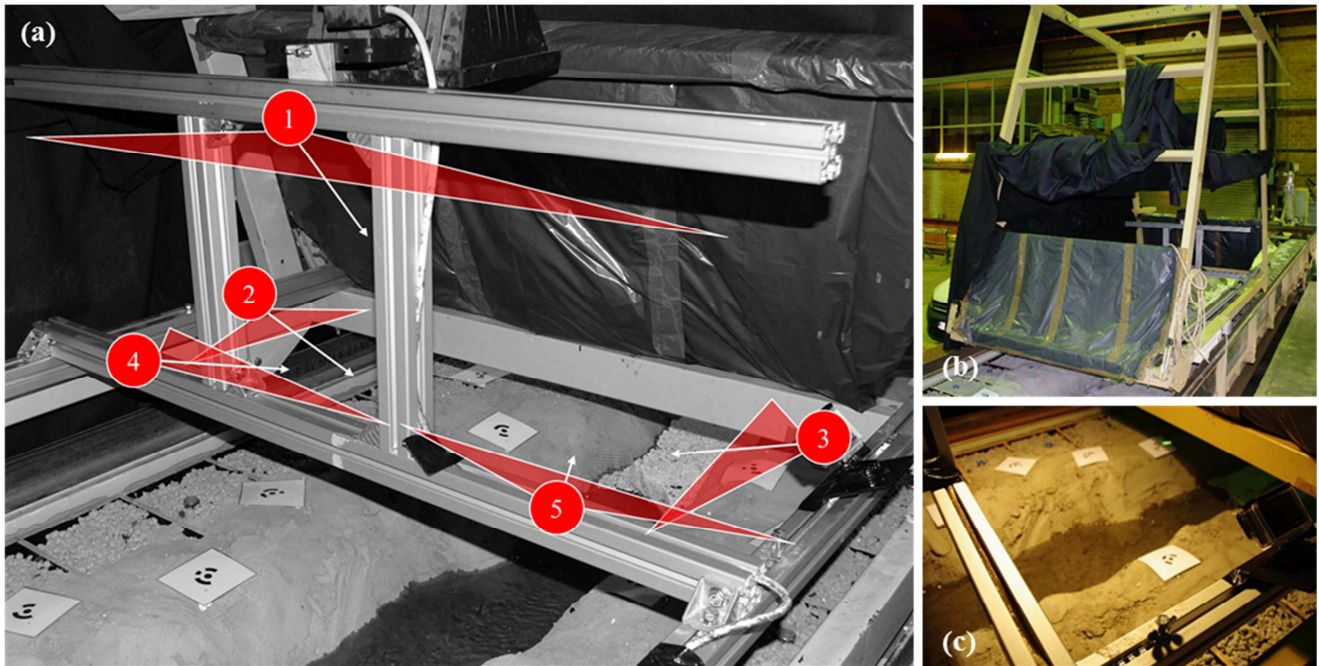


Figure 4: (a) camera positioning and orientation (5 different) on the travelling structure (b) travelling structure above the channel (c) view of the captured zone by the GoPro fixed in position 3

2.3.2 Software

The software used to perform the image treatment described in section 2.2 is the commercial package *Photoscan* by Agisoft, which is dedicated to SfM analysis. The accuracy and reliability of the results obtained with this software were demonstrated in numerous previous researches, e.g. Verhoeven (2011), Sansise *et al.* (2014). The several steps of the procedure, i.e. orthorectification of the images, feature points identification, construction of the sparse point cloud, identification of the RP, construction of the dense point cloud and extraction of topographical information, can be run manually by the user or automated by a script (Python in our case). As already mentioned, *Photoscan* also proposes a fisheye camera model allowing the use of wide-angle lens camera, such as the GoPro.

After obtaining the dense point cloud or the digital elevation model created with *Photoscan*, Matlab software is used to analyze the data, and especially to extract cross-sections and the corresponding water level and to compare these measurements with point method measurements obtained by means of ultrasonic probes.

2.3.3 Application to the experimental set-up

First, the bathymetry is measured. The scaled-model is thus imaged without water. The GoPro is fixed successively at five distinct positions above the model (Figure 4) to obtain different viewpoints. For each camera position, the travelling structure is moved along the channel at the speed of 0.1 m per second, and pictures are taken at a rate of 1 Hz. A single picture captures an area that is 0.75 m long and 1.2 m wide, yielding for a single travelling an overlapping between two successive pictures of more than 85%. The process is repeated for each camera position and a first set of images is obtained (dry set) consisting of about several hundred images.

The experiment is then run in steady flow conditions with two constant discharges ($Q_1 = 2.1$ l/s and $Q_2 = 3$ l/s). For each discharge, the same sequence of steps is repeated. The key difficulty with flowing water is the transparency of the water. In previous experiments by Franzini *et al.* (2016), the water was colored with blue dye in order to be identified on the images. However, it was observed that in shallow areas, the channel bed could still be seen through the water surface, resulting in measurement errors. So, here, in order to

materialize the free-surface, foam-ball tracers with a diameter of about 2 mm are disposed all over the free surface (Figure 2c). The two corresponding data sets are denoted Q_1 -set and Q_2 -set.

Each set of images (dry, Q_1 and Q_2) is analyzed using *Photoscan* following the different steps (1) image adaptation (orthorectification) (2) bundle adjustment, (3) generation of the sparse point cloud, (4) introduction of the reference points, (5) generation of the dense point cloud, and (6) creation of the DEM and orthophotos. Then, the DEM is analyzed using *Matlab* to extract two cross-sections (CS1 and CS2) along the river for each set of images, located in the upstream part of the channel as indicated in Figure 5.

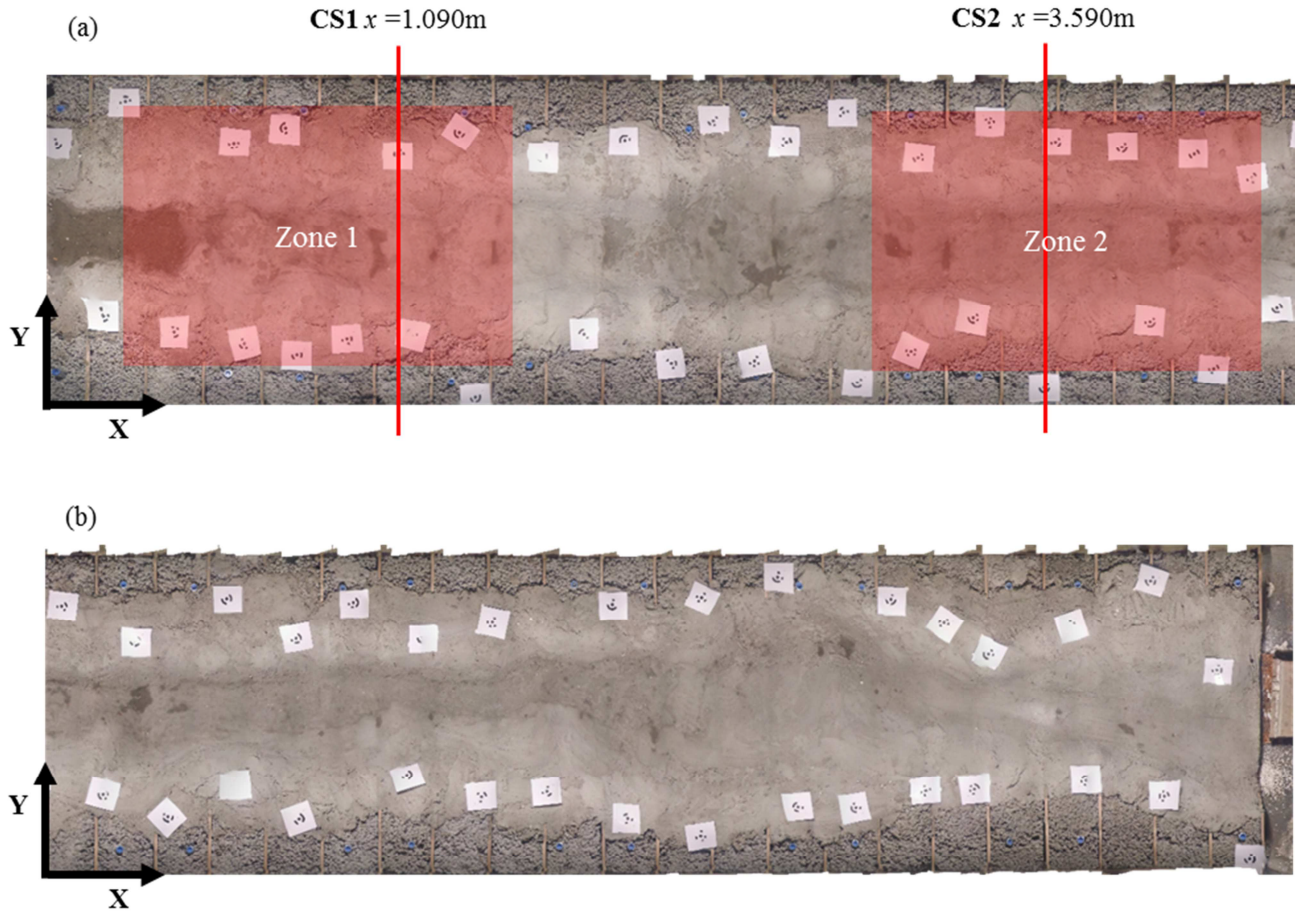


Figure 5: (a) plan view of the upstream part of the channel and identification of the two SfM studied zones and the cross-sections (CS1 and CS2) surveyed with Point Measurement method to compare the results (b) plan view of the downstream part of the channel

3. RESULTS AND DISCUSSION

The results are presented for two zones along the channel: Zone 1 for $x = [0.4 \text{ m}; 1.2 \text{ m}]$; Zone 2 for $x = [3 \text{ m}; 3.9 \text{ m}]$ as illustrated in Figure 6. The bathymetry and water levels at the two monitored cross-sections (CS1 at $x = 1.09 \text{ m}$ and CS2 at $x = 3.59 \text{ m}$) are compared to measurements achieved using point methods to assess the accuracy of the photogrammetry (Figure 7).

In Figure 6, we exposed the results under DEM form, in three columns: first, you observe the precise bathymetry, secondly, you observe the water level captured by SfM, and finally, you see the water depth given by the subtraction of the two previous DEM. These results are exposed for Q_1 and Q_2 on the two zones studied.

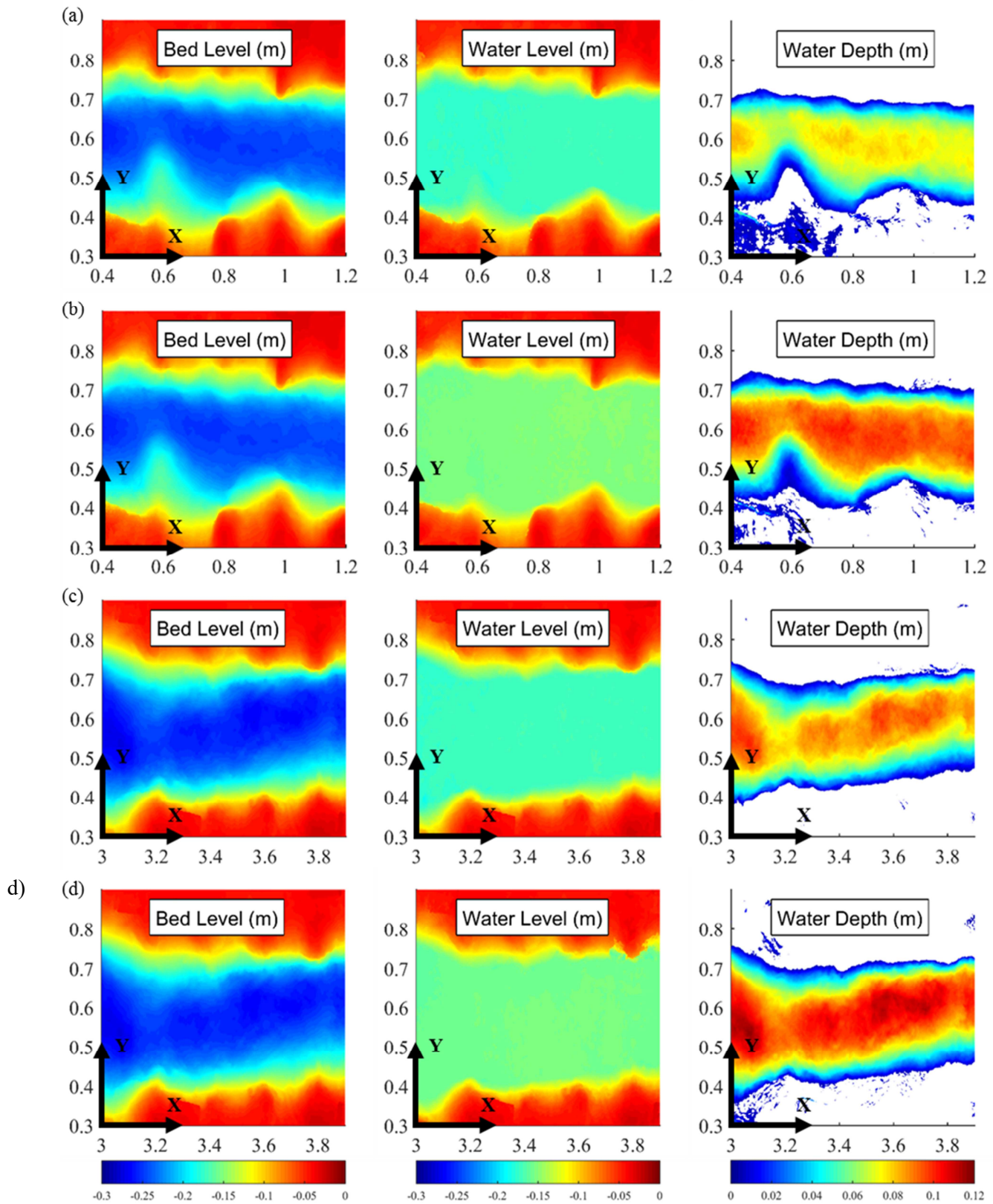


Figure 6: DEM views of the two studied zones. From left to right, bathymetry, water level, water depth: (a) $Q = 2.0$ l/s, zone 1 (b) $Q = 3.1$ l/s, zone 1 (c) $Q = 2.0$ l/s, zone 2 (d) $Q = 3.1$ l/s, zone 2

In order to assess the accuracy of the water level and water-depth measurements achieved using this technique, point gauges were used to survey the bathymetry and the free surface along the two cross-sections indicated in Figure 5. The comparisons are shown in Figure 7, where the continuous lines correspond to the SfM measurements and the circles to the point measurements. Both measurements appear to be in real good agreement, which is encouraging and shows that the SfM could be further developed as an interesting alternative to measure water levels in experimental conditions.

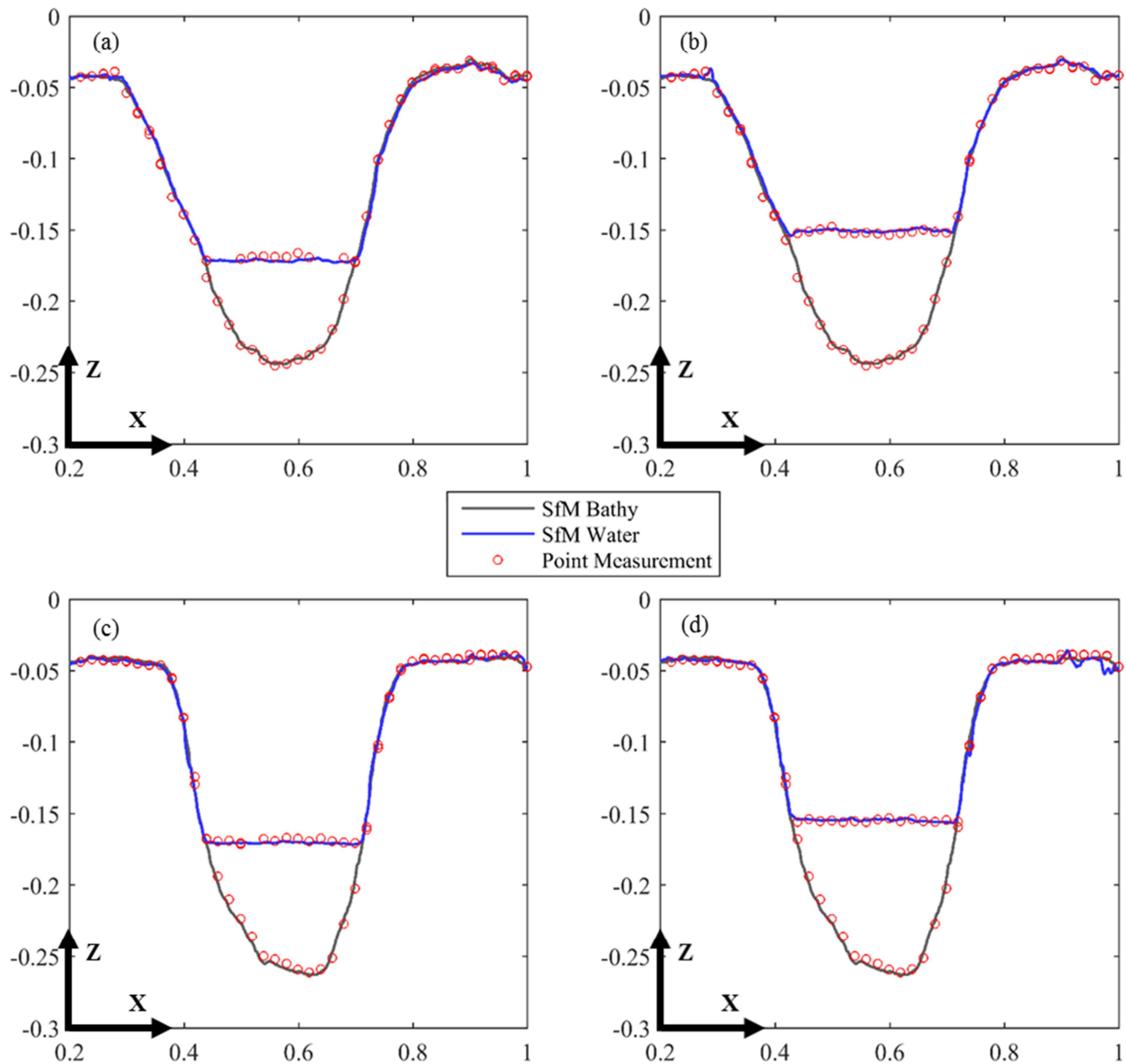


Figure 7: Comparison of the results obtained by point measurement method and Structure from Motion (SfM) Method, both for the bathymetry and water surface for the two considered cross-sections CS1 and CS2: (a) CS1, $Q = 2.0$ l/s (a) CS1, $Q = 3.1$ l/s (c) CS2, $Q = 2.0$ l/s (d) CS2, $Q = 3.1$ l/s

4. PERSPECTIVES

The advantages of the Structure from Motion method in different applications, and particularly in geosciences research domain, have been assessed in numerous researches. The objective of the present work

was to demonstrate that it could be a valuable alternative for measuring the flow free-surface in laboratory conditions using only low-cost equipment.

The reliability of the method has been shown in steady flow conditions on a complex bathymetry through the materialization of the free surface by floating elements. However, in order to extend the method to unsteady flow conditions, some challenges still have to be faced.

In order to enable the capture of the free-surface by SfM method, this free-surface cannot be transparent. Here, white foam ball are used to cover the area, which allows materializing it. However, this raises several questions: do these floating disturb the flow? How can the size of these elements be taken in account? If they move between successive photos, how does the SfM interpret the modification of their position? Future work will focus on addressing these issues by e.g. use dark colored dye in the water to render it opaque, or applying a covering oil-type film above the free surface in order to improve the accuracy of the surface capture.

Then, the application to unsteady flow conditions will have to be addressed. To this end, a combination of several synchronized cameras could provide a sufficient overlapping of the images at a given instant, yielding a sufficient range of images to run the SfM method successively for several times of a transient flow in the channel.

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