MODELLING URBAN COASTAL FLOODING THROUGH 2-D ARRAY OF BUILDINGS USING SMOOTHED PARTICLE HYDRODYNAMICS

Sohaib Alahmed[1] and Qingping Zou*

A Smoothed Particle Hydrodynamics (SPH) method is used to investigate the flood characteristics occurring in an idealized city with two different building layouts: aligned layout and 22.5o skewed layout with respect to the direction of the incoming flow. The model results show that the water elevation is higher for the skewed city layout than that for the aligned city layout. The force due to the flood impact on the majority of buildings tend to be higher for the former than that for the latter. The complex flow features including a hydraulic jump during the flooding event are well captured by the SPH model.

Keywords: smoothed particle hydrodynamics, flood impact force, urban coastal flooding, urban coastal inundation, SPH.

INTRODUCTION

Coastal flooding in urban areas can cause severe damages and casualties. The destructive potential of urban flooding can be assessed by determining the inundated water level, the flow velocity and the impact force on the structures. It is, therefore, important to predict these quantities accurately to characterize the coastal flooding and mitigate the flood risk.

Recently, Smoothed Particle Hydrodynamics (SPH) has become one of the most popular methods to analyze the free surface flow problems including the urban flooding (Ghazali and Kamsin 2008; Dalrymple and Herault 2009; Barreiro et al. 2013; Wu et al. 2013). SPH has been employed to investigate wave-structure interactions, wave impact and green water effect (Monaghan et al 2003; Gesteira and Dalrymple 2004; Vandamme et al. 2011; Shao 2009; Vandamme et al. 2012; St-Germain et al. 2013; Liu et al 2014; Cunningham et al. 2014; Lin et al 2015; Altomare et al. 2015; Aureli et al. 2015; Sun et al. 2015). Although slamming force evaluation is a critical consideration for structure design and safety, to the best of our knowledge, hardly any comprehensive studies has be conducted to evaluate the impact force on 2-D array of buildings using SPH.

In this study, we investigate the characteristics of a 3D flash flooding event in a coastal city using a Smoothed Particle Hydrodynamics (SPH) method coupled with Graphical Processing Unit (GPU). In contrast to previous studies (e.g. Altomare et al. 2015; Sun et al. 2015), we examine the net forces on the buildings due to wave impact. Also, we consider the effect of the building layout on the flooding behavior and characteristics. Our numerical results will be used to assess the robustness and efficiency of this method for predicting the complex flow features during urban flooding events.

METHODOLOGY

Smoothed particle hydrodynamics is a free surface flow solver adapted from the smooth particle method to simulate discrete particle motion (Monaghan 1992, 1994). The Lagrangian approach is used in SPH to exemplify the fluid using individual particles each of which has designated its physical quantities such as pressure, velocity, density, and mass. Thus, there is no need for computational grids (e.g. finite element). It uses the integral interpolation to represent a given function A in terms of its value as discrete particles as follows

$$A\,(r_a) = \sum_b m_b \frac{A_b}{\rho_b}\, W(r_a - r_b, h) \tag{1}$$

[1] Department of Civil & Environmental Engineering, University of Maine

*Corresponding author: qingping.zou@maine.edu

where the subscripts a and b refer to particles a and b, m_b and ρ_b denotes the mass and the density of particle b respectively, A_b denotes the value of the function at the location r_b of particle b and h is the smoothing length used in the weighting function $W(r_a - r_b, h)$.

In SPH, the momentum for the particle b of mass m and velocity vb can be expressed as

$$M_b = m_b v_b. \tag{2}$$

The total force on a structure due to wave impact can be evaluated by the summation of the forces acting on each individual particle

$$F = \sum_{i=1}^{np} m_i \frac{dM_i}{dt} \tag{3}$$

where np is the total number of the structure’s particles (Barreiro, 2013)

In the present study, we used the open source DualSPHysics code described by Crespo et al (2015).

MODEL SETUP

The model simulation uses the same layout as that of the experiment conducted by Sandra Soares and Frazão et al (2008). As shown in Fig. 1, a square city layout of 5 × 5 buildings is aligned at a 0o (Case 1) and 22.5o (Case 2) relative to the approach flow direction. Each building is 0.3 m wide and 0.3 m long. The heights of the buildings are chosen so that they are not overtopped. Roads are represented by the distance between the buildings, i.e. 0.1 m. The city configurations are located in a horizontal channel with a width of 3.6 m that is located 5 m downstream from the reservoir. The reservoir is 6.75 m long, and 3.6 m wide with initial water level of 0.4 m and 1 m wide opening gate as shown in Fig. 1.

The particle resolution is 5 mm in the current model. More than 73 million particles are generated for the model simulation. We used 54,332,726 particles represent the water for the both cases. The numerical results are recorded each 0.05 seconds over simulation time of 17 seconds. NVIDIA K80's are used as GPUs with 10.5 GB memory for each model. The CPUs used are two Intel E5-2540v3's at 2.6 Ghz with 8 cores each. The two CPU's consists of a total of 16 cores. The computational node has 128 GB of RAM.

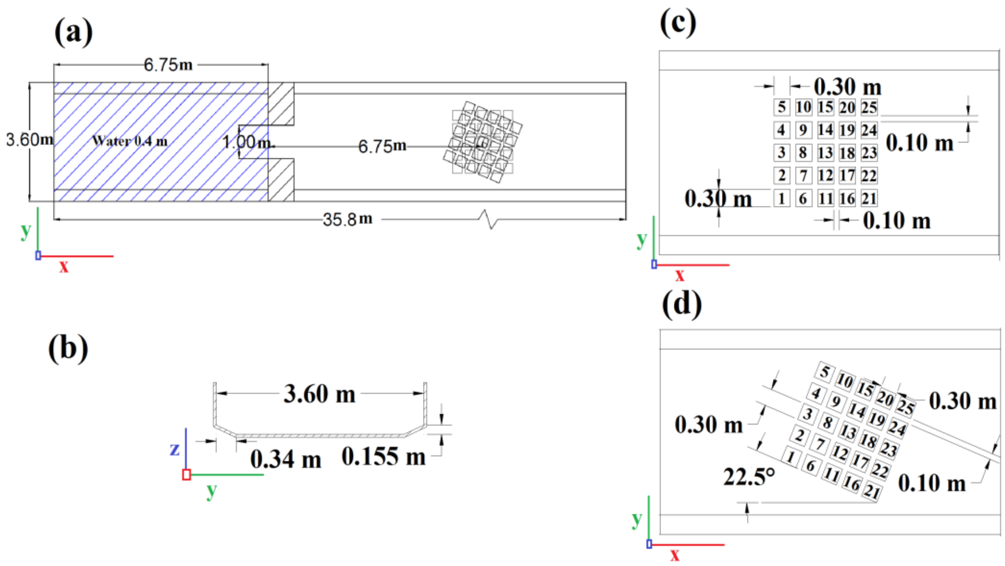

Fig. 1. The model setup: (a) the schematic view for the model setup, (b) the channel cross section, (c) buildings aligned at a zero (Case 1) and (d) buildings aligned at 22.5° angle relative to the approach flow direction (Case 2)

MODEL RESULTS

Water Level

In this work, the water level is examined in order to consider the inundation extent and severity. Due to the extensive amount of water that is released from the reservoir, both building layouts in the coastal cities are inundated after a certain time. Due to different layout of the cities relative to the location of reservoir and approaching flow direction, however, the spatial variation of the water elevation are different for these layouts. The wave collides with the buildings and generates a hydraulic jump at the front of the building arrays. The position, shape and size of the jump varies with the building layout of the cities. Fig. 2 illustrates the inundation distribution at T=5 s.

The water elevation is higher in Case 2 (skewed layout) than that in Case 1 (aligned layout). In Case 2, the city has greater area perpendicular to the flow direction to block the incoming flow. This results in a larger intensity of the hydraulic jump for Case 2 than that for Case 1. Hence, the skewed building layout in Case 2 has more potential to resist the incoming flow than the aligned building layout in Case 1. Thus, more buildings and streets will be flooded if the city is not laid out in the same direction of the potential flooding flow.

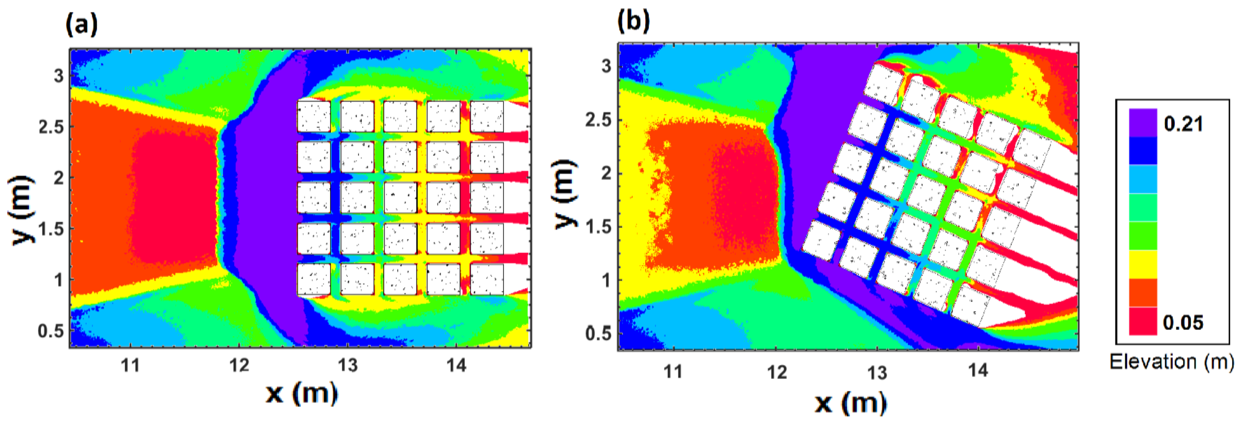

Fig. 2: The water elevation distribution at T=5 s and for buildings aligned at a (a) zero and (b) 22.5° angle relative to the approach flow direction.

Flow Velocity Distribution

The velocity distribution is evaluated in this section because the potential that a flood possesses to cause the damage is related to its flow velocity. Fig. 3 shows the velocity distribution for both Case 1 and Case 2 at the time instant of 5.0 s. The water velocity in the horizontal streets in Case 1 is shown to be higher than that in Case 2 because the streets orientation allows the water to go through without being redirected or blocked. The water velocity in vertical streets is relatively slower in Case 1. The skewed building layout in Case 2 allows the water to flow through the vertical streets faster than that in Case 1.

Flood Impact Force on Building

The characteristics and destruction potential due to the impact force by the incoming flow during the flooding event are examined for these two layouts in this section using the equation (2) and (3) in section 2. Fig. 4 show the magnitude of impact force exerted by the flooding water on building 10 (B10) and building 16 (B16) indicated in the model set-up in Fig. 1.

It is evident from Fig.4 that the impact force on majority of the buildings (18 out of 25) in Case 2 is much higher than the force in Case 1 for the same buildings. In other words, the destruction potential of the flood in Case 2 is significantly greater than that in Case 1. That is because the city layout in Case 2 block the flowing water more than the city layout in Case 1 due to its larger project area perpendicular to the flow direction as well as the increased water elevation at these buildings in Case 2.

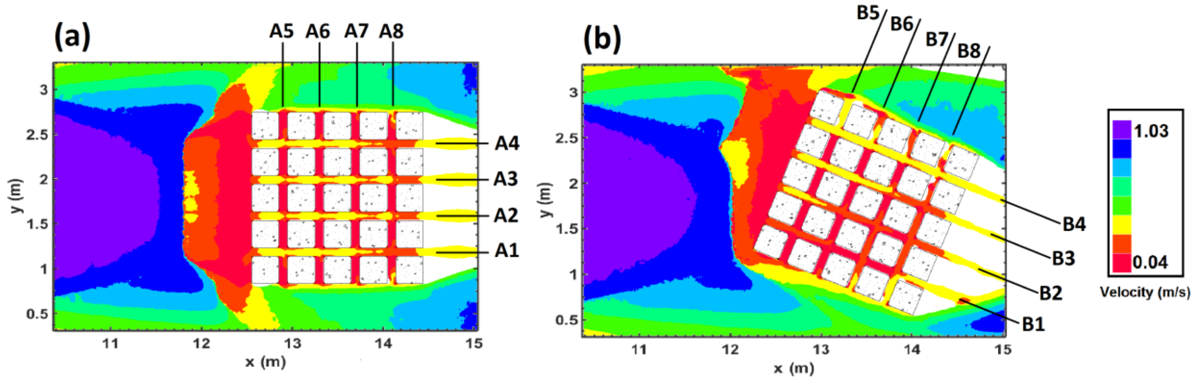

Fig. 3. The velocity distribution for the (a) aligned city buildings and the (b) skewed city buildings relative to the incoming flow at T=5.0 s

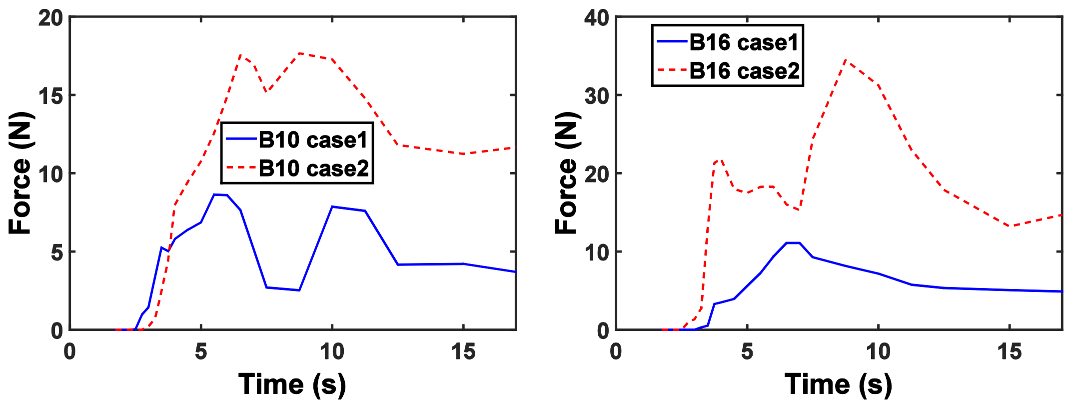

Fig. 4. The net impact force magnitude at building 10 and 16 indicated in figure 1.

CONCLUSIONS

We have presented 3-D modelling results for the influence of the city layout on the coastal urban flooding behavior using a Smoothed Particle Hydrodynamics (SPH) method. In particular, we examined the urban flooding characteristics through a coastal city with two layouts with different orientation relative to the direction of incoming flow during a flooding event. Our numerical results indicate that

a) The water elevation in a skewed city building layout is higher than that in a aligned city building layout.Consequently, therefore, more inundated buildings and streets are expected for the former .

b) The flow velocity in the horizontal streets in the aligned city was higher than that in the skewed city. The velocity in the vertical streets in the aligned city is negligible compared to that in the horizontal street. On the contrary, the flow velocity in the vertical and horizontal streets in the skewed city was both significant. Thus, the induced damage due to the flow velocity would be higher in the skewed city

c) The applied impact force for the majority of buildings in the skewed city is greater than the force in the aligned cities as shown in Fig.2.

In summary, our study indicate that the aligned city is more suitable and has more likelihood to survive a flood event more than the skewed city.

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