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Investigation of water-water interface in dam break flow with a wet bed

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ABSTRACT

The evolution of water-water interface between reservoir and ambient water in dam break flow with a wet bed is numerically investigated based on a two-liquid Volume of Fluid (VOF) method. The VOF method is employed to capture both the free surface and water-water interface under Eulerian grids. The modification to VOF method prevents the intersection problem from happening on the water-water interface. The initial stage and long channel propagation of dam break flow are investigated numerically according to the experiments of Jánosi et al. (2004) and Ozmen-Cagatay and Kocaman (2010). The comparison of free surface and water-water interface evolution have good agreement with the published experimental and numerical results. The evolution of water-water interface at the initial stage of dam break flow and the analysis of gate thickness, gate removal velocity and ambient water depth effects are further examined. Besides, propagations of dam break flow in a long channel are investigated, a time difference between the propagation of water-water interface and dam break wave front is found.

1. Introduction

A dam break flow is usually generated by a sudden failure of a barrier confining a reservoir filled with fluid. It can also be used to study green water prediction, storm surge and tsunami because the bore process and violent free surface motion are similar in these phenomena (Chanson, 2006; Buchner et al., 1995; Ryu et al., 2007). Thus it has both scientific importance and wide engineering applications in hydraulic, coastal and ocean engineering.

Ritter firstly derived an analytical solution to the free-surface profile evolution of an infinite volume of fluid over a dry bed with no resistance (Dressler, 1952). Later theoretical studies were usually based on solutions to the shallow water theory with the consideration of the effect of hydraulic resistance (Whitham, 1955; Lauber and Hager, 1998; Hogg and Pritchard, 2004). Although there exists difference between theoretical solution and the exact phenomenon, propagations of the bore is close to the exact phenomenon. However, this problem will be much more complicated if the dam break flow is initially with downstream ambient water (Which refers to as dam break flow with a wet bed). Fig. 1 shows the sketch of a typical wet bed dam break experiment. The reservoir water and ambient water is initially separated by a gate, and dam break flow is generated by the sudden removal of the gate. This flow process is not only involved with free surface deformation, but also involved with the mixing between reservoir and ambient water. Research about dam break with a wet bed is few compared with that in dry bed case (Crespo et al., 2008). Stansby et al. (1998) conducted a series of experiments about dam break flow with a wet bed. During their experiments, the free surface flow phenomenon was studied (e.g. a mushroom-like jet was firstly investigated), but the mixing between reservoir water and ambient water was not investigated. Following Stansby's research, Jánosi et al. (2004) and Ozmen-Cagatay and Kocaman (2010) conducted experiments of dam break flow with a wet bet. In their experiments, reservoir and ambient water were dyed with different colours, which enables the study of the mixing process by the investigation of water-water interface.

In recent years, numerical study has been widely used to study dam break flow. Numerical models based on shallow water equations (SWEs) have been widely adopted in studying dam break flow (Prestininzi, 2008; Ozmen-Cagatay and Kocaman, 2010;

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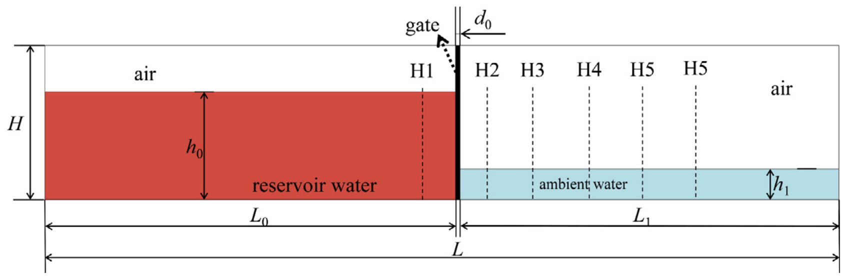

Fig. 1. Sketch of dam-break experiment and imaging measurement positions.

Chang et al., 2011; Kao and Chang, 2012). However, SWEs based models fail to accurately reflect the actual situation especially during the initial stage of the dam break flow (Kocaman and Ozmen-Cagatay, 2015). Thus the emphasis of research has shifted to the development of models based on Navier–Stokes equations. Models based on Navier–Stokes equations can be generally classified into two categories: mesh-based model and mesh-free model.

Mesh-based model uses an Eulerian description, computing and capturing free surface are always challenging works. One of the most popular methods dealing with free surface motion is the VOF method, which captures free surface by the reconstruction of volume function in computational grids (Hirt and Nichols, 1981). Another widely used method is the level set method, which implicitly determines the free surface by the zero-contour of a signed distance function (Sussman et al., 1994). Models based on these two methods have been widely applied in the studies of dam break flow with ambient water (Ozmen-Cagatay and Kocaman, 2010; Oertel and Bung, 2012; Trontin et al., 2012). The initial condition of those numerical studies is shown as Fig. 1. The reservoir and ambient water are treated as the same phase during their numerical simulations. Although they performed well in free surface motion and pressure, they failed to study the mixing process because they did not distinguish reservoir and ambient water in their studies. Owing to the property of Eulerian grids, even the accurate capturing of an interface is a challenging work. In this problem, two interfaces including free surface and water-water interface are captured simultaneously, showing a greater computational challenge than those problems involved with one moving interface. Thus it is not easy to trace both free surface and water-water interface under the framework of Eulerian formulation. In some recent studies, water-water interface tracing has been achieved by applying particle markers in Eulerian grids and computing those particles in a Lagrangian way and has been successfully applied to the studies of breaking wave and drop impact process (Yasuda et al., 1999; Lubin et al., 2006). Those models are capable of tracing the water-water interface, but they are usually much more complicated than the original VOF or level set model, and they have not been applied in the study of dam break flow.

Mesh-free model is not involved with the problem of interface tracing. The fluid is usually described as particles. The Lagrangian description of the particles traces the motion of every particle, making the study of water-water interface rather straightforward. Once the reservoir water and ambient water particles are marked in different colours as initial condition as shown in Fig. 1, the colour of every moving particle will be kept in the subsequent computational steps. Thus both free surface and water-water interface could be obtained automatically by different colours of the particles. Owing to this advantage, mesh-free methods, such as SPH method and MPS method, have been widely applied in the numerical study of dam break flow, with both free surface and water-water interface studied (Crespo et al., 2008; Khayyer and Gotoh, 2010; Shakibaeinia and Jin, 2011; Jian et al., 2015). Although some mesh-free methods such as SPH method have successfully modelled the motion of both free surface and the interface between two liquids, they have to face the challenge of the stability problem caused by boundary condition implementation, and also the computational cost is usually high.

In the present work, the main objective is to numerically investigate both free surface and water-water interface in dam break flow with a wet bed. A two-liquid method is proposed to trace both free surface and water-water interface under the Eulerian description. To correct the intersection between liquid phase, an intermediate step is applied to modify the value of volume function. Only little complexity is added in two-liquid VOF method when compared with original VOF method. Furthermore, this two-liquid VOF method is coupled with an immersed boundary method to achieve the modelling of fluid–structure interaction. The two-liquid VOF based model is applied to study dam break flow with a wet bed. Both the initial stage of dam break flow and dam break flow propagating in long channel with a vertical wall are investigated.

The outline of this paper is described as follows. In Section 2.1, the two-liquid VOF method will be explained. Section 2.2 describes the coupling of two-liquid VOF method with immersed boundary method. Numerical procedures and schemes are presented in Section 3 and the two-liquid VOF method will be validated with Zalesak's advection test (Zalesak, 1979) in Section 4. Section 5 investigates the initial stage of dam break flow with both shallow and deep ambient water, in which the effect of gate velocity, gate thickness and ambient water depth are discussed. Section 6 investigates the long channel case of dam break flow with a vertical wall locating at the downstream. Finally, we will draw some conclusions in Section 7.

2. Two-liquid VOF method

Models based on VOF method has been widely used to address dam break evolution. The VOF method is a methodology which deals with free boundary within Eulerian formulation. Hirt and Nichols (1981) firstly proposed the VOF method, then it has been improving to achieve higher accuracy and efficiency. During the past decades, this method has been successfully applied in numerical modelling and has been proved to be an efficient way of dealing with violent free surface flow.

Typical VOF function can be expressed as

$$\frac{\partial F}{\partial t} + \vec{u} \cdot \nabla F = 0, \qquad (1)$$

where F indicates the volume function. In this subsection, F is referred to as the volume function of liquid phase. The free surface of liquid phase can be constructed by solving Eq. (1) with VOF method. However, this one-liquid phase method does not have