Experimental investigation and numerical evaluation of the free surface of a dam break wave in the presence of an obstacle

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Abstract: Tsunamis, impulse waves, and Dam-Break waves have a high impact on the nearby areas. Scaled experiments allow to deeply understand hydrodynamic features of these unsteady flows and, on the other hand, to validate numerical models. The study shows the experimental set-up and the preliminary results of the tests performed at the Hydraulic Engineering Laboratory of the University of Naples "Federico II". We set a 3 m long Perspex tank in order to generate Dam Break waves by a pneumatic gate removal. Two high-speed CCD (Charge-Coupled Device) cameras are used to characterize the wavefront celerity and the free surface profile. Five pressure transducers are installed on a vertical wall, located at the end of the channel, in order to sample the force extent of the surge. The results of the numerical simulations realized with a depth-integrated model are compared with experimental data.

Keywords: dam break; experiments; image processing; depth-integrated model.

1. Introduction

Dam-Break waves cause huge damages, human fatalities, high economic losses, and ecological and environmental issues to the surrounded landscape [1]. Dam-Break could be modelled as waves that are generated by a sudden release of water, stored behind a wall, downstream. The resulting wave is defined as surge, if it flows on a dry bed, or bore, if it propagates on a wet bed. Tsunamis, tidal bores, and the collapse of artificial embarkment can generate similarly unsteady flows and drastic consequences [2]. Chanson stated that the behavior of a dam break wave is very similar to a tsunami surge that propagates on a dry coastal plain. In fact, in both cases, the surge front is a shock characterized by a sudden discontinuity and extremely rapid variation of flow depth and velocity [3]. Only a few studies showed in-field measurement, and often the available data are ex-post forensic engineering reconstructions of the event. Real field manifestations are, indeed, rare and it is very difficult to collect data and visual observations during their occurrence [2]. Moreover, some regions of the world have not yet experimented by tsunamis or dam-break waves in recent times, there are no field observations based on which policymakers can develop safety procedures to protect residences [4].

Scaled laboratory experiments of dam-break waves have a crucial role in understanding the hydrodynamic evolution and in validating numerical models. Chanson observed in 2009 that the numerical models implemented were validated by a limited data set [1]. In the last two decades, several experimental studies have been implemented to deeply investigate the flow characteristics [5], [6], [2]. Nevertheless, even more studies are investigating the interaction between water waves and structures in order to highlight the hydrodynamic behavior and the extent of the forces on the obstacles [7], [8],[9], [10], [11]. In addition, [12], [13], [8], [14], [15] among others, investigate the behavior of a dam-break flow over an erodible bed. Furthermore, Armanini has conducted several experiments to show the hydrodynamic of a debris flow generated by a dam-break event against a structure. Similar experiments have been implemented by [16-18] too.

The present study shows the preliminary results of an experimental investigation of a new laboratory channel at the Hydraulic Engineering Laboratory of the University of Naples Federico II. Secondly preliminary results of a dam-break wave against a vertical wall are presented, thirdly a comparison with a shallow water numerical model is discussed.

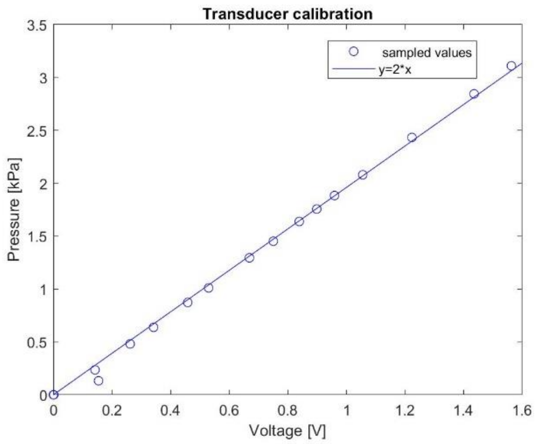
2. Materials and Methods

The channel, realized in Perspex, is a 3.0 m long, 0.4 m wide and 0.5 m high, it is divided into two parts by a movable lift gate. The lift gate can be translated up to 0.5 m from the upstream wall in order to change the volume of the reservoir and the downstream length. In these set of experiment, it is placed at the middle. Behind the gate the water is stored, the hydraulic seal is obtained by means of a rubber gasket and a thin strips of a watertight putty all around the gate. The dam break wave is generated by a sudden opening of the gate thanks to a pneumatic system. The pneumatic system is activated by an air compressor Fini set at 7 bar of pressure in order to allow an abrupt gate removal, i.e 1.35 m/s.

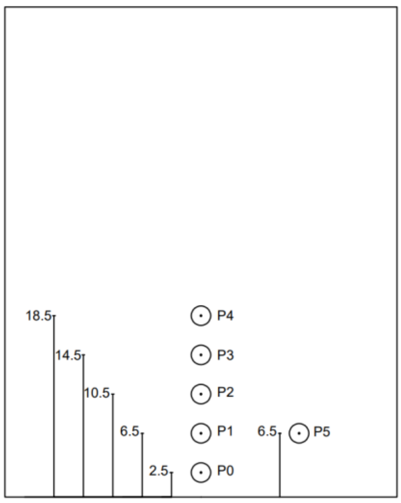
Behind the gate a hydrometric rod is located, in order to sample the depth of the water stored there.

Two high-speed CCD cameras are used to obtain the wavefront celerity and the free surface profile from image analysis. The cameras are two Iron 250 Kaya Instruments; the key features are: 5 MegaPixel of resolution and up to 164 frames per second. The data is acquired by means of two Predator II Frame Grabber. The Grabber receives video streams on the CoaXPress link and transmits it to computer memory through the PCIe interface. This product also provides GPIO for machine control signals such as triggers, shaft encoders, exposure control and general I/O, which can be controlled aside the video stream acquisition. A commercial software, StreamPix, is used to control and synchronize the CCD cameras.

At the end of the channel, it is placed a vertical gate with six pressure transducer Gefran TSA. They have a sampling range from 0.0 to 0.1 bar with an accuracy of the 0.15% on the full-scale output and the maximum acquisition's frequency is 2000 Hz. They are alimented by 10V and communicate with the PC by Labjack. The transducers are managed by means of the open-source software MAtlab. Thanks to MAtlab we can set the same acquisition frequency of the camera. Moreover, MAtlab has the same time as the computer as well as the cameras so that the two devices are synchronized. The calibration has been done with hydrostatic pressure and the calibration curve is shown in Figure 1 (a).The placement of the transducers, reported in Figure 1 (b), is set in order to obtain as many as possible local measurement of the pressure on the same axis, yet at the same time, taking into account the physical size of the single transducer. Transducers P_1 and P_5 are located at the same depth in order to verify the one-dimensionality of the motion (Figure 2). As Figure 2 shows, farther investigations are needed to understand the effect of the lateral walls to the fluid motion and to the pressure of the water on the downstream wall.



(**a**)



(**b**)

Figure 1. Calibration curve of a single transducer (**a**). Localization of the transducers on the downstream wall, the unit of measure is cm (**b**).

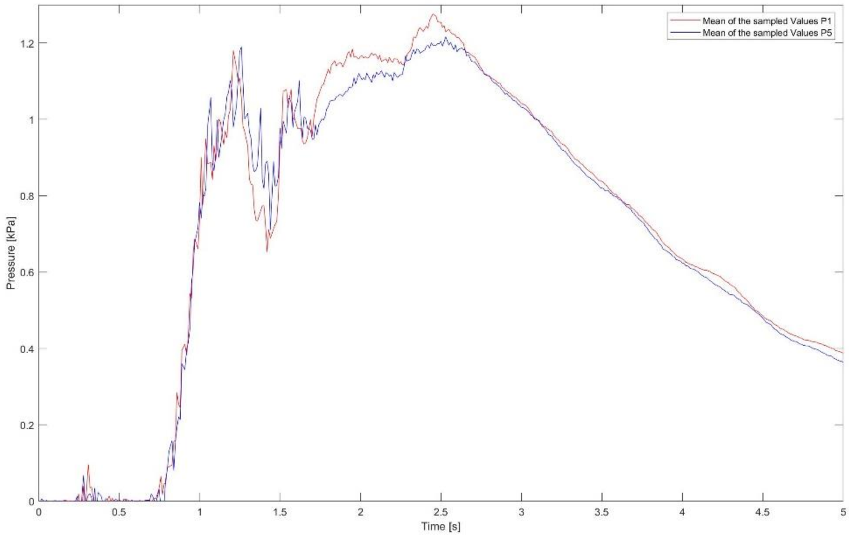


Figure 2. Comparison between the mean sampled values of the transducers P1 and P5.

The pressure transducers measure the local pressure, i.e. at the point in which they are installed. To obtain the instantaneous total force extent on the wall it is necessary to integrate along it the discrete measurements of the pressure.

3. Results

The Dam Break experiments has been carry out collecting the water surface profile and the force extents on the downstream vertical wall. The initial water depth behind the gate is 0.2 m. The velocity of the gate removal is compared with the characteristic time [5].

$$t_c = \sqrt{\frac{2h_0}{g}} \quad [\text{s}] \tag{1}$$

where h_0 is the initial water depth and g is the gravity acceleration. For 0.2 m of water, the removal time, i.e. the time that the gate doesn't touch the water anymore [5], is 0.120 s whereas the characteristic time is 0.201 s, for this reason for [5] the phenomenon can be said to be instantaneous since $t<t_c$. The lateral wall friction has been neglected due to the ratio between the wight of the channel and the water depth is at least 4 at the initial stage of the phenomenon. After the impact the water depth increase but the waterfront celerity is about 1 m/s, for this reason wall friction can be neglected also in this case. The bottom friction has been considered in the simulations of the numerical model.

In order to obtain the water surface profile, the two high-speed cameras are located alongside the channel at the same altitude. Two cameras are used to obtain a 1D record of the flow, in fact, one is located perpendicularly to the gate whereas the other is located perpendicularly to the final wall. The two images are then joined with MAtlab to have a complete view of the channel. They have been previously calibrated with a MAtlab toolbox, MAtlab stereo camera calibrator, in order to eliminate focal distortion.

No other sensors are needed to obtain the celerity of the propagated front and the water surface. In fact, with the image processing technique, it is possible, if the image is georeferenced, i.e. calculating the pixel-centimeters ratio of the images, to draw the water profile. Moreover, knowing the time gap between two consecutive frames, the front celerity can be obtained.

The impact force on the wall is calculated by integrating the pressure values sampled by the transducers. This can be obtained assuming that the phenomena is 1D, thus the values sampled by P_i transducer is extended to a fix influence area, and neglecting the values sampled by transducer P_5.

The same experiment has been repeated ten times in order to verify its reproducibility. Mean and root mean square values of the ten-time histories of the force have been calculated and plotted in the Figure 3.

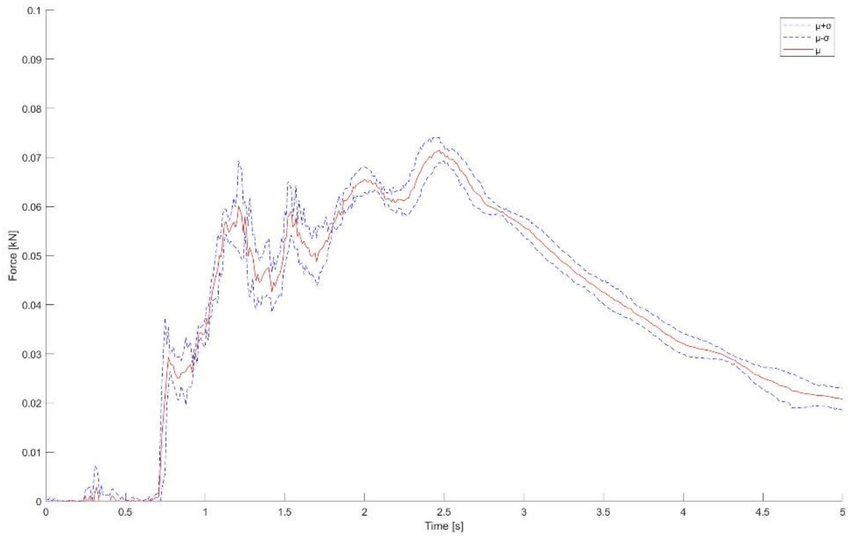


Figure 3. Time history of the force extents on the wall**,** μ is the arithmetic mean and σ is the RMS of the force extent on the wall for the set of ten experiments.

As can be seen in Figure 3 there is a good reproducibility of the experiments, with an error of 3.64% on the maximum values of the force.

4. Discussion

The experimental data are compared with the numerical results of a depth-integrated model [19]. The governing equations are numerically solved with a Finite Volume scheme which is second-order accurate in space and Total Variation Diminishing (TVD), and first-order accurate in time. The boundaries conditions imposed at both the upstream and downstream end of the channel are of solid wall type, which induces a complete wave reflection. This boundary condition at both upstream and downstream of the channel has been implemented through the ghost cells technique [20]. The roughness of the channel as the dimensionless Chezy coefficient for the steady flow is 22. The lateral wall friction has been neglected.

Figure 4 shows the time histories of the measured force extent on the wall. For the sake of the comparison the numerical predictions are also reported.

Figure 4 shows that the impact of the wave against the downstream wall occurs at $t_I \sim 0.7\ s$ and an abrupt increase of the force is detected. After the impact, the force continues to increase (in not a monotone way) reaching its maximum value (F_m= 0.072 kN) at $t_M \sim 2.5\ s$. For $t > t_M$ the force smoothly decreases and at $t \sim 7.5s$ a second abrupt increment of the force is detected. Such a force dynamic is essentially due to the formation of a bore at t_I caused by the wave impact. The bore starts to propagate in the upstream direction, impacts against the upstream wall and reverses its propagation direction. At $t \sim 7.5\ s$ the bore impact against the downstream wall occurs.

The results shown in Figure 4 suggest that the depth-integrated model is able to predict with a sufficient accuracy the experimental evidence. Indeed, the difference between the calculated and measured value of the maximum of the force is 3.37%.

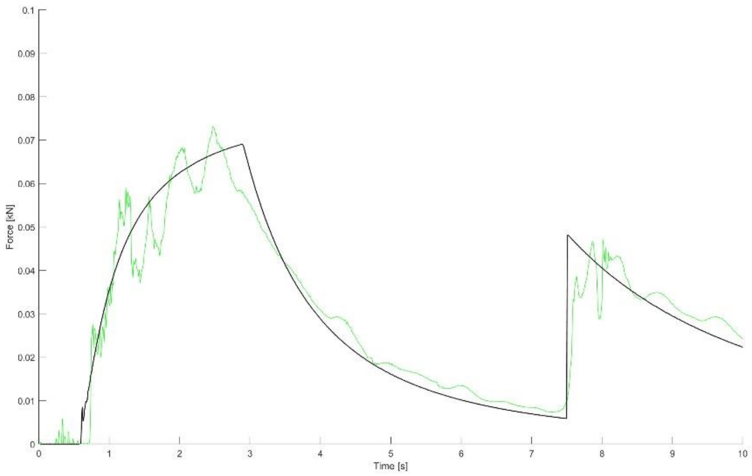


Figure 4. Time history of the force against the downstream wall. Numerical results: solid line. Experimental data: dashed lines.

Figures 5 shows the free surface at two instants, i.e. t= 0.54s (a), t= 1.38s (b), from the gate opening, along with the numerical predictions. Figure 5 suggests that the SW model is able to reproduce with sufficient accuracy even the local features of the process.

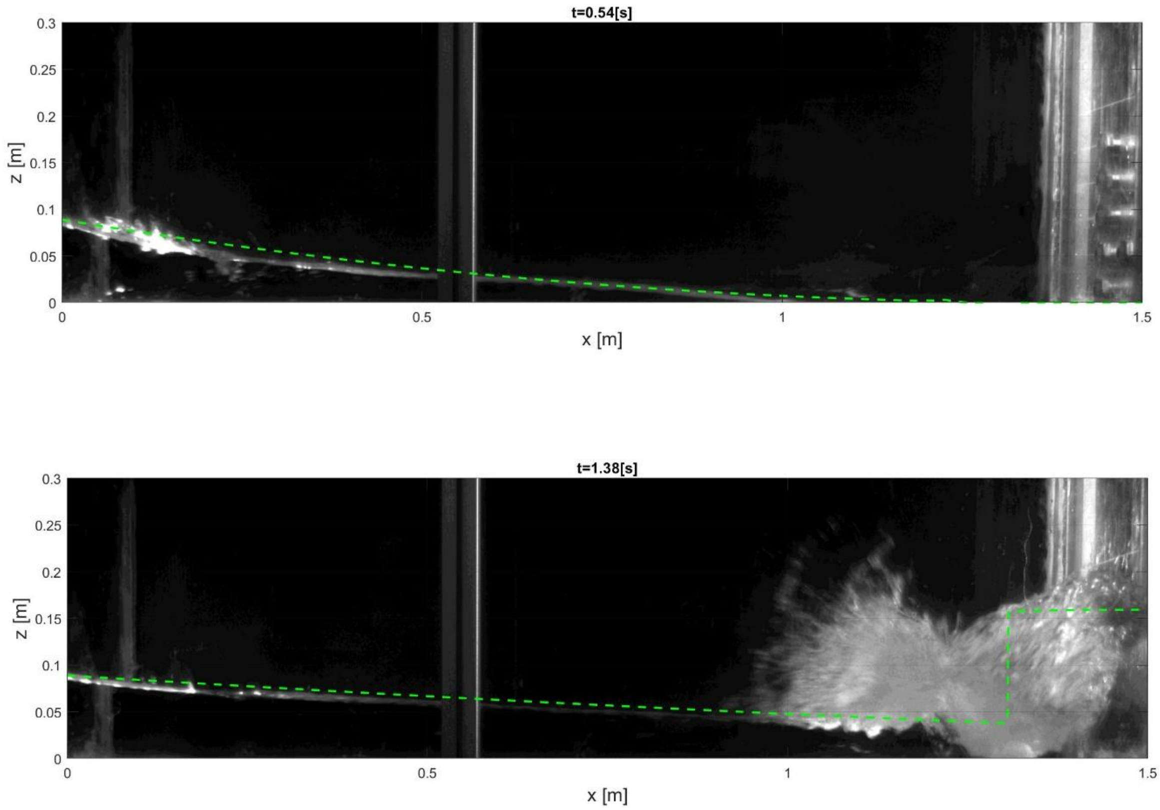


Figure 5. Free surface: (a) t= 0.54s, (b) t=1.38s. The green lines refer to numerical results.

5. Conclusion

Our experimental study aims at investigating Dam-Break flows and the interaction of the resulting unsteady flow with structures. For this purpose, five pressure transducers have been synchronized with two high speed cameras, and both water surface and forces on the wall have been measured. The preliminary results show a good repeatability of the experiments and a good agreement with the numerical model both in terms of forces and free surface, so for this reason, the hypothesis made on the wall friction are therefore significant. Indeed, an error at most of the 3.37 % is done on the maximum value of the experimental force.

Our preliminary results represent a fundamental starting point from which future studies about the interaction between dam-break flows and structures will be developed. Next studies will focus on the influence of a movable bed to a dam break flow that impacts against a structure; in particular the influence of the roughness and of the bed load to the pressures and forces extent on different types of obstacles.

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