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Investigation of dam-break induced shock waves impact on a vertical wall

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SUMMARY

In the present study, experimental tests and VOF-based CFD simulations concerning impact of dam-break induced shock waves on a vertical wall at downstream end were investigated. New laboratory experiments were carried out in a rectangular flume with a smooth horizontal wet bed for two different tailwater levels. Image processing was used for flow measurement and time evolutions of water levels were determined effectively by means of synchronous recorded video images of the flow. This study scrutinized formation and travelling of negative wave towards upstream direction, which was resulted from the reflection of flood wave against downstream end wall. In numerical simulation, two distinct approaches available in FLOW-3D were used: Reynolds- averaged Navier–Stokes equations (RANS) with the k-ε turbulence model and the Shallow Water Equations (SWEs). The measured results were then compared with those of numerical simulations and reasonable agreements were achieved. General agreement between laboratory measurements and RANS solution was better than that of SWE.

1. Introduction

Dam-break phenomena have been main research interest in unsteady flows for many years. Since it causes a catastrophic flooding, urban areas or farmlands at downstream are dramatically devastated. Forecasting of the severe flood is necessary for an emergency evacuation from the flooded area to prevent live losses and huge damages. In literature, due to the significant differences in flow behaviours, dam-break problem was studied separately in domains with initially dry or wet bed. In general, dam-break induced shock waves propagate over downstream with initially wet bed. During a sudden failure of a dam in real-field, presence of any man-made structure (weir, bridges) at dam downstream can act as a vertical wall that producing shock waves reflecting against these structures. Therefore, a negative bore (reflected wave) occurs and propagates with high velocity towards dam axis. The bore propagation induced impact of dam-break shock waves on a vertical wall at wet downstream end can represent similar bore propagation caused by a tsunami wave breaking on the coastline (Visscher and Hager, 1998; Chanson et al., 2000). The velocity and depth of the shock waves over time are the important factors to be determined for taking precautions against harmful impacts of the flooding.

In the past, Dressler (1954) provided experimental data concerning the dam-break flow over wet bed in rectangular channel and Stoker (1957) extended Ritter's (1892) analytical solution by solving the Saint–Venant equations using the method of characteristics. However, the analytical solution did not produce accurate results particularly for wet bed during initial stages of dam-break (Stansby et al., 1998; Cagatay and Kocaman, 2008). Fraccarollo and Toro (1995) developed a shallow water model for 2-D dam-break type problems on a dry bed and validated the model with laboratory experiment. The conservative formulation of the 2D shallow water equations (SWEs) for free surface shallow flows were solved by shock-capturing methods (Brufau and Garcia-Navarro, 2000; Toro, 2001). Recently, 2D numerical solutions based on SWEs with shock-capturing solver were widely investigated in dam-break flow simulations involving wetting and drying (Aureli et al., 2008a; Prestininzi, 2008; Liang and Marche, 2009; Liang and Borthwick, 2009; Song et al., 2011; Kesserwani and Liang, 2012). Chang et al. (2011) developed a numerical model, which solves SWE based on smoothed particle hydrodynamics. However, instabilities in results show that SWE-based numerical models may not well simulate initial stages of the dam failure.

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Audusse et al. (2014) proposed a new multi-layered finite volume model for shallow water flows with mass exchange. Actual behaviour of the dam-break flow during the initial stages can be well-represented by Reynolds-averaged Navier–Stokes (RANS) equations with the turbulence model. Nevertheless, there are limited studies in literature with RANS (Shigematsu et al., 2004; Quecedo et al., 2005; Ozmen-Cagatay and Kocaman, 2011; Kocaman and Ozmen-Cagatay, 2012; Marsooli and Wu, 2014). Ferrari et al. (2010) compared the weakly compressible 3-D Navier–Stokes model solved by using the meshless SPH (smoothed particle hydrodynamics) model with the classical 2-D SWEs solved by using the unstructured third order weighted finite volume scheme. Goater and Hogg (2011) investigated bounded dam-break flows with tailwater using the nonlinear shallow water equations.

Laboratory experiments play crucial role in understanding the real dam-break phenomenon and validation of numerical models due to difficulties in obtaining field data. While various numerical studies are available, a few laboratory data exist concerning dam-break flow (Bellos et al., 1992; Fraccarollo and Toro, 1995; Lauber and Hager, 1998; Stansby et al., 1998; Bukreev and Gusev, 2005; Chen et al., 2013; Ozmen-Cagatay et al., 2014). In recent years, with the developing technology, image processing has been applied in laboratory works (Soares-Frazao and Zech, 2007; Aureli et al., 2008a; Kocaman and Ozmen-Cagatay, 2012). With increasing capacity and performance of the computers, computational fluid dynamics (CFD) based softwares involving finite volume solution have been used in dam break simulations (Biscarini et al., 2010; Ozmen-Cagatay and Kocaman, 2010; Oertel and Bung, 2011; Fu and Jin, 2014). To the best of our knowledge, there is no detailed experimental study available concerning impact of dam-break flow on vertical wall over initially wet downstream.

In this paper, the impact of dam break-flood waves on a vertical wall at downstream end was investigated in the laboratory over initially wet channel with two distinct tailwater levels. In the laboratory tests, digital image processing was adopted as a measuring technique. The flow along the downstream channel was synchronously recorded with three adjacent CCD cameras. Time evolutions of water levels were determined directly from the recorded video images without disturbing the flow. This measuring technique does not require test repetition for obtaining panoramic view. Experimental data was then compared with CFD-based numerical solution results, which were obtained from SWE, and RANS approaches in the FLOW-3D (Flow Science Inc., 2007).

2. Experimental setup

2.1. Facilities and instrumentation

The experiments were performed in a rectangular flume of 8.90 m in length, 0.30 m in width, and 0.30 m in height (Fig. 1) with a horizontal bottom (Kocaman, 2007). Both the bottom and the walls were glass. A vertical gate was installed at a distance of 4.65 m from upstream entrance, dividing the flume into two parts, of which, first part representing reservoir while the second part was initially wet downstream channel. The dam failure was simulated by instantaneous removal of the gate. Hence, a mechanism including pulley system was arranged in which a weight was suddenly released from 1.50 m above the floor, then the gate was rapidly opened in a very short time ($t = 0.06$–0.08 s). The schematic view of the arrangement can be seen in (Ozmen-Cagatay and Kocaman, 2010). The downstream end of the channel was closed with a steel gate for providing wet bed. Two series of experiments were carried out for different initial tailwater levels. In the first series, initial tailwater depth was taken as 0.025 m, and in the second series, it was 0.10 m. Prior to tests the reservoir was initially filled

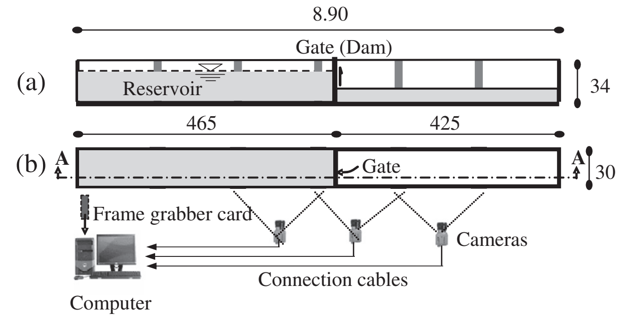

Fig. 1. Experimental facility (a) section A-A; (b) plan, lengths in (cm).

with water up to height of $h_0 = 0.25$ m. Thus, depth ratios were $\alpha = h_1/h_0 = 0.10$ and 0.40, where h_0 and h_1 initial reservoir depth and initial tailwater depth, respectively. Herein, $\alpha = 0.1$ and $\alpha = 0.4$ represent shallow and deep tailwater conditions, respectively. Stansby et al. (1998) investigated initial stages of dam-break flow for similar depth ratios: $\alpha = 0.10$ and $\alpha = 0.45$. The reservoir water and tailwater were coloured by two different dye colours in order to observe the flow behaviour well.

Image processing was applied for flow measurement. The measuring system requires a computer, a frame grabber card within the computer and CCD cameras (Fig. 1). Flow measurement was conducted in three main steps. First, as soon as the dam-break flow was recorded with three high-speed CCD cameras that were placed at distances with equal interval, the recorded flow images were simultaneously transferred to the computer with the aid of the frame grabber card. The recorded raw images were digitized as 768 × 576 pixels at 50 frames/s. Second step involved calibration process of the original images. In the last step, three synchronous images were combined, providing an extensive view through entire downstream channel without changing the camera positions. Herein, filtering was applied to the images in order to avoid background noise and unwanted reflection of any ambient object caused by lighting device. The measuring technique used in this experimental study achieves complete visualization of the flow behaviour along the entire downstream channel without test repetitions unlike similar studies in the literature (Stansby et al., 1998; Soares-Frazao and Zech, 2007).

2.2. Calibration process

The calibration process was required due to radial and tangential distortions of the images emerging from wide-angle lens usage. Hence, a planer checkerboard containing 6 horizontal and 7 vertical uniform black and white coloured square meshes was used for correction of these distortions. Using the software "Camera Calibration Toolbox for Matlab" (Bouguet, 2004), the calibration parameters were determined one by one for each camera by matching the predetermined coordinates of the corners on the images, which were filmed from different orientation of the checkerboard. In calibration process, twenty-five selected video images were used for each camera. Geometric and optical characteristic (intrinsic parameters), as well as the 3D position and orientation of the camera frame relative to a certain world coordinate system (extrinsic parameters) were calculated, and then, the raw images with barrel distortions were corrected by the aid of this calibration parameters using the toolbox. Image filters and threshold values are required for sharpening air–water interface to better identify the edge. Hence, a low pass binomial image filter was applied to raw images for smoothing the image to minimize unwanted stain-like traces. Afterwards, the air–water interface was sharpened by contrast adjustment. To provide panoramic view of the downstream channel, video images