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Computational Modeling of Density Current over Rough and Uneven Bottoms

Yijiu Jiang*, Xiaofeng Liu† and Rusen Sinir††

* University of Texas at San Antonio
Department of Civil and Environmental Engineering
e-mail: jaq526@my.utsa.edu

† University of Texas at San Antonio
Department of Civil and Environmental Engineering
One UTSA Circle, San Antonio TX 78249 USA
e-mail: xiaofeng.liu@utsa.edu, web page: http://engineering.utsa.edu/~xiaofengliu/

†† University of Texas at San Antonio
Department of Civil and Environmental Engineering
e-mail: rusensnr@gmail.com

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Summary. The dynamics of density currents over rough and uneven bottoms are investigated by numerical simulations. Methods are developed to represent the surface geometry of regularly arranged shaped bottom and irregularly shaped rough bottom. Large eddy simulations (LES) are conducted to calculate the dynamics of density currents over various types of rough bottoms. Numerical methods were developed to deal with the bottom shapes. The results of front positions and velocities obtained from numerical simulations are compared with laboratory experiments.

1 INTRODUCTION

Density currents occur frequently in both natural and industrial flows. The density difference between two different fluids can be caused by salt, temperature or other conservative scalars. The development of density currents over smooth bottom has been studied intensively. However, the boundary of the developing density current is usually far from smooth and horizontal. The effect of the boundary over which the density current passes has been investigated during the past years. For example, Bonometti et al.[1] investigated the wall effects on the development of density current and the energy dissipation using DNS; Acton et al.[2] investigated 2D density current flow over porous medium.

In this work, rough and uneven bottoms are considered in our large eddy simulations (LES). The configuration we considered is the lock-exchange flow. For comparison, laboratory experiments were also done in a 12ft flume with two fluids of different density, which were initially separated by a gate in the middle of the flume. Fresh water (1000 kg/m^3) and salty water

(1010kg/^{3}) were used as the two fluids. More details about the experiment can be found in Jiang and Liu[3].

The structure of this paper is as the following. First we will introduce the numerical models. The generation of the meshes, which is apparently difficult for rough bottoms, will be discussed. Then the results of the simulations will be presented. At the end, this paper will be concluded with some discussions.

2 NUMERICAL MODELS

2.1 LES model and code

Large eddy simulations (LES) are conducted using the open source computational fluid dynamics code OpenFOAM[4]. It is an open source computational fluid dynamics (CFD) code and is freely available. OpenFOAM is primarily designed for problems in continuum mechanics. It uses the tensorial approach and object oriented techniques[5]. OpenFOAM provides a fundamental platform to write new solvers for different problems as long as the problem can be written in tensorial partial differential equation form. For all the LES simulations, a one equation eddy viscosity model is used. The filter width model (delta) is chosen as the cubic root of the cell volume.

2.2 Meshing strategy for roughness elements and uneven bottoms

To model the roughness element and the irregularly shaped bottoms, it is very challenging due to the randomness. Sometime it might not be possible to generate a body fitted mesh for the domain. To make matters more complicated is that on many occasions the exact shape and arrangement of the bottom is not available. To consider the effect of the bottoms, these challenges should be considered and an affordable solution needs to be proposed.

Unfortunately, there is no general technique which can be used for all cases. Depending on the regularity of the bottom, we used two different strategies. For simple cases such as regularly arranged shapes, we generated body fitted meshes. The surfaces of these rough elements are fully resolved and faithfully represented in the model. This method can only be used to certain extend since it is very tedious and prone to error.

On the other hand, body fitted meshes are not feasibly for irregularly shaped rough elements. Instead, we represent them in our model using immersed boundary method (IBM) which can use a simple fixed grid[6]. A new IBM method based on unstructured mesh has been developed in our group based on the OpenFOAM platform. The reasons that we develop an IBM method on unstructured mesh are the following. First, unstructured meshes are versatile to model arbitrary domains and it is much easier to model other parts. And secondly, the OpenFOAM platform we use is purely based on unstructured meshes.

The use of immersed boundary method only partially solves the problem. The other challenge for irregular rough elements is how to know their arrangement in space. In natural river and ocean environment, the roughness arrangement (sand and gravels) is the result of their dynamical transport process. Numerical models should capture the dynamics of motion for each roughness element. This turned out to be another very difficult problem when the number of elements increases and their sizes varies. The tools of collision detection and rigid body dynamics can be used to arrange then. Collision detection is a fundamental problem in many computer based research and applications, such as robotics, computer animation, physically-based modeling and even computer games, because one object's motion is controlled by collisions with others and by its own dynamical constraints. Collision detection algorithms have been extensively studied and many efficient algorithms have been proposed[7, 8]. In our study, a method to physically arrange them according to computer graphics and collision detection theories has been developed.

In this paper, four bottom cases are considered. They represent different bottom roughness conditions, namely smooth flat bottom, sine-shaped bedforms, half ping-pong balls paved bottom, and gravel paved bottom (see Figure 1). For all four cases, the excessive density ratio is 0.01. The domain is 12 ft long, 1 ft wide and 0.92 ft deep. The gate was positioned in the middle of the flume. Bottom slope of all cases were zero. Results of front positions and velocities obtained from experiments and numerical models are compared. This research demonstrates the feasibility of our proposed method for investigating the rough bottom effects on density current and provides a good computational tool.

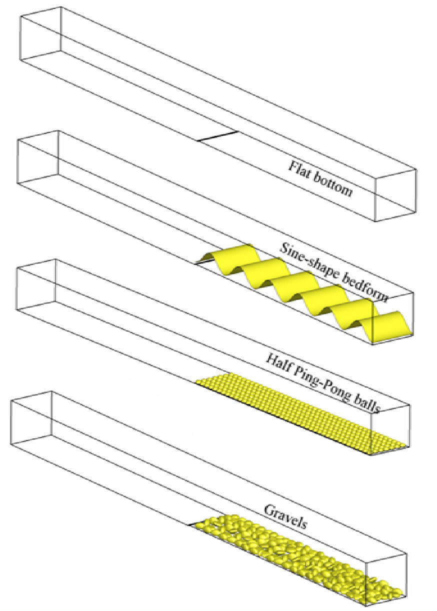


Figure 1. Configurations of the four roughness cases (adapted from Jiang and Liu, 2012)

In this study, we used OpenFOAM's meshing tools for these four different cases.

- For the flat bottom case, the native *blockMesh* tool was used to generate a mesh with 2.67 million hexahedral cells.

- For the sine-shaped bottom case, a background mesh was generated as in the flat bottom case. Then the sine-shaped portion was deformed to its position by using the *moveMesh* tool[9].

- For the case of half ping-pong balls, we used the native *snappyHexMesh* tool of OpenFOAM. This utility generates 3-dimensional meshes containing hexahedra (hex) and split-hexahedra (split-hex) automatically from triangulated surface geometries in Stereolithography (STL) format[4].

- For the case of gravel bottom, we digitized them first use our 3D laser scanner. Then they were placed in the bottom of the domain by our collision detection and rigid body dynamics tool. To be close to experiment condition, manual interaction with the tool was done at the end of the simulation to move some gravels around. The resulting arrangement of the gravels is physical. In the experiment, only one layer of gravels (total count 216) was paved on half of the flume bottom. Immersed boundary method was used for these gravels. However, no turbulence modeling was considered due to the complexity of the code.

3 NUMERICAL SIMULATION RESULTS

In this section, we present some of the simulation results. There are a lot of details revealed by the model (for example, see Figure 2). Due to the length limitation, we will only discuss part of it. In general, due to the roughness and unevenness, it is more difficult for density current develop. The retardation effect is very clearly seen in the result.

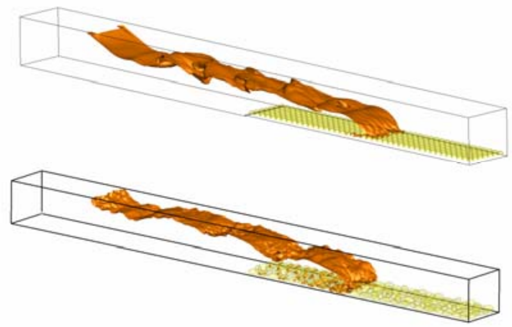


Figure 2. Example plots of density current over half ping-pong balls and gravels

For the case of sine-shape bottom, the front has to first climb up stoss side and then decline on the lee side which consumes energy. In Figure 3, a typical process of the front travels over a sine-wave is plotted. We observed a clear "climbing" and "declining" cycle. The front first impinges onto the stoss side and is pushed upwards. Then the front eventually loses its upward momentum and starts to decline under the influence of gravity. The front starts to fall back to the lee side and accelerate again. This cycle repeats itself.

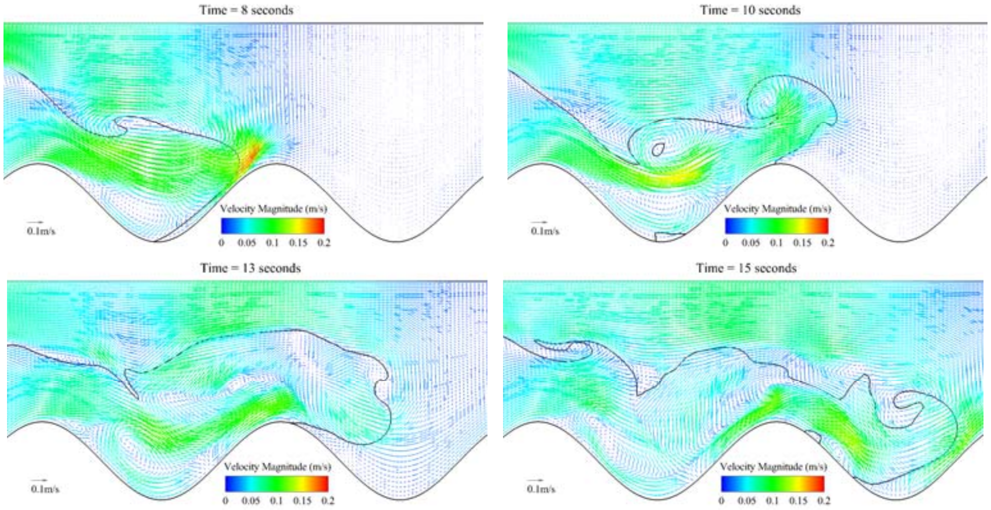


Figure 3. Typical development of the front over one bottom sine-wave

The comparison of the front locations and velocities are plotted in Figure 4. We observed good agreements between numerical modeling and experiment. For flat bottom, the agreement is excellent. The numerical model slightly over-predicts the front velocity. It is interesting to see the velocity development of density current over large sine-shaped bedforms. Due to the cycle of "climbing" and "declinig", the velocity of the bottom front oscillates depending on its position relative to the sine waves. The front velocity alternates between accelerating and decelerating which is clearly demonstrated by the large amplitude of the velocity curve.

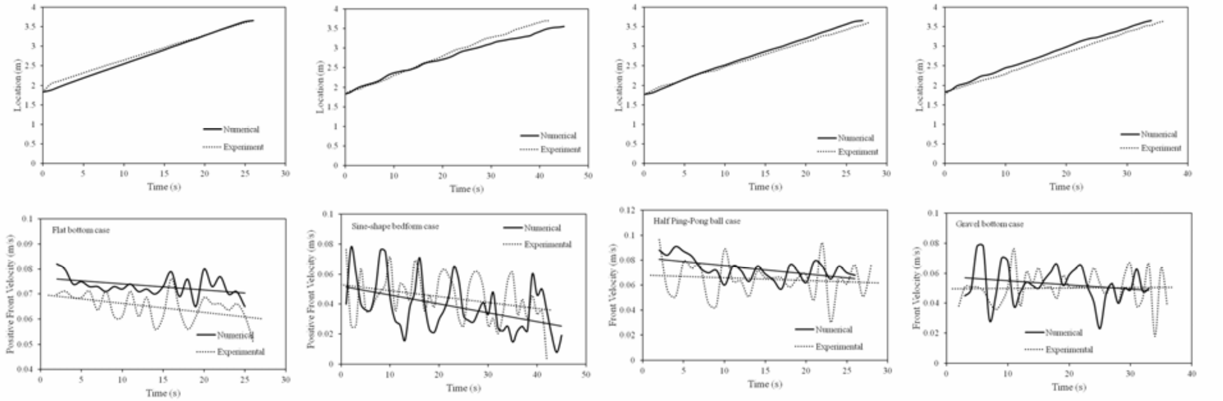
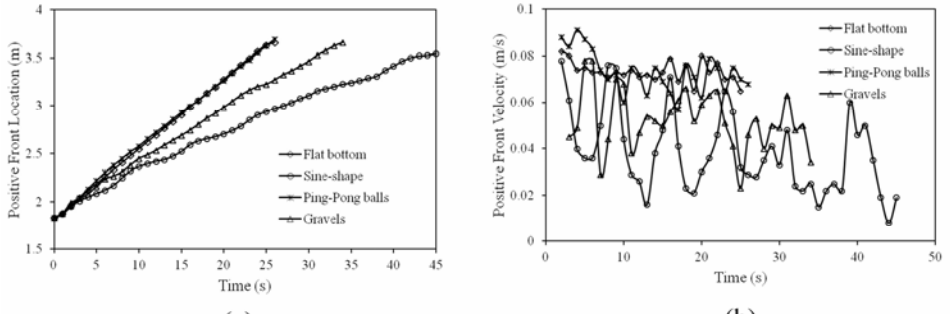


Figure 4. Comparison between numerical and experimental results for front location and velocities for the four cases

To compare the effects of the bottoms, the numerical results for all the four cases are plotted in Figure 5. It is obvious that the rough bottoms have more significant impact on the fronts which directly interact with them. The positive front over the flat bottom reaches the end of the flume almost at the same time as the ping-pong ball case, which indicates that the roughness due to the ping-pong balls has minimal effect. This conclusion needs to be further verified by experiments in longer flumes since the roughness might need more distance (and time) to work on the front.



(a) (b)

Figure 5. Comparison of numerical results for front locations and velocities for different bottoms: (a) Front location, (b) Front velocity

4 CONCLUSIONS

New numerical methods and strategies have been proposed to deal with the computational challenges associated with the density current over rough and uneven bottoms. There is no "one-fit-for-all" method. In particular, the innovation of using collision detection and rigid body dynamics to generate gravel beds and the new immersed boundary method provide a good way reveal more details of the dynamical process. From the simulations, we found that the bottom condition is of great importance for the overall development of the current.

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