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Research paper

Investigation of dam-break flood waves in a dry channel with a hump

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Abstract

Dam-break represents a potential flood hazard for population at downstream due to the sudden release of the water stored in the reservoir. The prediction of dam-break wave parameters is complicated furthermore by the presence of irregularities in the channel. This paper aims to present an experiment and numerical simulations of dam-break flood wave in an initially dry flume with a hump. A triangular-shaped bottom obstacle was placed downstream the dam site in the channel to provide the effects of both bottom slope and abrupt change in topography on propagation of dam-break flood waves. A new experiment was carried out in a smooth rectangular cross-section channel by using digital image processing. Flow behaviour was synchronously recorded with three adjacent CCD cameras through the glass walls of the entire downstream channel. This adopted measuring technique eliminates the necessity for test repetition due to capturing the whole flow field at once. Not only continuous free surface profiles at various times but also time evolutions of the water levels for selected locations were simply acquired from the video records of the image processing by virtual wave probe. Furthermore, dam-break flow was numerically simulated by the VOF-based CFD commercial software package FLOW-3D, which utilizes two distinct approaches, namely the Reynolds-averaged Navier−Stokes equations (RANS) with a k-ε turbulence model and the simple Shallow Water Equations (SWEs). Comparison between the computed results and the experimental data shows that both numerical models reproduce the flow behaviour with reasonable accuracy and the agreement is slightly better in RANS model compared to simple SWE model. Current experimental data can be useful for validation of other numerical models.

Keywords: Dam-break; Flood wave; Image processing; Hump; FLOW-3D; VOF; RANS; SWE

1. Introduction

Significant hazard is posed by dam-break which causes catastrophic floods at downstream since a large amount of stored water is suddenly released from the reservoir. It is important to predict dam-break waves in order to assess and manage flood hazard risks accurately. Rapidly varying unsteady flows resulting from dam-break are considerably affected by the topography of the downstream channel subject to flooding. The presence of either bed slope or man-made obstacles like bridges or natural obstacles (trees, local sills) results in sudden changes in flow behaviour. In addition, irregularities in a valley cross-section, e.g. abrupt constriction or expansion, have effect on the flow characteristics. Hence, predictions of the flow depth and wave propagation velocities are important for emergency response during serious floods.

Experimental data play crucial role in helping to understand the physics of the phenomena. Owing to the difficulties in obtaining field data for such a flow, limited experimental data concerning dam-break were acquired in recent years, while many numerical methods were developed. As an early work, Ritter (1892) presented an analytical solution concerning velocity and flow depth for 1D dam-break waves over dry bed. Dressler (1958) improved the analytical solution for sloping channel. Experiments of dam-break flow have been carried out for different bed slopes (Bellos et al., 1992). Progression of dam-break wave front and water depth variations

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with time have been experimentally examined (Bell et al., 1992). Lauber and Hager (1998) conducted an experiment in a sloping dry-smooth channel to investigate propagation of positive and negative wave fronts of dam-break flow. Bed slope effect on dam-break problem has been examined both experimentally and numerically with shallow water approximation (Nsom et al., 2000). Orendorff et al. (2011) utilized particle tracking velocimetry to obtain the surface velocities upstream, downstream, and through experimental embankment dam breach channels at all stages of breach development. A simple solution based on the St.Venant equations was introduced by Chanson (2009) to predict the wave tip profile and compare the results with numerical and experimental data.

Some researchers carried out experimental works on dam-break flows, in the presence of obstacles and over a bottom sill adopting digital imaging techniques (Aureli et al., 2004; Soares-Frazao et al., 2004; Soares-Frazao, 2007; Aureli et al., 2008a; Ozmen-Cagatay and Kocaman, 2011). Furthermore, the numerical solution of similar problems was presented by several researchers Brufau and Garcia-Navarro (2000); Brufau et al. (2002); Quecedo et al. (2005). Aureli et al. (1999) investigated both experimentally and numerically dam-break flow over two trapezoidal humps placed at the dam section and downstream. Herein, presence of a triangular-shaped bottom obstacle (hump) having inclined surfaces on both sides practically provides bed slope at a distance downstream and causes the formation of a bore on the upstream side of the hump which later propagates in the upstream direction.

Most of the early numerical works on dam-break described the flow using shallow water equations (Mohapatra and Bhallamudi, 1996; Garcia-Navarro et al., 1999; Liang et al., 2006; Aureli et al., 2008a; Liang and Marche, 2009; Liang and Borthwick, 2009; Ying et al., 2009). Jeong et al. (2012) presented a numerical investigation based on the SWEs including 2-D unstructured finite volume model. The standard SWE models generally do not consider the flow turbulence due to its simplified Reynolds-averaged form. Pu et al. (2013) proposed a numerical model to combine the SWEs with k-ε turbulence equations for shallow open channel flows. Due to the turbulent characteristic of the flow under investigation, RANS equations involving the turbulence modelling were adopted (Abdolmaleki et al., 2004; Shigematsu et al., 2004; Quecedo et al., 2005). Recently, 3D VOF-based CFD modelling softwares (FLOW-3D, CFX, Fluent, OpenCFD, Star CD, etc.) have been widely used to analyse unsteady free surface flows due to the increasing computational power provided by the advancement in computer technology. These modelling softwares are based on various turbulence models (k-ε, LES, RNG, etc.). Some researchers have adopted the CFD modelling software for numerical solution of dam-break flows (Vasquez and Roncal, 2009; Ozmen-Cagatay and Kocaman, 2010; Biscarini et al., 2010). Oertel and Bung (2012) investigated the initial stage of a two-dimensional obstacle-affected dam-break wave and compared experimental results with the VOF-based commercial code FLOW-3D. Kocaman and Ozmen-Cagatay (2012) conducted an experiment to investigate the effect of lateral channel contraction on dam-break flows in a flume with horizontal bed and compared experimental data with numerical simulation results.

The purpose of the current study is to present new experimental data on dam-break flow in a channel with hump by using image processing technique and also to test the validity of the two different mathematical approaches, namely RANS and SWEs. An experiment was carried out in a smooth rectangular flume with a horizontal bed. A triangular-shaped bottom obstacle (hump) was placed at a certain distance downstream from the dam site in the initially dry flume. The flow was synchronously recorded with three adjacent CCD cameras along the entire downstream channel through the glass walls. The adopted measuring technique, digital image processing, eliminates the need for test repetitions to obtain synchronous images of the flow by capturing the whole dam-break wave behaviour at once. Continuous free surface profiles for various times as well as time evolution of water levels at selected sections along the channel downstream were directly determined from the recorded video images by using virtual wave probe. The novelty of this paper is the application of digital imaging on only one continuous image frame obtained from three synchronous cameras. To compare experimental data with computed results, the flow under investigation was numerically simulated by VOF-based CFD model, FLOW-3D (Flow Science Inc., 2007). This model enables the solution of both Shallow Water Equations (SWEs) and Reynolds-averaged Navier–Stokes equations (RANS). In RANS simulation, k-ε turbulence closure model was adopted. Since there are challenges in obtaining field data concerning dam-break flow particularly over irregular bottom topography, new experimental data can be valuable in validation of numerical models used by the researchers in future applications.

2. Experimental and numerical models

2.1. Experimental facility

The experiment was conducted at Civil Engineering Hydraulics Laboratory of the Cukurova University, Turkey (Kocaman, 2007) using a rectangular smooth horizontal channel having the dimensions of 8.90 × 0.30 × 0.34 m with glass bottom and walls (Fig. 1a). The plate representing the dam was located at 4.65 m from the channel entrance. The upstream reservoir initially consisted of 0.25 m of water at rest. Dye was added into reservoir to colour the water for better determination of the free surface levels from recorded images (Cagatay and Kocaman, 2008). The downstream channel was initially kept dry at downstream of the breach. A symmetrical triangular-shaped bottom obstacle with 1.0 m base length and 0.075 m height was located 1.50 m downstream from the dam site (Fig. 1a).

For dam-break modelling, a mechanism allowing for the sudden removal of the vertical plate was constructed. A schematic view of the mechanism is seen in Fig. 1b. The 4 mm thick plate, made of rigid plastic, coated with aluminium was used and two steel bars also were attached to the plate for reinforcement. Grease oil was used to prevent leakage from