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Numerical simulation of water level surge based on sediment mass algorithm

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ABSTRACT

Mountain areas are prone to landslides, debris flow and other geological disasters, resulting in a large amount of sediment into rivers and changing the movement of the flow and sediment. In order to study the effect of the flow and sediment condition change on the water level, the numerical model based on the sediment mass algorithm in the framework of the SPH method was applied to research the water level surge caused by sediment transport. The numerical results showed that the sedimentation caused the water level to increase rapidly at the deposition position, and much higher than the normal water level.

KEY WORDS: SPH; mountainous river; bed-load transport; sediment deposition; water level.

INTRODUCTION

The mountain area of the world accounts for about one third of the land area. Particularly, in the southwestern part of China, the mountain area accounts for as much as 95% of the land area. Complex climatic conditions have led to extreme events such as heavy rainfall and floods, which leads to more landslides disasters threating the safety of individuals. This has become a major concern in disaster's prevention and mitigation. When the flow with high sediment concentration enters the gentler downstream in the mountainous river, the sedimentation changes the shape of the riverbed surface, resulting in disasters. Recent experimental studies found that the sedimentation can cause the water level many times higher than the clear water level when the sediment supply intensity in mountain area is more than critical value (Li et al., 2015). Therefore, it is necessary for mountain torrents research to consider the additional disasters caused by strong sediment transport condition (Cao and Liu 2016).

1D bed-load numerical models such as 3ST1D (Papanicolaou et al., 2004), TOPKAPI (Konz et al., 2011) and SETRAC (Chiari and Rickenmann, 2011) can accurately estimate the quantity of bed-load through a certain section. However, 1D numerical models can not obtain the variation of physical quantities along the water depth direction. 2D models can calculate the effect of hydraulic factors on the bed-load transport along the cross section, and overcome the shortcomings of 1D models. One of the 2D steep slope bed-load transport models is the FLO-2D (O'brien et al., 1993). But 2D models have large differences from the actual condition when the bed-load transport of the mountain torrents is simulated. The main reason is that only the continuity of the bed-load is considered. So the exchange position and volume between the bed-load and riverbed deviate from the actual situation because bed-load movement is random and the time and space are out of synchronization between the bed-load and flow movement. In addition, the grid-based numerical algorithm has difficulty in dividing the complex space meshes and adapting the static meshes to the large deformation. So it is difficult to deal with the free surface in the turbulent state and simulate the development process of the hydraulic jump especially under the strong sediment transport condition. Therefore, this paper attempts to simulate this phenomenon by Smooth Particle Hydrodynamics (SPH), a mesh-free method without distortion and reconstruction of the mesh, and studies water level surge in mountainous rivers with different slopes in the case of the sufficient sediment supply.

REVIEW OF NUMERICAL MODEL AND SOLUTION METHOD

The proposed sediment mass algorithm method, which will be used to investigate the water level surge, has been detailed in a previous work by Zheng (2014) for steep open channels under strong sediment transport condition.

Here only a brief review of the model is summarized since our main focus in present study would be the water level change. In general, the Navier-Stokes (N-S) equations are used as follows:

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla \cdot \vec{u} = 0 \tag{1}$$

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla P + \vec{g} + \vec{\Theta} \tag{2}$$

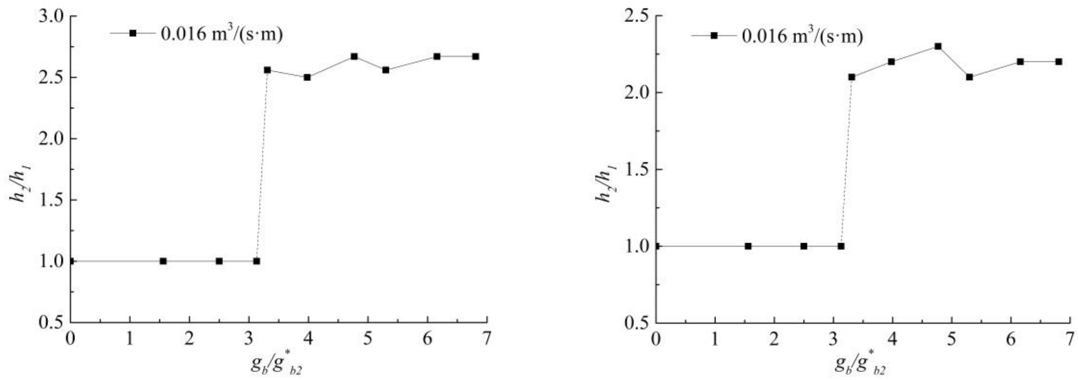
where ρ is fluid particle density, t is time, $\vec{u} = (\mathrm{u}, \mathrm{v})$ is particle velocity vector, P is particle pressure, $\vec{g}$ is gravitational acceleration vector and $\vec{\Theta}$ is diffusion term. The fluid in the SPH formalism is treated as weakly compressible, so the fluid pressure is calculated by the equation of state.

This approach is to consider the critical velocity of the fluid flow acting on the sediment boundary, and treat the sediment boundary as a movable solid wall. The motion of the two materials is described using the SPH method to discretize the continuity equation and momentum equation into the Lagrangian form. The core content of the water-sediment interaction is to realize the effect of sediment on the water flow by increasing the boundary particles vertically. The flow movement affects sediment particles movement, finally affects the siltation and erosion of the riverbed.

MODEL APPLICATIONS

The above model is applied to simulate the water level surge in flumes with different slopes and sediment supply intensity when the per unit width inflow discharge is unchanged. The results of water level surge over the 5% slope and 1% slope are shown in Figures 1(a) and (b), respectively, where h_2 is the water depth after hydraulic jump, h_1 is the water depth before hydraulic jump, g_b is the sediment supply intensity, g_{b2}^* is the maximum sediment transport capacity in the 1% channel. The water depth in this paper represents the distance from the water surface to the initial riverbed.

When the sediment supply intensity is 3 times higher than g_{b2}^*, the water depth increases to 2.6 times that of the clear water over the 5% channel. And the water depth increases to 2.2 times over the 1% channel. Under the same sediment supply intensity, the larger increase of the water depth is over the steeper channel. Over the same channel, the multiples of water depth increase remain substantially constant under different sediment supply intensity. This shows that the water level increase caused by strong sediment transport is related to water flow conditions (channel slope and discharge), and sediment supply intensity has less effect on the water level increase. So the water depth caused by strong sediment transport over the steep channels can reach 2-3 times higher than the clear water depth, which can cause disasters in practical engineering applications.



(a) (b)

Figure 1 Water depth change over different slopes: (a) 5% slope channel; and (b) 1% slope channel

CONCLUSIONS

Over steep slopes, the siltation of the riverbed surface caused by strong sediment transport is severe, which causes significant increase of the water level. The grid methods can not accurately simulate the large deformation and moving boundary due to the distortion of meshes. The SPH method is a mesh-free method and has advantages in dealing with these problems and can solve difficulties encountered by grid methods. The numerical simulation results preliminarily show that the water level can increase more than twice when the sediment supply intensity is about 3 times higher than the maximum downstream sediment transport capacity in the mountainous rivers.

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