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Turbulent Flow Overtopping a Dam - A CFD Modeling Study

TURBULEBNT FLOW OVERTOPPING A DAM
— A CFD MODELING STUDY

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ABSTRACT

Enhanced understanding of the mechanisms of dam failure is critical for reliable flood risk assessment. This paper presents a computational study of the flow over-topping a dam with the CFD software FLUENT. The results show that the flow velocity increases rapidly along the distance after over-topping, which may cause extremely intense effects on the dam surface. There exists a maximum of boundary shear stress and a minimum of static pressure around the turning point of the dam top, but the reverse holds around the foot of dam. This may favour erosion at the top of the dam, and collapse around the foot of the dam. The stage hydrographs of a shallow water hydrodynamic model and the FLUENT model are compared. Being qualitatively consistent with each other, the stage hydrographs from both models feature appreciable difference quantitatively, and therefore the applicability of shallow water hydrodynamic models to the turbulent flow over-topping a dam may not be fully justified.

Keywords: dam break, VOF model, Reynolds stress model, air-water two-phase flow

1. INTRODUCTION

Dams play significant roles in reliable and safe water supply, flood control, navigation, hydroelectric power generation and recreation. However, dams could also bring flooding catastrophe if failed. Due to climate change and human activities, the potential of the occurrence of dam-break flooding continues to be existent. Examples of the major dam-break flooding disasters include the 1959 Malpasset dam failure in France, the 1975 Banqiao dam-break in China, and the 1985 Stava dam failure in Italy (Graham, 1998).

Dam-break is a process of soil-water-structure interaction. Over recent decades, there have been continuing efforts to enhance the understanding of dam-break mechanisms. Constrained by the comparatively small spatial scales that can be accommodated in laboratories realistically, physical experiments may not be able to fully reveal the long-term mechanisms of dam-break flooding. This applies not only to the early dam-break experiments over fixed beds, but also to the recent mobile-bed experiments (Capart *et al.*, 1998; Leal *et al.*, 2001). Field measurements and mobile-bed models of dam-break are adopted in recent studies with many features are not yet sufficiently justified, such as the earthen dam breach studies of the CADAM (EU Concerted Action on Dam Break Modeling) and the IMPACT (Investigation of Extreme Flood Processes and Uncertainty) projects in Europe. For computational studies, the fixed-bed models are built upon the assumption that the flow involves no or weak sediment transport and morphological deformation in early stage (Wang *et al.*, 1999; Zoppou *et al.*, 2003), which will totally fail for dam-break flooding over erodible beds. Recent mobile-bed models consider the eroding capability of the flood flow and the related morphological evolution of riverbed. One-dimensional models have involved either capacity or non-capacity descriptions of sediment transport, and have yielded substantially enhanced results (Capart *et al.*, 1998; Fraccarollo *et al.*, 2002; Cao *et al.*, 2004). Two-dimensional models are more suitable for complex topographic conditions, but still cannot resolve the distributions of hydraulic characteristics along the flow depth. (Cao *et al.*, 2007; Simpson *et al.*, 2006). Most previous numerical simulations have been developed for the propagation of dam-break floods, based on the assumption of instant and full collapse of dams, while recent mathematical models have successfully reproduced the dam breaching process (Gens *et al.*, 2006; Wang *et al.*, 2006, 2006a, b, 2007). And yet, the inherent uncertainty of soil-water interaction mechanisms during dam-break continues to be far from clear.

Over-topping destruction is one of the major forms of dam failure, especially for earth-rock-filled dams (ICOLD, 1998). High-velocity over-topping flow often causes great breach erosion and eventually dam failure. This paper employs the CFD software FLUENT to simulate 2D whole field turbulent flow of dam over-topping so as to reveal the characteristics of flow and its effect on the dam surface, including the velocity, the stage hydrographs, and the static pressure and boundary shear stress on dam surfaces. Shallow water hydrodynamic models based on the assumption of hydrostatic pressure have been widely used for flood modelling. Yet, turbulent flow over-topping dams may feature non-hydrostatic pressure distributions. To date, it remains poorly understood if shallow water hydrodynamic models can properly resolve the stage hydrographs of the flow over-topping dams. This issue is addressed by comparing the model of Cao *et al.* (2007) with the FLUENT model.

This CFD simulation is the first step to resolve the detailed information of the 3D over-topping flow and its effect on dam surface during dam failure. It will be helpful to enhance the understanding of the water-soil interaction mechanisms of dam-break, and will physically improve approaches to forecasting dam-break flooding.

2. FLUENT MODEL

The CFD software FLUENT version 6.3 is utilized to model the flow over-topping a dam. The control-volume-based technique is used to solve the equations. The VOF model is employed to model two-phase flow by solving a single set of momentum equations and tracking the volume fraction of each fluid throughout the domain. A Reynolds stress model of turbulence is implemented.

The convective fluxes in the momentum and turbulence closure equations are discretized by employing a conservative, first-order accurate upwind scheme. The transient free surface is captured by deploying the VOF method under the air-water two-phase open channel flow framework with the geo-reconstruct scheme. The SIMPLE algorithm is used to couple velocity and pressure field. The viscosity layer near the wall is dealt with the standard wall function.

3. MODELING APPLICATIONS

Computational domain and mesh's generation

The model is shown in Figure 1. It is made up by 3 parts: (I) Upstream of dam profile

(2000 m long); (II) Downstream of dam profile (1000 m long); (III) Dam profile (278 m long). The part (I) and (III) are river channels with a slope of 1:100 and a length of 3000 m. The part (II) is a 40 m high dam, including a 1:3.5 up slope, a 1:3 down slop and a 10 m wide top. It is located at x =2000 m of the channel.

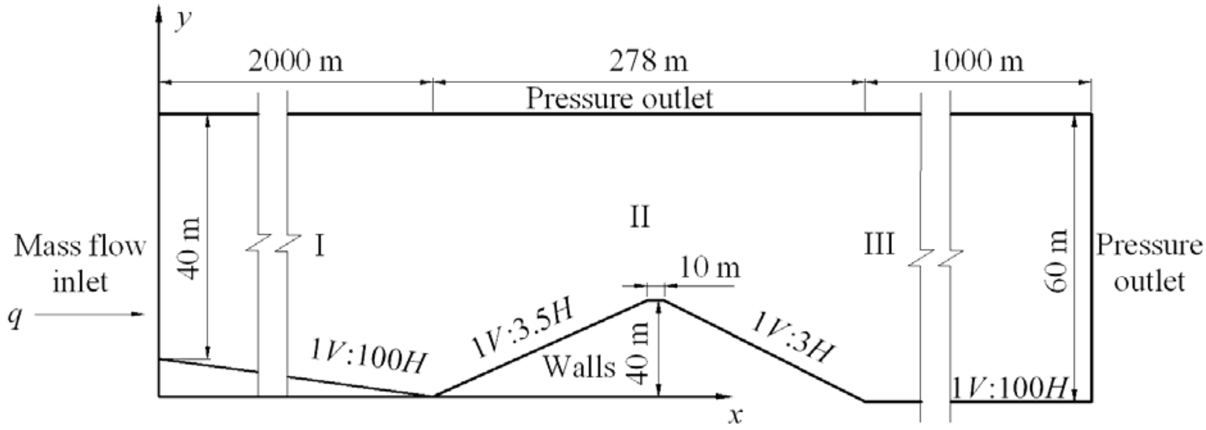

Figure 1. Computational domain and boundary conditions

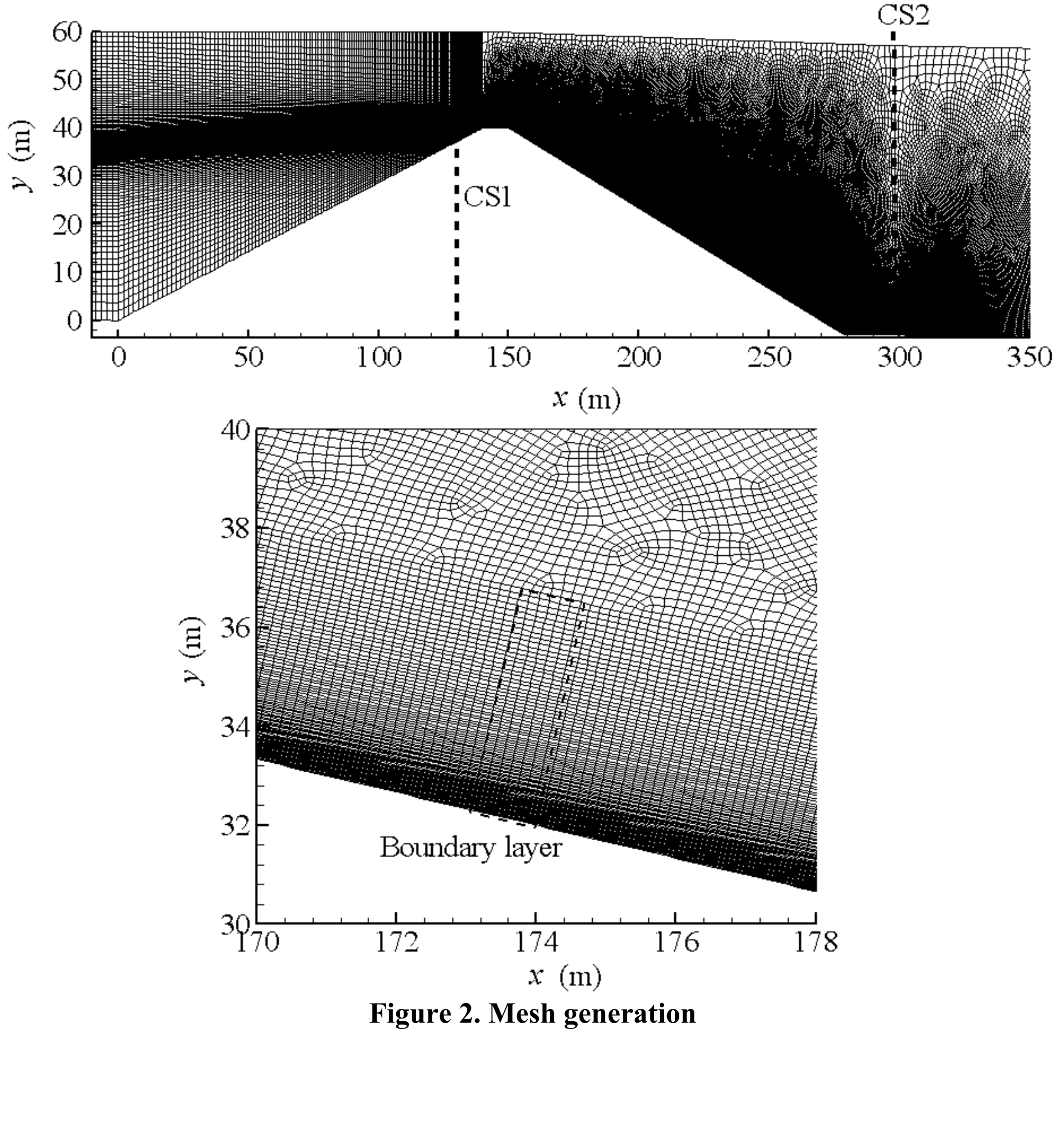

Figure 2. Mesh generation

Unstructured grids which have high flexibility to fit the complex geometric boundary of the dam are used to discretize the control volumes. A 95 rows boundary layer is generated on the surface of dam top and back-slope within 4.5 m to get a more accurate result (Figure 2). The total flow domain is discretized into 256000 quadrilateral cells. The minimum size of the cell is $7.85\times10^{-3}\,\mathrm{m}^2$, which is located at the surface of back-slope. The maximum size of the cell is 19.97 m^2, located at the outlet of the domain. Two cross sections are set in order to monitor the stage hydrographs (Figure 2).

Boundary and initial conditions

The boundaries are shown in Figure 1. The inlet section consists of the inlet of water on the lower part and the inlet of air on the higher part. This section should be far away from the dam to avoid the reflection effect, which is located at 2000 m upstream of the dam. Numerical simulation is done for a unit discharge of q =25 m^3/s, and the incoming flow is assumed to be steady. The upstream open boundary condition for velocity is worked out from the discharge intensity and reservoir water level. The downstream boundary should be located based on the range of interested domain. For the study of the flow over-topping a dam, the downstream boundary should have no effect on the flow upstream, which is located 1000 m down the dam. Because the boundary between water and air at the downstream outlet cannot be distinguished, it is defined as a pressure-outlet boundary. The up air boundary is 60 m above the river so it has no effect on the river flow. This boundary is set as pressure-outlet on which atmospheric pressure is assumed. All of the walls are set as the stationary, non-slip wall. The initial water level is z =37.5 m, 2.5 m below the dam top, and the flow field over the dam is full of air. Through the time-dependent simulation, the water flows over the dam and produces air-water two-phase flow.

4. RESULTS AND DISCUSSIONS

Starting from the prescribed initial conditions, the flow is modelled until the outlet discharge reached a value of 20 m^3/s (i.e., 80% of the inlet discharge). This computation resolves the evolution of the turbulent flow in a period of 730 s.

Hydrographs

Figure 3 shows comparisons between the stage hydrographs of FLUENT model and shallow water hydrodynamic model at CS1 (x =2130 m) and CS2 (x =2298 m). The water-level rising processes can be divided into 3 distinct steps. Figure 3(a) reveals that, in the first 80 s of the flow over-topping, the FLUENT model shows numerical instability for the accidented initial free surface of water caused by the deflection of meshes. Given this observation, the following analyses of numerical solutions are focused on the time after the very initial period of 80 s.

The shallow water hydrodynamic model's result shows that, the over-topping flow will become stable at about 3000 s after 10 water-level rising steps, however, according to the previous model experiments and dam-break observations, the main characteristics of over-topping flow has already existed within the first 730 s (3 water-level rising steps), what's more, the dam breach usually develops so fast that the shape of dam has already changed within this period. The main purpose of this numerical simulation is to capture the static pressure and boundary shear stress distributions on the dam top and back slope surfaces under the assumption that the boundaries are stationary; therefore, this paper only considers the first 730 s results with 3 distinct water level rising steps.

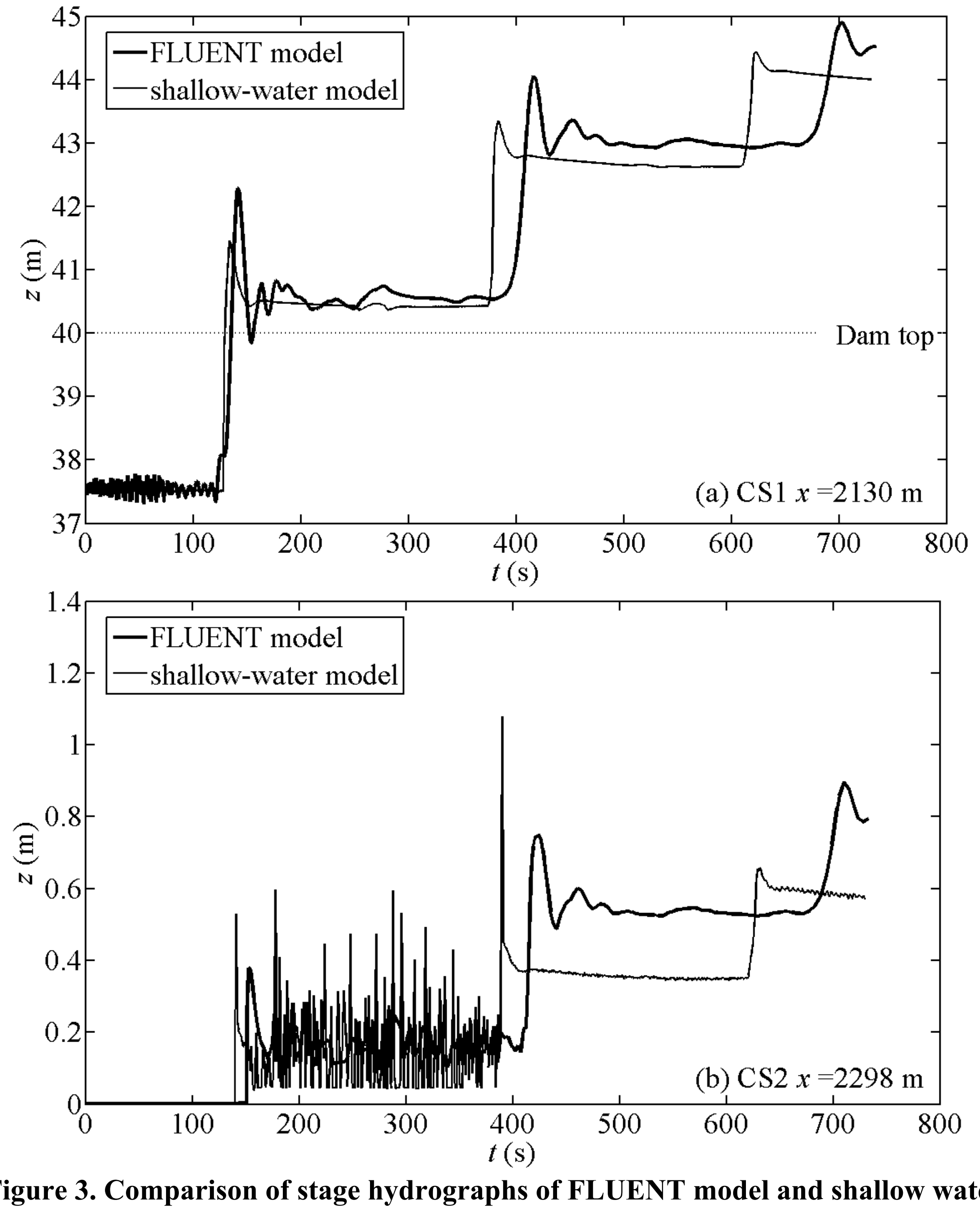

Figure 3. Comparison of stage hydrographs of FLUENT model and shallow water hydrodynamic model: (a) upstream of dam and (b) downstream of dam

Two models both simulate the shapes and the tendencies of the stage hydrographs around the dam qualitatively well (Figure 3). The step-form elevations of stage hydrographs are captured. Each step is composed by an undulation section in the front and the subsequently horizontal section. Physically, when the flow advances to the dam, although the incoming discharge is steady, for the dam reflection, backwater appears. The water level will rise gradually from the dam to the inlet. The stage hydrograph undulates until the current propagates to the dam and forms a new water level rising process again. This phenomenon is also discovered in the experiment of Hoeg *et al.* (2005). Quantitatively, the FLUENT model is set with higher resolution grids (dx =1 m) compared with shallow water hydrodynamic model, especially at CS2. The assumption of hydrostatic pressure in shallow water hydrodynamic model may hardly to be satisfied around the dam for the rapid change of the dam surface's geometry. The difference of numerical schemes between these two models is also significant. Thus the two computational results exhibit considerable quantitative differences. Theoretically, the FLUENT modelling result is more credible. The applicability of shallow water hydrodynamic models to the dam over-topping problems still needs further investigation.

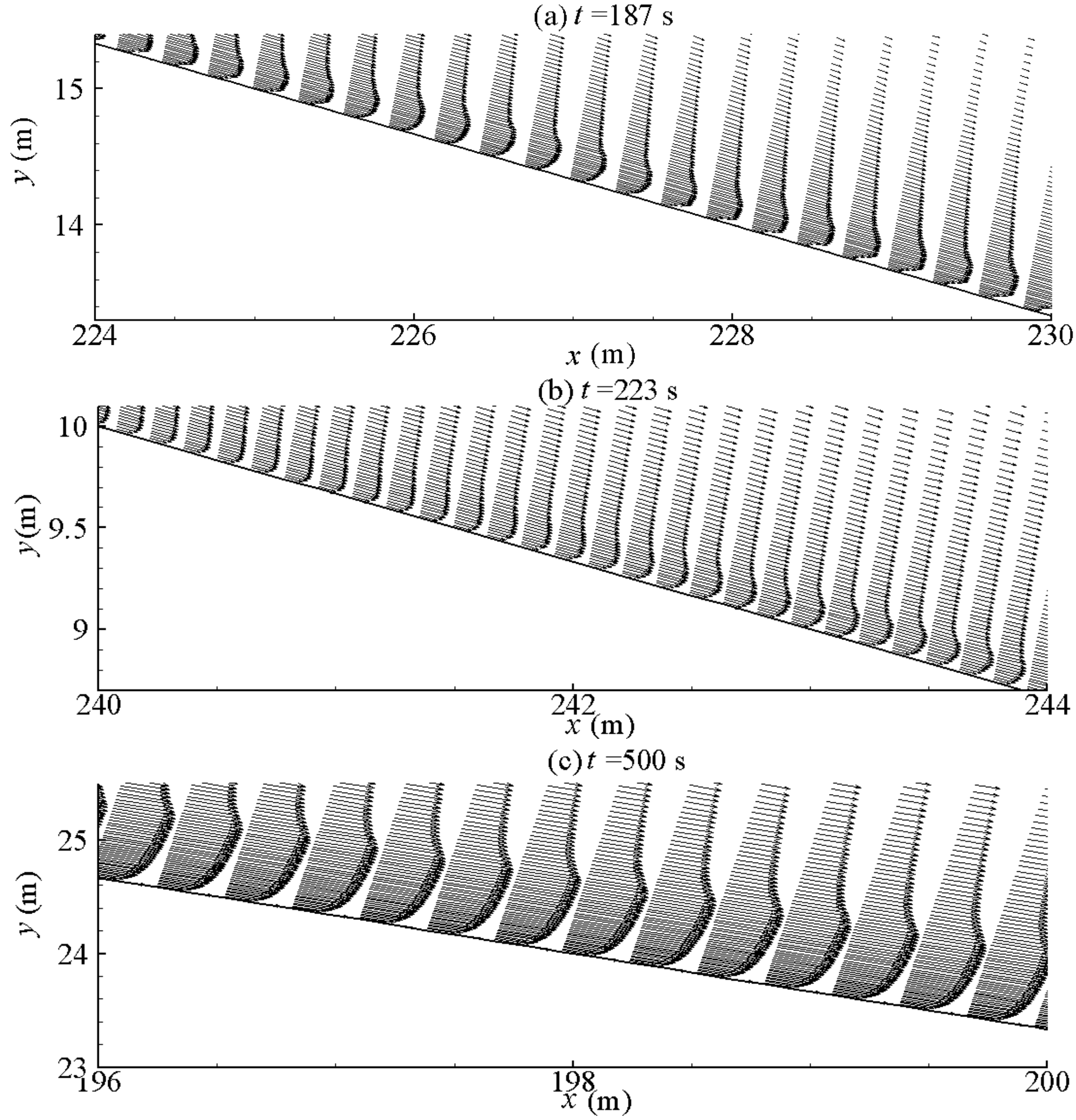

Figure 4. Velocity distributions of the over-topping flow at different time

Flow profiles and propagation

In undulation section of the stage hydrograph, each wave crest of stage hydrograph forms a peak flow discharge and propagates downstream. Figure 4(a) and Figure 5(a) show a propagation process of a peak flow discharge in this section. It can be seen that, both the flow velocity distribution and fluid are all discontinuous. As the fluid propagating downstream, this phenomenon becomes more distinct, but gradually vanishes after the flow crosses the foot turning point of dam. Figure 4(b) and Figure 5(b) show the fluid and velocity distributions of the horizontal section in the first water level rising step. In this section, the flow is shallow but with high-velocity, this induces the undulation of flow free surface on back slope of the dam. In above two sections, the flow depth on back-slope of dam is small, but the velocity of flow is very high, the boundary shear stress induces the discontinuity of the flow, and, for the differences of the incoming flow upstream, the intensities of the discontinuity along with the impacts onto the dam surface are all distinct. At t =500 s the depth of flow on the back-slope of dam reaches 0.5 m (Figure 4(c) and Figure 5(c)). The flow velocity increases from 5 m/s to 25 m/s along distance of the back-slope. The free surface of water on back slope of the dam is smooth. The above features are also manifested by static pressure and boundary shear stress distributions.

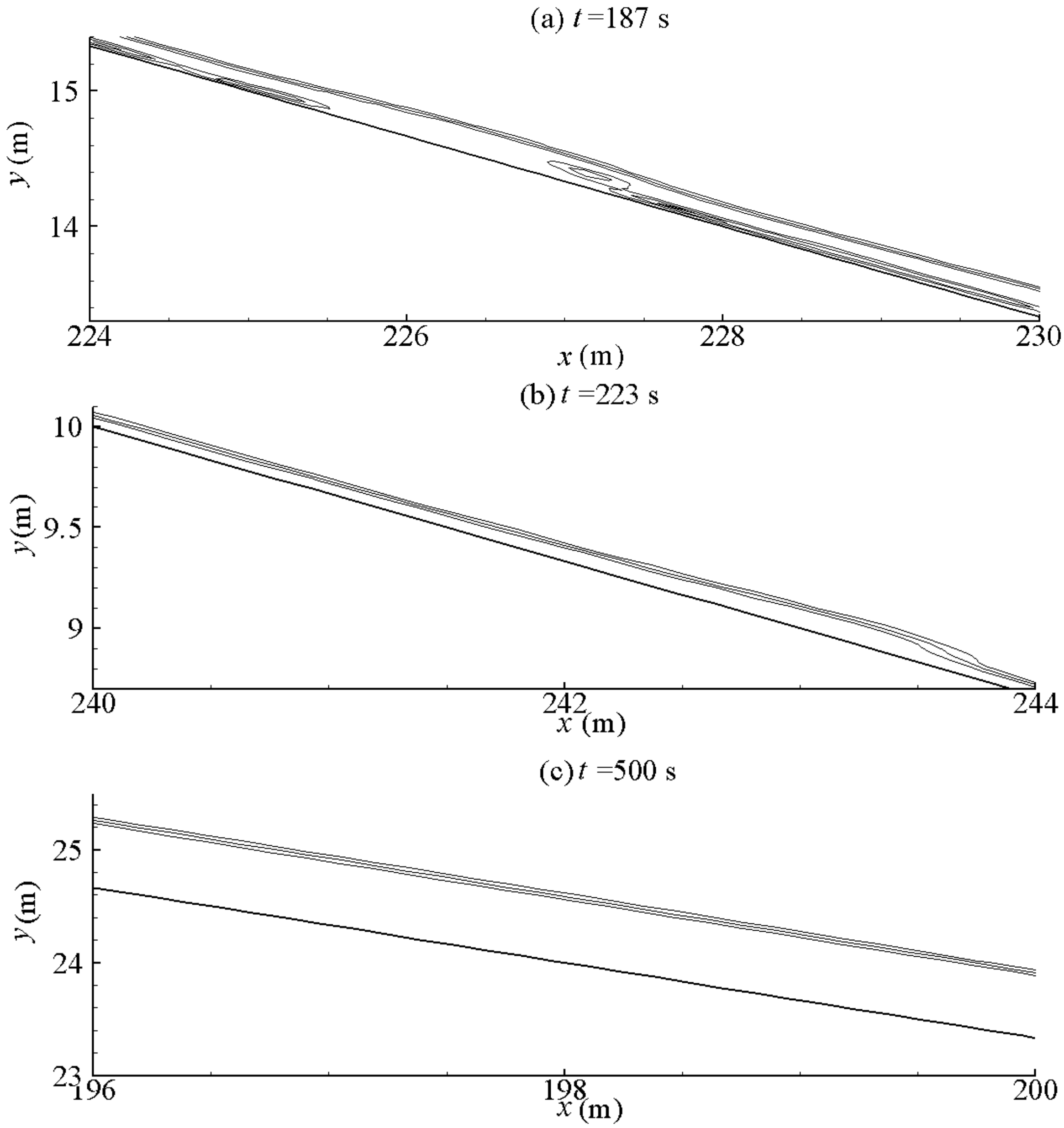

Figure 5. Fluid profiles of the over-topping flow at different time

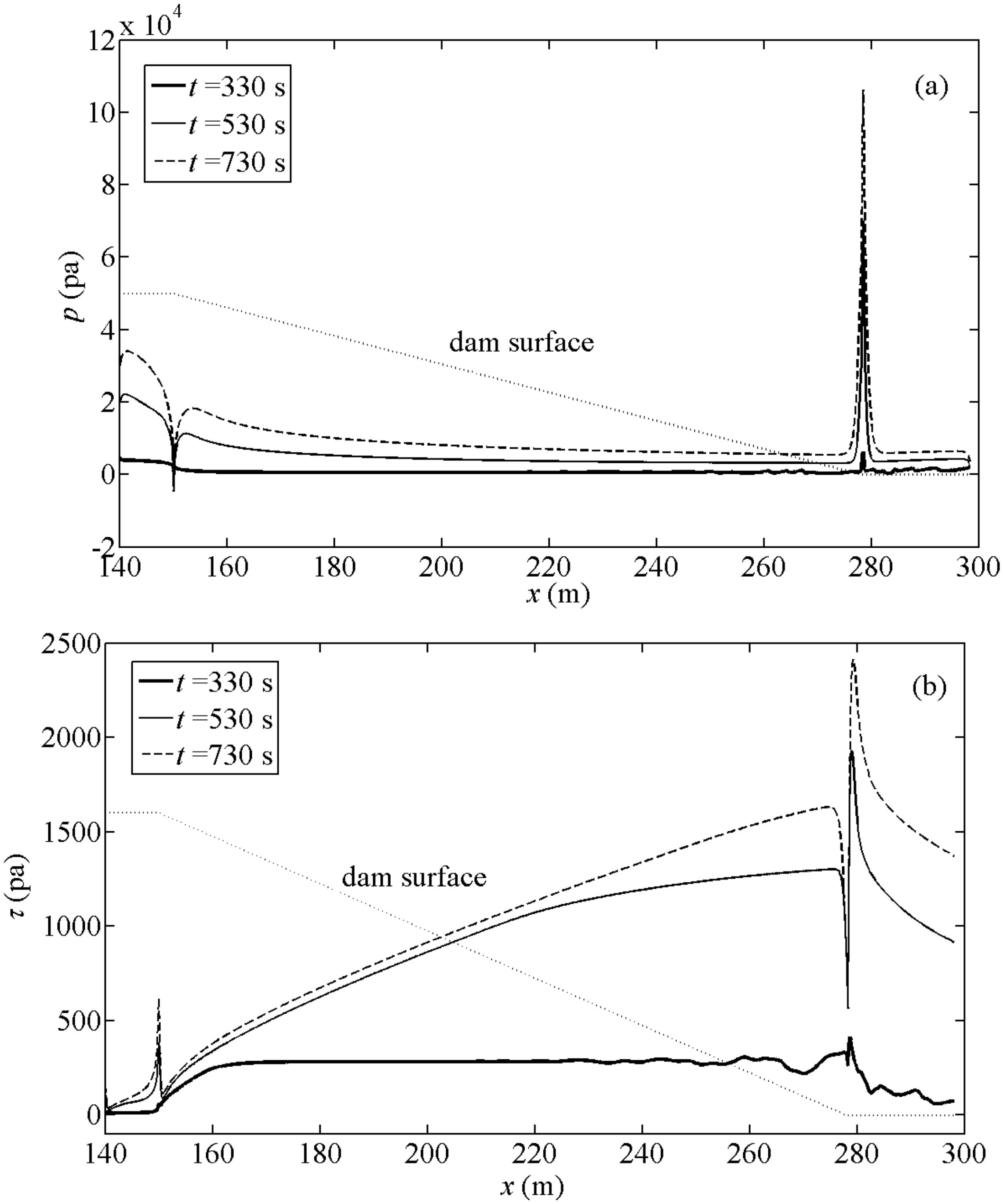

Figure 6. Static pressure and boundary shear stress profiles on back-slope of dam at different time: (a) static pressure and (b) boundary shear stress

Static pressure and boundary shear stress distributions

Figure 6 shows profiles of static pressure and boundary shear stress at different time. From Figure 6 along with Figure 3, the followings are observed.

The water level of the dam front considerably affects the static pressure and boundary shear stress distribution on dam surface. Along with the water level rising, the discharge increases, the static pressure and boundary shear stress grow right with it, and this often induces a higher degree of breach erosion. The slightly rise of water level in front of dam will cause great increase of impact on dam surface, so the water level in front of dam is one of the sensitive factors during the dam over-topping destruction.

Figure 6(a) shows that, a minimum of static pressure (even the negative value) exists at the turning point of the dam top (x =2130 m), and a maximum appears around the turning point of the dam foot (x =2278 m). Figure 6(b) illustrates that a peak value of boundary shear stress exists at the top turning point of the dam, while an abrupt fall turns out around the foot turning point. In the initial stage of dam over-topping (t =330 s), the occurrence of distinct maximum/minimum values of static pressure and boundary shear stress around the turning points at the dam top and foot is just appreciable, but will become more and more significant as time (and discharge) increase.

For the differences of stress conditions and structure characteristics at these two points, the destruction processes will also be different. Generally speaking, the top of dam experiences erosion, whilst the dam bottom may see the collapse destruction. This observation seems to echo the analysis of Wang *et al.* (2007) by a one-dimensional modelling of head-cut migration processes.

5. CONCLUSIONS

Turbulent flow over-topping a dam is simulated with the FLUENT software. The static pressure and boundary shear stress on dam surface may explain the dam breaching process. The maximum of boundary shear stress and the minimum of static pressure exist at the top turning point of dam back-slope, and the reverse holds around the foot turning point. This may induce erosion at the top of the dam, and collapse around the dam foot. The applicability of the shallow water hydrodynamic model to simulate the stage hydrographs of flow over-topping a dam is addressed by comparing with the stage hydrographs resolved by the FLUENT model. Quantitative differences exist, although the stage hydrographs of the FLUENT and the shallow water hydrodynamic model are consistent with each other qualitatively. The applicability of shallow water hydrodynamic models to the dam over-topping problems still needs further investigation

To fully resolve the breaching process of dams, further enhanced understanding of the hydrodynamic-dam interactions is critical. The present work needs to be extended to three dimensions.

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