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Before the dam breaks: Analysis of the flow behind a downward moving gate

R. Aleixo
GHT Photonics, Padova, Italy

S. Soares-Frazão & Y. Zech
Institute of Mechanics Materials and Civil Engineering, Université Catholique de Louvain, Louvain-la-Neuve, Belgium

ABSTRACT: Laboratory-scale dam-break flows are often modeled by a moving gate that will release almost instantaneously a large body of water. Two main strategies are often considered to model these flows: a downward moving gate or an upward moving gate. In this paper the motion of a downward moving gate is investigated and, by means of PIV analysis, its effect on the water column is studied. A characterization of the flow just before the dam-break flow starts is presented. This analysis is important to understand the initial stages of the dam-break flow.

1 INTRODUCTION

The importance of dam-break flow studies is obvious when one considers how devastating these flows can be. The events of November 5th in Minas Gerais, Brazil, have again shown how terrible such disasters can be (BBC, 2015). Other examples have been reported in the past (ICOLD, 1995) which demonstrate the need for a detailed understanding of such flows. Since the pioneer work of Ritter (1892) much was learnt from experimental and numerical models. Experimental modelling of dam-break-flows is still a valuable tool since it provides a detailed insight on the flow physics as well as data for numerical model calibration and validation. Experimental modelling of dam-break flows usually involves a sudden re-lease of a significant amount of water in a short time interval. This is achieved in the laboratory by means of a moving gate that separates a reservoir from the rest of the channel, as depicted in Figure 1. Two main strategies are often used: an upward moving gate and a downward moving gate. Different authors have been using these two strategies. Upward moving gates were used e.g. by Dressler (1952), Lauber & Hager (1997), and Leal et al. (2009) for example, whereas downward moving gates have been used e.g. by Spinewine & Zech (2007), Aleixo et al. (2011), to mention a few. Despite its importance for the experimental dam-break flow modelling, not many studies exist regarding the gate effect on the flow since dam-break flow analysis are usually concerned with the flow after the sudden water release.

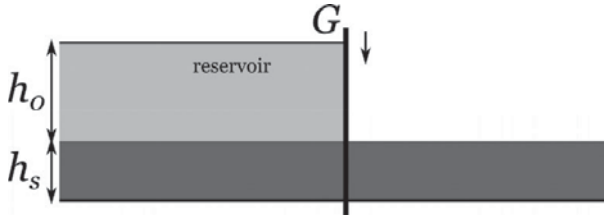

Figure 1. Dam-break flow modeled with a downward moving gate (G); h_0 refers to the initial water height and h_s refers to the initial sediment height.

In this paper however the focus will be placed on the flow taking place immediately before a downward moving gate (Fig. 1) is completely opened.

1.1 *Downward vs. upward strategies*

To experimentally study the dam-break flow a sudden release of water is simulated by means of a moving gate. To remove this gate different methods and strategies exist. The two most used strategies are upward and downward moving gates, respectively. These two strategies have advantages and disadvantages that are here discussed. An upward moving gate is usually easier to implement, and it does not affect the channel bed, however is not necessarily phenomenologically correct, whereas a downward moving gate, despite phenomenologically correct implies a discontinuity in the channel structure and a corresponding leakage problems. The major advantage of the downward moving gate comes when dealing with sediment beds. The downward moving gate, contrarily to the upward moving gate, will not artificially entrain sediments into the stream. This is a major virtue of the downward moving strategy together with the fact that it is possible to consider more realistic gate opening models to create a breaking wave for example.

1.2 *Gate removal time*

One of the hypotheses in Ritter's (1892) seminal paper was to consider an instantaneous dam-break removal. This case corresponds to the most severe occurrence of a dam-break. Experimentally there are limitations to an instantaneous gate removal. It is possible, under certain conditions, to consider the gate removal as instantaneous. Lauber & Hager (1991) have proposed a time removal criterion for which the gate removal can be considered instantaneous. Later, Aleixo et al. (2013) have proposed a criterion based on the water surface deformation for the particular case of the downward moving gate case. They found that the downward moving case criterion was more stringent than the upward case.

2 FLOW ANALYSIS

2.1 *The initial stages of the dam-break flow*

The flow immediately behind the moving gate is closely related with the initial stages of the dam-break flow. Not many studies exist regarding the initial stages of the dam-break flow. Pohle (1952) was probably the first to analyze this flow. Estrade (1967) made some experimental contributions. Stansby et al. (1998) presented a numerical model together with some experimental results for the initial stages of the dam-break. Oertel & Bung (2012) presented a numerical and experimental study of the initial stages. Aleixo (2013) studied the initial stages of a dam-break flow over different types of beds fixed and mobile. However, these works were devoted to the flow immediately after the dam-break, whereas in this paper the focus is placed on the flow immediately before the dam-break.

2.2 *Qualitative analysis of the flow*

The flow in analysis is complex; depending on the conditions, namely gate removal time, it may look like a water-column collapse if the gate removal time is small, or it may look like a spillway flow if the removal time is large. The following steps are a qualitative description of the observed: first, with the gate moving the water column side will be exposed to the atmosphere; second, as the gate is removed the water column will lose the supporting

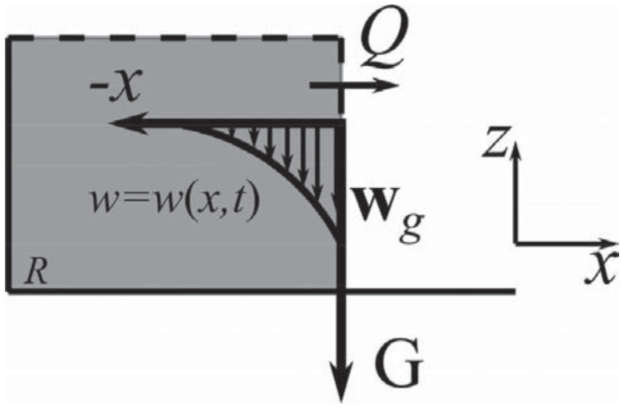

Figure 2. The different factors playing during the gate, G, removal with a velocity $\mathbf{w}_g$. In the reservoir R, the gate removal will induce the vertical water motion. As the gate is removed the water will eventually flow with a flow rate Q over the moving gate. The dashed line represents the free surface.

wall and will tend to collapse, or to spill over the gate. Third, the gate velocity is not uniform, and usually has an accelerated motion; together with the no slip condition, a transient boundary layer will appear. These factors are exemplified in Figure 2, where over a gate moving with a velocity $\mathbf{w}_g$ will expose part of the water in the reservoir R to the atmosphere. Over this gate, and depending on its velocity, a flow Q can be observed.

3 EXPERIMENTAL SETUP

3.1 *The channel*

The experiments were performed in the dam-break channel of the Institute of Mechanics Materials and Civil Engineering of the Université catholique de Louvain, Louvain-la-Neuve, Belgium. This channel is $L = 6$ m long, 0.25 m wide and 0.50 m height. It is divided in two equal reaches of 3 m by a downward moving gate. The channel has glass windows to allow for optical access to the flow. A complete description of this channel can be found in Bailly. & Van Reybroeck (2003) and Spinewine & Zech (2007).

The channel is then filled with an initial sediment level $h_s = 0.10$ m, and the initial water depth above the sediment layer in the upstream reservoir is set at $h_0 = 0.325$ m (Fig. 1). The sediments used in this experiment are PVC pellets of approximately cylindrical shape. Their physical properties are the following: $d_{50} = 3.3$ mm, $\rho_s = 1.1 \times 10^3$ kgm^3.

The water in the reservoir was seeded with pliolite particles to allow the determination of the flow velocity by means of imaging techniques.

Measurements of the gate removal time with and without sediments showed that there was no significant difference, the measured removal time were 0.06 s and 0.075 s respectively.

3.2 *The downward moving gate*

In the channel of Figure 1, the upstream reservoir is divided from the test-section by means of a downward moving gate. This gate is an aluminum plate with 5 mm thickness. This gate is attached to a pneumatic piston that pulls it downward by means of an external electrical command.

With this system it is possible to have very short removal times. For the present case, the gate position was measured using a fast speed camera and the gate position as function of time is depicted in Figure 3. In this case the determined removal time was $t_r = 0.075$ s. In this paper, $t = 0$ s is considered as the time for which the gate is fully removed.

It is important to mention that the gate top is initially about 7.5 cm above the water level.

A second order polynomial was fit to the data and the trajectory equation $z = z(\mathrm{t})$ is given by:

$$z(t) = -19.28t^2 - 5.87t - 0.0029 \qquad (1)$$

where z = gate trajectory and t = time.

From eq. (1) it is easy to obtain the instantaneous velocity by means of its derivative, therefore:

$$w_g = -38.56t - 5.87 \qquad (2)$$

where w_g = gate velocity and t = time. This equation is depicted in Figure 4.

3.3 *Instrumentation*

The flow images were acquired by means of a Photron fast camera. This camera allowed for acquisition frequencies up to 1 kHz in full resolution of 1 MPixel. For the present case, the image resolution was set at 768 × 1024 pixels and the acquisition frequency was set at 1 kHz.

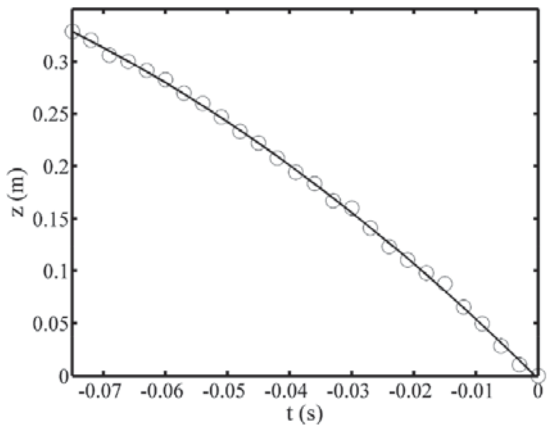

Figure 3. Gate removal trajectory measured with the fast acquisition camera. A 2nd order polynomial was fit to the data.

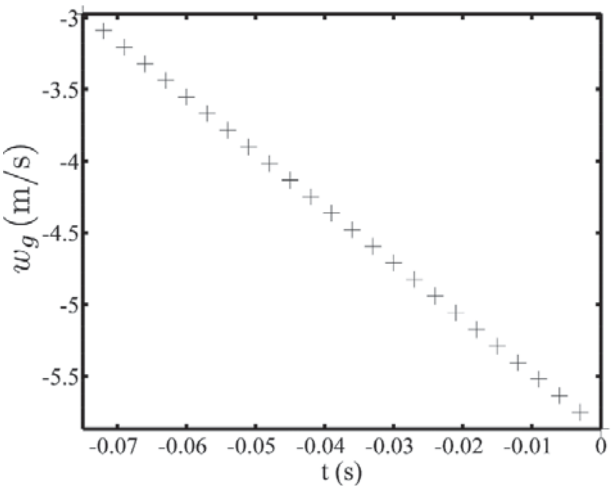

Figure 4. Gate instantaneous velocity, w_g obtained from the experimental data.

To light the flow a diode laser light sheet was used. The power output was 40 mW and its wavelength was 865 nm. This lower power prevented measurements in the middle section of the channel, therefore the measurements were made at a distance of 2.5 cm of the channel side window.

3.4 *Particle Image Velocimetry*

Particle Image Velocimetry (PIV) is a quantitative measurement technique used to extract the velocity field from images taken of a flow that was previously seeded with small tracers. This technique is based on image cross-correlation and it is nowadays an established and mature technique. Major milestones of this technique are the papers by Meynart (1982, 1983), Keane & Adrien (1992) introduced the concept of image cross-correlation and later Scarano & Riethmuller (2002) proposed the interrogation window deformation method to better solve the flow gradients. A general overview on this technique can be found in Raffel et al. (2007).

The cross-correlation principle on which PIV is based is illustrated in Figure 5. Two consecutive flow images are divided in smaller images, referred as interrogations windows and then, these interrogation windows are cross-correlated consecutively. The result of this operation is a function, whose peak is a measure of the most probable displacement of the ensemble of tracers inside the correlation window (Fig. 6). Since the time interval between two images is known the velocity

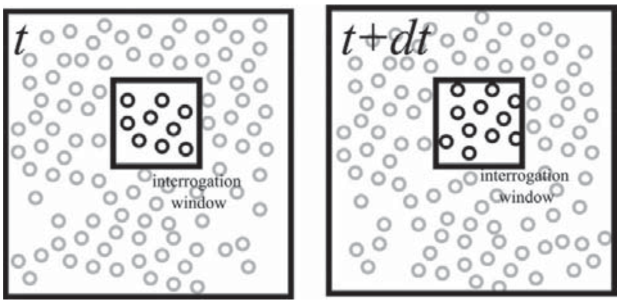

Figure 5. Illustrating the image division into interrogation windows to perform the cross-correlation.

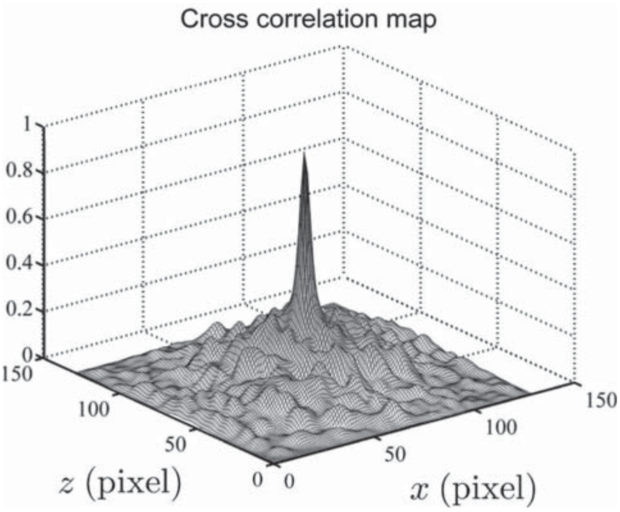

Figure 6. Example of the cross-correlation peak obtained from PIV images. The peak location is a measure of the most probable displacement of particles inside the interrogation window.

associated with each interrogation window can be calculated as:

$$\mathbf{v}_i = \frac{d\mathbf{x}_i}{dt} \tag{3}$$

where $\mathbf{x}_i$ = is the displacement vector associated to the interrogation window i and $\mathbf{v}_i$ = velocity vector.

4 EXPERIMENTAL RESULTS

4.1 *Flow images*

The flow images depicted on Figure 7 show some frames of the flow raw images. It is possible to observe the gate motion by the deformation of the free surface. To improve contrast a step of image pre-processing was added prior to the PIV processing. It is also possible to see the light reflected by the seeded pliolite.

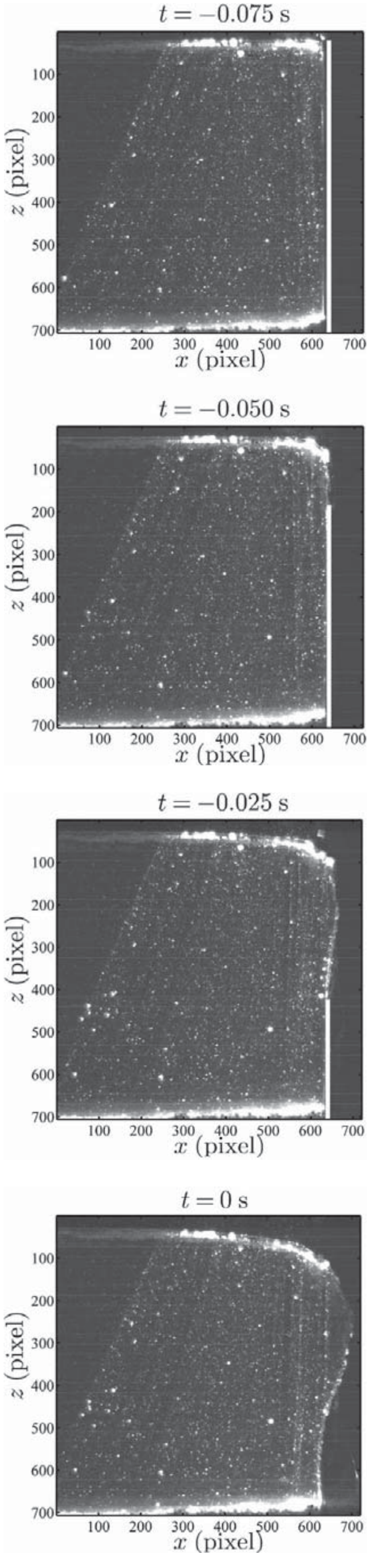

Figure 7. Flow images depicting the gate removal and the flow evolution, vertical white line represents the gate. The bed level is at z = 700 pixels.

4.2 *Velocity field*

For PIV processing an iterative window approach was followed. The initial interrogation window size was 256 × 256 pixels and the final window was 64 × 64 pixels. An overlap between interrogations windows of 50% was also considered. With these settings the obtained spatial resolution was of 0.016 m.

With an acquisition frequency of 1 kHz, 75 images of the flow were acquired before the gate complete removal. To filter the noise an ensemble average strategy was adopted. The ensemble average was made considering a set of five images, $\Delta t = 0.005$ s, whose center is the time under analysis. For example, $t = -0.055$ s corresponds to an ensemble average between: $t = -0.057$ s and $t = -0.053$ s. The obtained velocity fields are depicted in Figure 8. It is possible to see that the water flow, due to the downward gate motion, does not start at $z = 0$ but around $z = 0.25$ m.

To complement this information different velocity profiles were drawn at different sections.

To scale the velocity profiles the following variables were used. The velocity scale chosen was the wave celerity given by:

$$c_0 = \sqrt{gh_0} \tag{4}$$

where c_0 = is the wave celerity; g = gravity acceleration; and h_0 = initial water level in the reservoir. The horizontal coordinate, x, was scaled with the channel length, L, and the vertical coordinate was scaled using the initial water height, h_0.

At the vertical section defined by $x/L = -0.0158$ the velocity profiles for both u and w were plotted in Figures 9 and 10. With increasing time it is possible to observe the increase of the velocity. The maximum occurs at $t = -0.015$ s for $z/h_0 \approx 0.6$. In the vertical component profile it is possible to see how its sign changes with time as it was seen in Figure 8 for $t = -0.055$ s and $t = -0.025$ s.

At $z/h_0 = 0.88$ m, the profiles of u and w at different instants are plotted in Figures 11 and 12. As it can be seen, both components increase (in absolute value) with time. At the aforementioned section the horizontal component u reaches values up to $0.05c_0$, whereas the vertical component reaches values of about $-0.2c_0$ for $t = -0.002$ s.

For the same time $t = -0.025$ s, it is possible to plot different horizontal profiles as shown in Figures 13 and 14. At this time the gate position is located at $z/h_0 = 0.11$. It is possible to see that the velocity components u is dominant for $z/h_0 > 0.5$, because as stated before, the flow starts before the complete removal of the gate. The vertical component profiles show that in the upper layers w is negative, whereas for the lower layers w is positive. For this time instant this is related with the fact

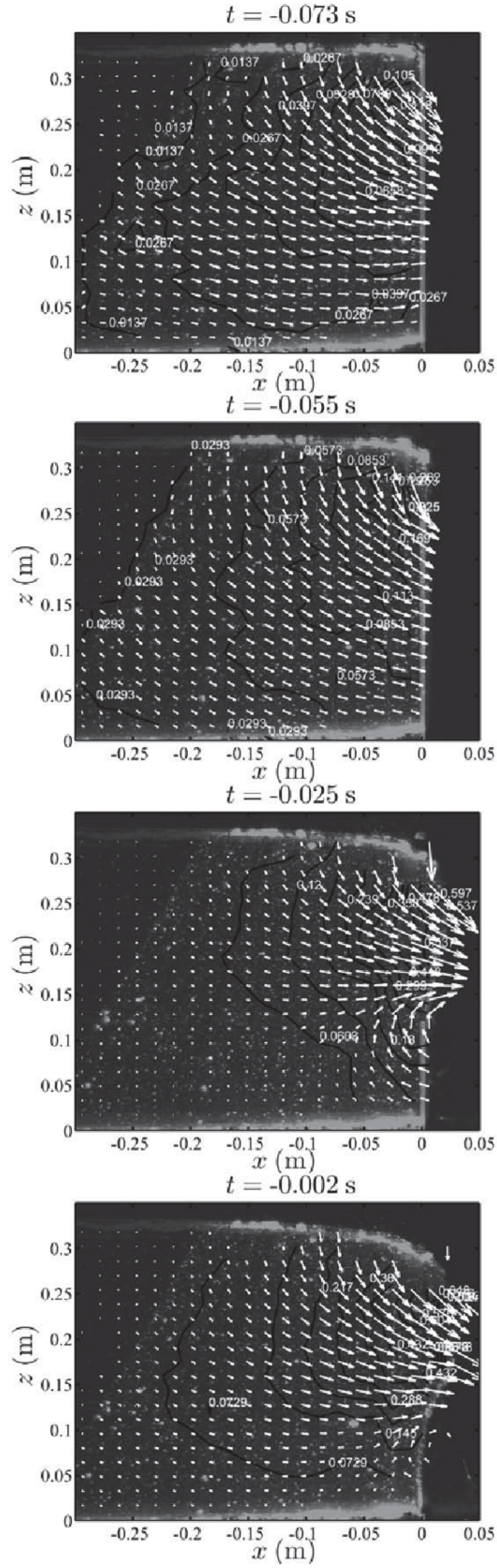

Figure 8. Velocity fields in ms^{-1} at different times before the gate is completely open. Bed level is at $z = 0$ m.

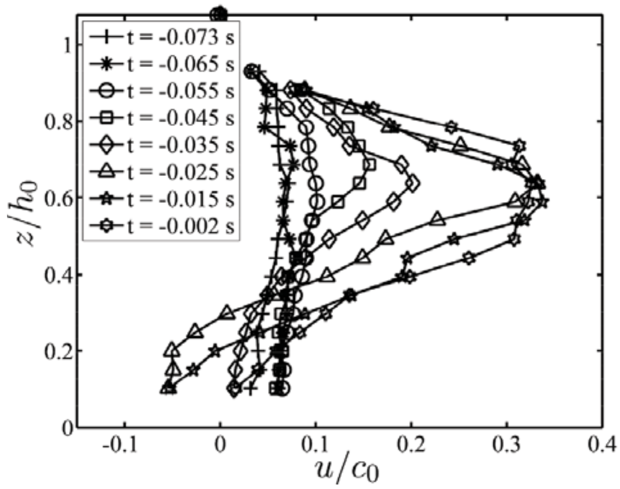

Figure 9. Horizontal component u profiles at $x/L = -0.0158$ m for different times.

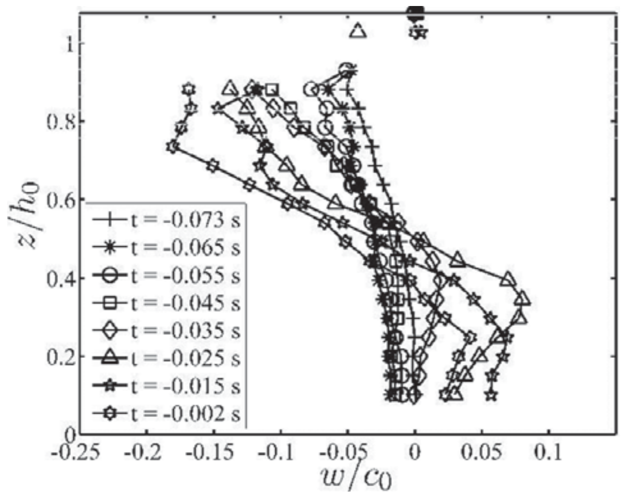

Figure 10. Vertical component w profiles at at $x/L = -0.0158$ m for different times.

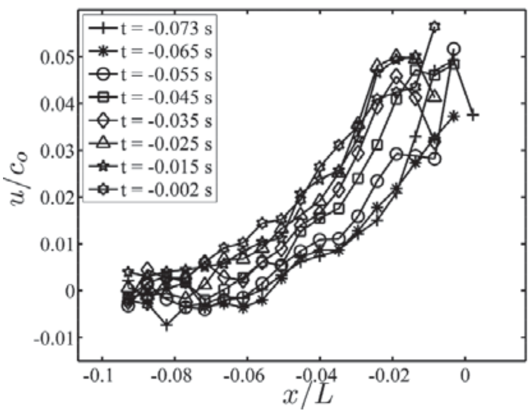

Figure 11. Horizontal component u profiles at $z/h_0 = 0.88$ for different times.

that water starts to flow in the region $z/h_0 > 0.5$ as seen in Figure 8 for $t > -0.055$ s.

It should be remarked that resolution is not fine enough to capture zero relative velocity at

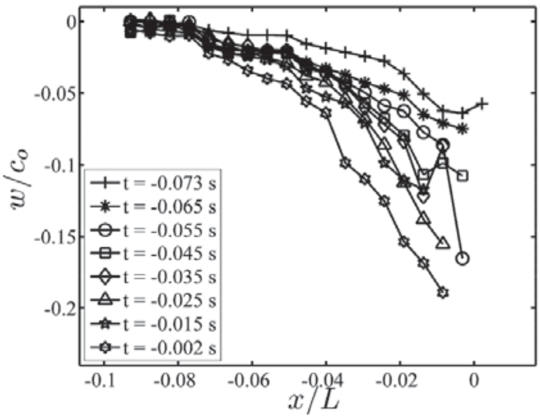

Figure 12. Vertical component w profiles at $z/h_0 = 0.88$ for different times.

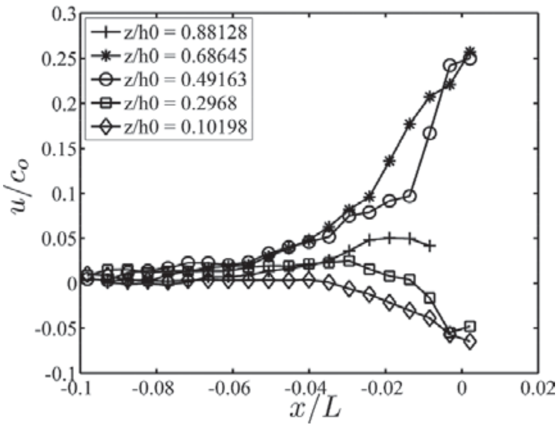

Figure 13. Horizontal component u profiles measured at different horizontal sections for $t = -0.025$ s.

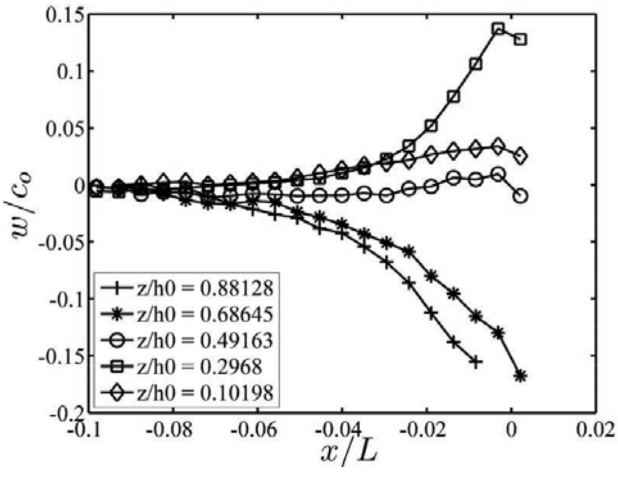

Figure 14. Vertical component u profiles measured at different horizontal sections for $t = -0.025$ s.

the moving wall. Two main reasons have contributed for that: i) the spatial resolution was set at 64 × 64 pixels, or about 1.6 cm; ii) in the PIV algorithm used it is not possible to impose the interrogation windows coinciding with the moving wall, thus not being possible to ensure the correct description of the region. This can be achieved with a new set of experiments using a higher spatial resolution near the moving gate.

5 CONCLUSIONS

A set of experiments regarding the effect of a downward moving gate in the water column flow was presented. The flow was analyzed using images techniques and the following conclusions were derived from the results analysis.

The gate removal motion is a uniformly accelerated, and the gate is fully removed after 0.075 s. Despite this small interval it was possible to observe that the flow started before the complete opening of the gate. This observation was made possible by the use of a fast acquisition camera and PIV.

From the flow patterns and velocity profiles it was possible to conclude that the maximum horizontal velocity at $x/L = 0.0158$ was measured at $z/h_0 \approx 0.6$ for $t = -0.015$ s. For the same section it was possible to observe how the vertical component changes its sign with time. This is probably induced by the flow that starts in the upper layers ($z/h_0 \approx 0.6$).

A major limitation of the methodology put forward was also identified: the measurements have shown that the spatial resolution was not enough to determine the water velocity near the gate directly from the PIV measurements. This can be explained by the need for a higher spatial resolution near the moving gate, furthermore it is not possible to set the origin of the interrogation windows in the PIV software package used to allow for a better description near the moving gate.

This work consists in a first step of analyzing the flow behind a moving gate leading to a dam-break flow. The analysis here put forward can be extended to the upward moving gate strategy for comparison of the flow features. Moreover the experimental results here obtained form a valuable database to be used for numerical model validation.

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