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Simulation of floating debris in violent shallow flows

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Abstract

Storm surge and tsunami may induce violent shallow flows and carry dense debris, causing tremendous damage to human lives, buildings and structures. This work presents a series of laboratory experiments to investigate the debris movement in the extreme flows. Subsequently, a new modeling tool featured with a finite volume shock-capturing hydrodynamic model fully coupled with a discrete element model is introduced. A new coupling method totally depending on the hydrodynamic characteristics is proposed to simulate the complex debris-enriched floods induced by tsunamis or storm surges. The experimental measurements are used to validate the reliability of the coupled model. The numerical results agree satisfactorily with the experimental measurements, demonstrating the model's capability in simulating the complex fluid-debris interactions induced by violent shallow flows.

1 Introduction

In recent years, extreme marine disasters have become more frequent, e.g. the 2004 tsunami, 2011 Japan tsunami, 2012 hurricane Sandy, among many others, leading to catastrophic consequences to both people and their properties [1, 2]. One of the striking features of these large-scale disaster events is the dense floating debris of different shapes and sizes carried forward overland by the advancing flood front. Field investigations imply that water flow alone is much less destructive than the debris-enriched flow during a tsunami run-up event [3].

However, the role of floating objects is rarely considered in the design codes for flooded and coastal areas. A number of physical modelling studies and theoretical analysis have been carried out to understand the basic behaviours of floating objects driven by surges. Riggs *et al.* [4] conducted full-scale and flume experiments to test the velocities and impact forces of a wood log and a shipping container under different flow conditions. Nistor *et al.* [5] and Goseberg *et al.* [6] introduced a series of basin experiments using a novel technique to track debris in real time. A horizontal platform with a vertical quay wall was constructed in the basin to reproduce the flow environment in a typical container-stacking harbour under tsunami attacks. The particle-tracking technique was enabled by the so-called 'Smart Debris' system that used motion sensors to record the trajectory, orientation and acceleration of

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individual object. Initiated by a solitary wave, the maximum longitudinal displacements and spreading angles were recorded to study the detailed movement of down-scale shipping containers during a tsunami impact. Stolle *et al.* [7] performed flume experiments to examine the trajectory and velocity of the debris in dam-break hydrodynamic conditions. Their work showed that statistical characteristics of the debris motion could be determined and the lateral displacement of the debris could be evaluated using a normal distribution. However, these physical model experiments are limited to the laboratory environments and the understanding of the complex dynamics of floating debris is still at the preliminary discussion stage.

Theoretical analysis has also been carried out following laboratory experiments to better understand and describe the interaction between fluid flow and floating debris. Matsutomi *et al.* [8] carried out experiments to discuss the debris concentration at the surge front of a dam-break flow, and introduced a simple theoretical model. The model adopted the notion of the conventional bore theory to estimate the velocity of floating debris. The resistance induced by the floating bodies piling up at the surge front was found to increase bore depth but decrease debris velocity and bore front propagation. The debris velocity was found to be always less than or equal to the bore front velocity. Imamura *et al.* [9] conducted experiments in an open channel with cubic and rectangular blocks released in dam-break flows to investigate the boulder transport process during a tsunami. They proposed a theoretical model based on force balance of the boulder in contact with the ground, taking into account various transport modes, including saltation and rolling. Shafiei *et al.* [10] recorded the accelerations of debris in dam-break flow conditions utilizing an embedded tracking sensor. The equation of debris velocity was derived using a force balance theory assuming that debris entrainment begins after the leading edge of the bore passes the debris and that average stream-wise velocity behind the bore is constant. These theoretical analysis works have tried to understand and interpret the physical processes induced by the interaction between fluids and solids. But these studies are all developed under idealised or simplified conditions and are difficult to extend to wider practical engineering applications.

Numerical modelling as a more adaptable research and practical tool has been increasingly adopted to simulate the interaction between fluid and debris. In the field of river hydraulics, Hopkins and co-workers have attempted to develop strategies to couple shallow water models with discrete element models (DEM) to simulate the movement and accumulation of floating ice floes in channels [11]. However, the floating objects as observed during a tsunami or storm surge event are much more complex than ice floes, including objects of different size and shape, e.g. cars, houses, shipping containers, lamp poles, etc. Stockstill *et al.* [12] developed a one-way fluid-to-solid coupling model using a finite-element shallow water dynamic model and DEM to simulate the interaction between floating objects and navigational structures in the river channel. However, these models, lack of shock-capturing capability, cannot be directly applied to simulate the floating debris driven by the more violent flows caused by tsunami or storm surge.

Recently, attempts have also been made to couple Smoothed Particle Hydrodynamics (SPH) with DEM to simulate the dynamics of floating debris. For example, Ren *et al.* [13] presented a vertically 2D two-way SPH-DEM model to simulate the interaction between waves and the massive irregular blocks on a slope. The blocks were impacted by wave-induced hydrodynamic pressures, and the fluid-solid interaction was considered through an interactive force balance approach. Canelas *et al.* [14] introduced a fluid-solid interaction model by incorporating a distributed-contact DEM in the SPH framework. The boundary particles of the rigid bodies were taken as fluid particles for coupling and the contact forces were considered as a combination of a repulsion force and a damping force. The model was able to simulate the motion of individual particles and was validated comparing with experimental data [15]. Robb *et al.* [16] developed a two-way coupled SPH-DEM model for simulation of small-scale river ice jams and other similar problems involving free surface flows containing solids. Both fluid-solid and solid-solid interactions were resolved using a partial Riemann solver, and the force exerted by the solid on the fluid was calculated through SPH interpolation of neighbouring fluid particles. But, the numerical instability inherent to the SPH method was considered to be an issue that may lead to the fluctuation of calculated wave forces [13]. There are also several other attempts using SPH to simulate free-surface flows and the transport of moving bodies simultaneously [17, 18]. However, these models also cannot be directly applied to predict the dynamics of floating debris induced by a tsunami or extreme flood event because SPH models are computationally too demanding for large-scale applications [19].

Therefore, there is a lack of the physically based understanding of precisely how floating objects interact with a propagating wave front; the development of sophisticated numerical models to represent the complex fluid-debris-structure interactions is still at a preliminary stage [19]. It is necessary to develop a computationally more efficient model suitable for robust simulation of the complex fluid-debris-structure interactions in a more violent hydrodynamic context. Herein, the aim of this work is to investigate the physical mechanism of the interaction between extreme flows and debris through laboratory experiments. The experimental data are then used to calibrate and validate a new fully coupled model consisting of a shock-capturing shallow flow model with a DEM, which has a great potential for practical engineering applications.

2 Laboratory experiments

(a)

(b)

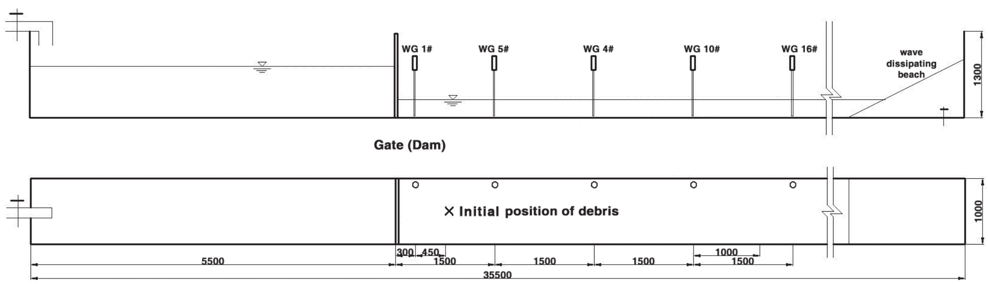


Figure 1: The flume and laboratory setup: (a) vertical view; (b) horizontal view (unit: mm).

(a) (b)

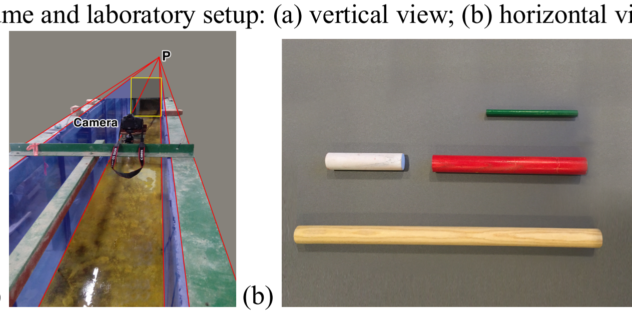


Figure 2: Photo of: (a) Camera and flume in one-point perspective; (b) Four cylindrical debris model.

A series of flume experiments were designed and carried out at the hydraulic laboratory in Hohai University, China. The flume is 35.5 m long, 1 m wide and 1.3 m deep. The bottom of the flume was painted in yellow. The two sidewalls of the flume are made of glasses supported and connected by green steel brackets, and both sidewalls are marked with tapes every 0.5 m during the experiments to better extract the data of debris positions. The experimental layout is illustrated in Figure 1 with a gate installed at the upstream section to separate the flume into two parts with different water levels. During the experiments, the extreme flow conditions were created by instantly opening (less than 0.15s) the gate to generate dam-break waves [20]. The initial position of debris model is set at 0.75 m downstream side of the gate (6.25 m from the left boundary). Five calibrated wave gauges (WG) installed along one side of the channel were used to record time histories of water depth without blocking the debris.

A digital camera mounted at the top of the flume (1.5 m behind the WG 16#) was used to capture the flow dynamics and the motions of debris, as shown in Figure 2(a). The size of the record videos was set to be 1028 pixel × 720 pixel with 50 frames per second. Figure 2(a) also shows the composition principle of one-point perspective used in following graphic analysis. The part of the photo except the flume is covered in grey for clearer performance, and all auxiliary lines were made in the graphics processing software (*Photoshop*) to make sure straight. The flume is made up of lines either directly parallel with the camera's sight (red lines) or directly perpendicular (horizontal yellow lines), and all parallel red lines converge at a vanishing point (P). Hence, the photo of flume conforms to one-point perspective principle and the video token during the experiments can be then analysed in this way. The translucent blue covering area represents the glass sidewalls of the flume, and the rectangular shadow plane in the yellow frame is the plane of the gate. Figure 2(b) shows four different sizes of cylindrical woody debris used in the physical experiments. Their colours and sizes are listed in Table 1. Over 15 experimental tests were performed with different debris and different water depth upstream and downstream of the gate, including the dry bed cases. Debris of different sizes was used in each test. The initial water levels upstream and downstream of the gate of all tests and corresponding debris models are shown in Table 2.

Debris	**Colour**	**Length (m)**	**Radius (m)**
D1	Green	0.12	0.01
D2	White	0.10	0.02
D3	Red	0.20	0.02
D4	Nude	0.4	0.02

Table 1: The detailed information of experimental debris

Test Number	**Initial upstream water level (m)**	**Initial downstream water level (m)**	**Debris**
Case 1	0.2	0	D2, D3, D4
Case 2		0.1	D1, D2, D3, D4
Case 3	0.3	0	D2, D3, D4
Case 4		0.1	D1, D2, D3, D4
Case 5	0.4	0	D2, D3
Case 6		0.1	D2, D3

Table 2: Initial water levels and corresponding debris models

3 Coupled shallow water and DEM model

In this section, the fully coupled model consisting of a shallow water equation model and a DEM is introduced for simulation of debris-enriched shallow flows.

3.1 Shock-capturing shallow water equation model

The 2D non-linear shallow water equations (SWEs) have been widely adopted to describe the hydrodynamics of shallow water flows including tsunamis and storm surges. The dimensionality of the 2D SWEs can be reduced further to 1D if the flow is homogeneous in one of the horizontal dimensions:

$$\frac{\partial \mathbf{q}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} = \mathbf{s} \quad (1)$$

where t and x represent respectively the time and x coordinates (flow direction), and **q**, **f** and **s** are the vectors containing the flow variables, fluxes and source terms. The vectors are provided as follows

$$\mathbf{q} = \begin{bmatrix} \eta & uh \end{bmatrix}^{\mathrm{T}}; \ \mathbf{f} = \begin{bmatrix} uh & u^2h + g(\eta^2 - 2\eta z_b)/2 \end{bmatrix}^{\mathrm{T}}; \ \mathbf{s} = \begin{bmatrix} 0 & -\tau_{bx}/\rho - g\eta \partial z_b/\partial x + S_{vx} - S_{px} \end{bmatrix}^{\mathrm{T}} \quad (2)$$

where η and z_b represent the water surface elevation and bed elevation above datum with $h = \eta - z_b$ being the total water depth; u is the depth-averaged velocity; g is the acceleration due to gravity; ρ denotes the water density; $-\partial z_b/\partial x$ defines the bed slope; τ_{bx} is the bed friction stress; S_{vx} is the turbulent (viscous) term; and S_{px} contains the extra forces to facilitate the balanced force coupling with a DEM model, which will be introduced in Section 3.3.

The above SWEs are solved using a second-order finite volume Godunov-type scheme implemented with an HLL approximate Riemann solver for evaluating interface fluxes. The second-order accuracy in both space and time is achieved through a two-step MUSCL-Hancock method. Detailed implementation of the numerical method can be found in [21].

3.2 Discrete element model

In a discrete element model [22], the following discretized equations are normally used to calculate the translational and rotational motions of the elements:

$$m_i \frac{d\mathbf{w}_i}{dt} = \mathbf{F}_i^p + \mathbf{F}_i^f + \mathbf{F}_i^g; \; I_i \frac{d\boldsymbol{\omega}_i}{dt} = \mathbf{T}_i^p + \mathbf{T}_i^f \tag{3}$$

where i is the index of element/particle, m_i and I_i are the mass and moment of element i; $\mathbf{w}_i$ and $\boldsymbol{\omega}_i$ are the velocity and angular velocity; $\mathbf{F}_i^p$ and $\mathbf{T}_i^p$ are the sum of contact forces and torques acting on element i by other elements or objects; $\mathbf{F}_i^f$ and $\mathbf{T}_i^f$ are the sum of fluid forces and torques on the element; and $\mathbf{F}_i^g$ represents the gravity force.

For each particle, the combined forces and torques are used to calculate the acceleration, velocity and displacement at every time step. In this preliminary study, circles or circular discs are adopted to idealize the floating objects.

3.3 Coupled model

Buoyancy, hydrostatic and hydrodynamic forces are taken into account when coupling the SWE model with DEM. In the vertical direction, the buoyancy is calculated as

$$F_i^b = \rho g V_i \tag{4}$$

where V_i is the volume of fluid displaced by the particle under consideration, which may be quantified differently for particles that are “completely submerged” and “floated”.

In the horizontal direction, hydrostatic and hydrodynamic forces are calculated from the flow variables predicted by the SWE model. The total pressure p_i^h at an arbitrary point on particle i is given by

$$p_i^h = p_i^s + p_i^d = \rho g z + \rho\left(\beta u - w_i\right)^2 \tag{5}$$

where p_i^s and p_i^d are the static and dynamic components of the point pressure, respectively; z is the water depth from the surface to the point of interest; u and w_i are the depth-averaged flow velocity and the velocity of particle i, obtained respectively from the SWE model and DEM; β is a correction factor introduced to better estimate the surface flow velocity. The total fluid impact moving debris/particle i can be obtained as follows

$$F_i^h = p_{i\,B}^h S_B - p_{i\,F}^h S_F \tag{6}$$

where the subscripts, B and F, indicate the ‘Back’ and ‘Front’ of the particle, and S_B and S_F are the areas of ‘Back’ side and ‘Front’ side of the particle submerged in the water. The SWE model will be coupled to the DEM by adding the counter-forces as source terms in the governing SWEs as given in Eq. (2), i.e.

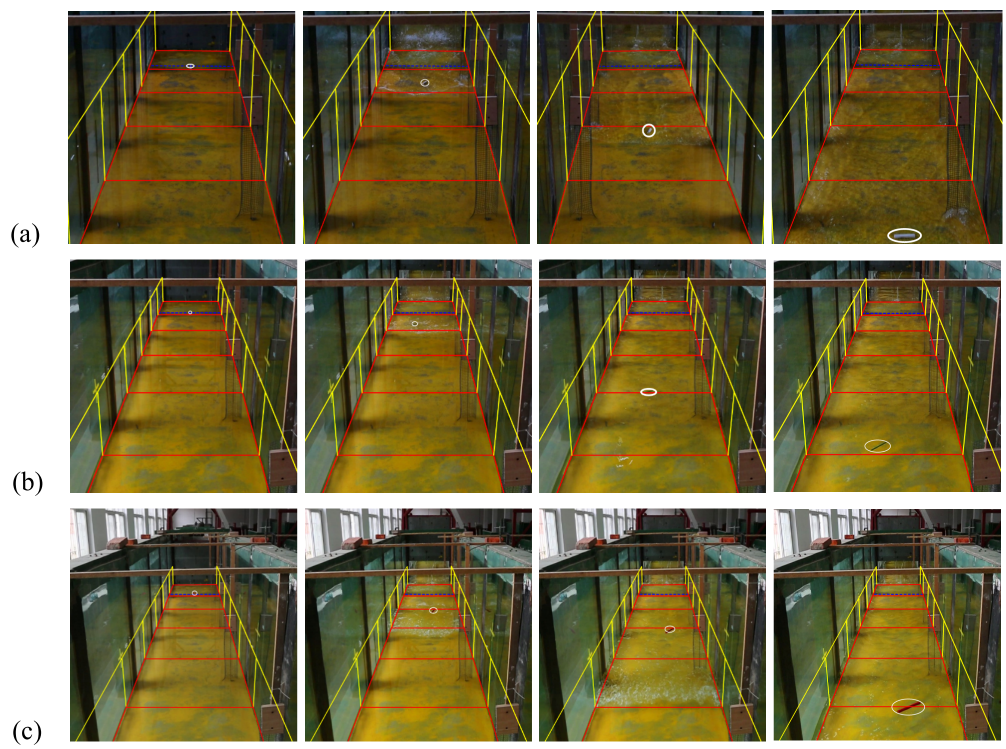
$$S_{px} = {p_i^h}/{\rho} \tag{7}$$

4 Results and discussion

This section presents and discusses the laboratory observations, which are then used to validate the coupled floating debris model introduced in the last section.

4.1 Laboratory Observations

Videos have been recorded during the experiments to capture the flow and debris process. Each frame of the video files was extracted for one-point perspective analyse. To reflect the tape marks on the side wall, the vertical yellow solid lines on the side wall were drawn digitally to indicate the distances from the gate. The position of the horizontal red solid lines were determined by the intersections of the yellow lines the boundaries of the bottom of the flume. In order to determine the displacement of the floating object moving in the flume, the relationship between the two red lines was also analysed by perspective principle. Figure 3 presents the screenshots of some representative tests at different times after the gate was opened. The wooden object is outlined in white circle to highlight its location. The blue dotted line represents the starting position of the floating object. In order to show more clearly, only the red solid lines with 1 m interval from the gate are drawn, which means from the top of each screenshot, the red solid line respectively represents x = 5.5 m, 6.5 m, 7.5 m, 8.5 m, and so on.



(d)

(e)

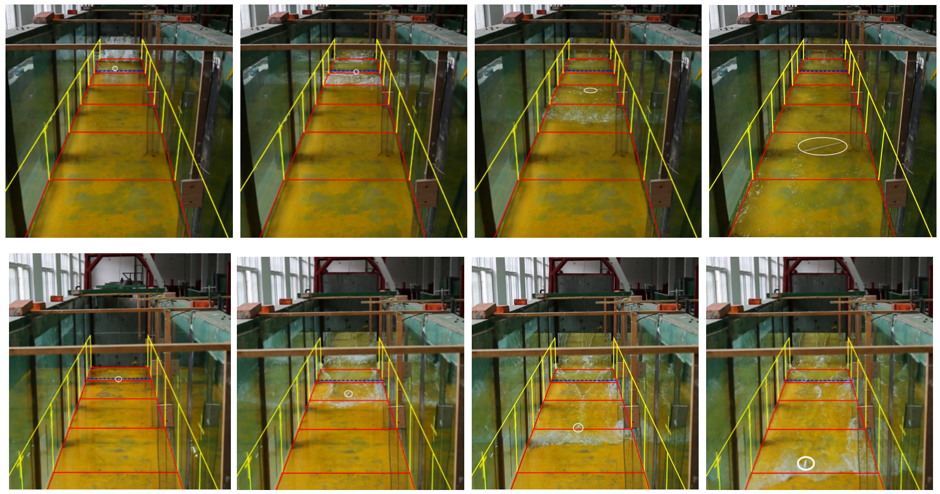


Figure 3: Screenshots of the video recording the motion of debris at different time: (a) Case 1 with D2 at $t = 0$s, 1s, 2s and 3s; (b) Case2 with D1 at $t = 0$ s, 2 s, 6 s and 8 s; (c) Case 4 with D3 at $t = 0$ s, 2 s, 3 s and 5 s; (d) Case 4 with D4 at $t = 0$ s, 1 s, 2 s and 4 s; (e) Case 5 with D2 at $t = 0$ s, 0.8 s, 1.3 s and 1.6 s.

4.2 Numerical Model Validation

The new coupled model has been successfully applied to reproduce the aforementioned flume experiments. For example, Figures 4(a)&(b) present the results of the simulation carried out for a dry-bed test and a wet-bed test, respectively. The time serious of water depth at WG 5# and the positions of the floating object in the x-direction are compared satisfactorily with experimental measurements. Successful reproduction of these experimental tests demonstrates the model's ability in simulating the complex motions of floating debris driven by violent dam-break flows.

(a)

(b)

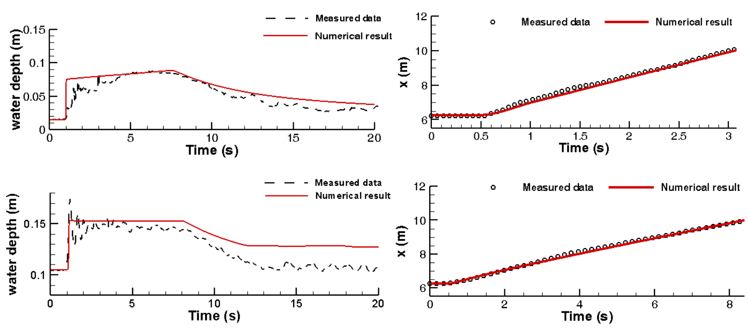


Figure 4: Predicted and measured time serious of water depth and x-position of the floating object for (a) Case 1 with D2; (b) Case 2 with D3.

5 Conclusion

In this paper, physical experiments have been conducted to observe and better understand the physical processes of floating debris moving in extreme hydrodynamic conditions. The trajectory data of debris is extracted by analysing video using graphic composition principle. A new modelling strategy is proposed to simulate the complex behaviours of floating debris driven by shallow flows under extreme hydrodynamic conditions. A shock-capturing finite volume Godunov-type numerical model and a DEM are coupled through the balance of buoyancy force, hydrostatic and hydrodynamic force.

The new coupled model has been successfully validated against flume experimental tests, showing the model's ability to quantitatively capture the dynamics of the floating objects. The coupled model has great potential for practical applications.

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