Drift Behavior of Automobiles in Tsunami

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It is important to known the movement of large drift, i.e. automobiles, in tsunami and its collision behavior to tsunami evacuation tower, a facility used to protect the safety of life and property in the tsunami-affected areas. For this purpose, laboratory experiments with 80 automobiles colliding with both Bridge type of tsunami tower (with a large distance between pillars) and Conventional tsunami tower (with beams between pillars) are carried out. In addition, a numerical model based on 3D Lattice Boltzmann Method (LBM) is developed for simulating the behavior of drifting automobiles due to tsunami inundation.

Key Words : drift behavior, tsunami evacuation tower, automobiles, Lattice Boltzmann Method

1. INTRODUCTION

The importance of tsunami evacuation tower, a facility used to protect the safety of life and property, is recognized especially after the Great East Japan Earthquake in 2011. A tsunami evacuation tower is usually constructed in plazas or parks with large parking place in the coastal land area, where involve dense population and automobiles but no upland nearby for people to evacuate in case of a tsunami inundation. However, large tsunami drifting debris, such as automobiles, always collides to the pillars of a tsunami evacuation tower and may cause damage to the tower in a tsunami flooding. Worse more, automobiles accumulate in front of the tsunami evacuation tower if the intervals between pillars are not long enough, and repeatedly collide, which may lead to blocking the tower. Hence, study on the movements of large drifts and their collisions to the tsunami evacuation tower becomes one of the key subjects in the design of tsunami evacuation tower.

Numbers of both physical experiments and numerical simulations have been done to study the drift behavior in tsunami run-up. Kumagai et al.¹) established a simple numerical model coupling with a 2D horizontal tsunami and drift bodies with DEM to study the drift behavior of containers and estimate the collision force. Tomita and Honda²) developed a numerical model with the fluid force simply calculated from fluid models of STOC-IC and STOC-ML without drift bodies, to deal with multiply tsunami-drifted vessels colliding with both floating and fixed bodies. Kawasaki et al.³) proposed a numerical solid-gas-liquid phase flow model, based on CIP method and an extended SMAC method, with a series improvements of resolving mass conservation problem, adding LES, developing from 2D to 3D and extending from single rigid body to multiple rigid bodies. Nakamura et al.⁴) applied the 3D coupled fluid-structure-sediment interaction model with a main solver based on an extended N-S equation for computing the incompressible viscous air-water multi-phase flow and three modules including VOF module for air-water interface tracking, IB module for movable structure motion and sediment transport module, to analyze the drift behavior of the container more precisely. However, most of these numerical models disregard the 3D interaction between fluid and large drift, only include the collisions between drift bodies or between drift and other structures.
In this paper, laboratory experiments with 80 automobiles (made of Expanded polystyrene) colliding with both Bridge type of tsunami tower (with a large distance between pillars, short for B-type in the following paragraphs) and Conventional tsunami tower (with beams between pillars, short for C-type) fixed in a hydraulic flume are carried out. Collision number and collision speed of automobiles together with the snapshots taken by high-speed camera are investigated in the experiments. For the numerical study, a 3D numerical model based on Lattice Boltzmann Method (LBM) is applied, and the interactions between fluid and drift, drift and drift can be solved by this method using a link-bounce-back scheme. The present numerical model is verified through the experimental data.

2. HYDRAULIC MODEL EXPERIMENT

(1) Model set-up and experimental method

Using a length scale of 1:60, the hydraulic model experiment is carried out in 11,350×1,490mm concrete hydraulic flume. A distance of 7,488mm is set before the wave propagates to the automobiles. Totally 4 lines of automobiles (80×28×26mm), each line with 20 automobiles and each two lines with an interval of 90mm, are arranged 70mm in front of the tsunami evacuation tower. Other details of the experiment layout are shown in Fig. 1.

Figure 2 shows the dimensions of both B-type (488×88×150mm) and C-type (250×190×150mm) tsunami evacuation tower. B-type tsunami evacuation tower is constructed by 6 cylinder pillars, each of which has a circle section with diameter of 12mm; while C-type tsunami evacuation tower includes 12 cuboid pillars, each of which has a 10×10mm square section. The intervals between two adjacent pillars of B-type tower along the line perpendicular to the wave propagation direction are long enough for two abreast automobiles passing, while those of C-type tower is suitable for one automobile. Since the dimensions of these two tsunami evacuation towers are not identical, we will only focus on the behaviors of drift automobiles colliding against, blocking in front of or passing through the tsunami evacuation towers.

The specific gravity of model automobile is adjusted to 0.235 by installing a weight for the engine part in the front part (see Fig. 3b). This attachment gives a weight distribution of 60:40 for front: rear. Tsunami flooding is generated by pumping water through an open gate in a hydraulic flume, and sponge is used to reduce turbulence. The experimental data are obtained from electromagnetic flow meter, capacitance-type wave height meter and high-speed camera used for PIV. A discharge of 45l/s is applied and the corresponding maximum measured wave height is 3.3cm and average flow velocity is 30cm/s after noise reduction.

(2) Collision number and collision speed

Figure 4 shows the snapshots of automobiles with 4 lines colored by yellow, blue, red and white and numbered Line 4 to Line 1, respectively. Namely, automobiles of Line 4 are located facing tsunami incoming current, while Line 1 is next to the tower. Set the time when the forefront wave propagates in front of automobiles of Line 1 (Fig. 4a,c) as 0s, then Fig. 4b,d show the snapshots of automobiles after 5.0s. More than 10 automobiles accumulated in front of C-type tsunami evacuation tower (Fig. 4d) due to the narrow distances between pillars. This implies when B-type is applied, collision frequency of automobiles to pillars is less as more automobiles can pass through, and when C-type is used, the drag force caused by tsunami increases as the active area (proportional to drag force) is larger. Hence less damage will be expected for B-type tower.
In order to know the characteristics of these two types of tsunami evacuation tower against automobile drifts, the details of collision number and collision speed are listed from Table 1 through Table 4. The collision number is calculated by the sum of the number of automobiles colliding with pillars, and the number of automobiles accumulated in front of the tsunami evacuation tower after collision. As a result, the collision number for B-type is less than C-type, especially for Line 2, where the number is reduced from 6 to 1. In the case of B-type tsunami evacuation tower, automobiles do not stay near the pillars after collision and are swept away by the ambient current, while in the case of C-type, automobiles of Line 1 remain in the vicinity of pillars after collision and accumulate automobiles of the other lines near the front tower.

Table 1  The collision number of automobiles for B-type tsunami evacuation tower.

<table>
<thead>
<tr>
<th>Line</th>
<th>Left pillar</th>
<th>Mid pillar</th>
<th>Right pillar</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Line 2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Line 3</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Line 4</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 2  The collision number of automobiles for C-type tsunami evacuation tower.

<table>
<thead>
<tr>
<th>Line</th>
<th>Pillars</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>No differences</td>
<td>7</td>
</tr>
<tr>
<td>Line 2</td>
<td>between pillars</td>
<td>6</td>
</tr>
<tr>
<td>Line 3</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Line 4</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>19</td>
</tr>
</tbody>
</table>

Table 3 and Table 4 list the collision speeds of automobiles (one random example for each Line), which are calculated from the snapshots taken by high speed camera, and defined as the moving distances of automobiles just before collision over the corresponding short time interval. For instance, the horizontal collision distances between the selected automobile in Line 2 of Table 4 and the end pillar of C-type tower is 20mm, which is calculated from the short straight line from the trace (orthogonal projection on x-y plane), and the corresponding time is 0.142s from the camera frame rate of 120 frames/s. The collision speed of one automobile in Line 4 is twice larger than that in Line 1, because the moving distance of automobile in Line 4 is considerably longer than that in Line 1. Based on the collision speed \( \nu \) given in Table 3 and Table 4, the maximum collision force is calculated as \( F = \frac{m \nu}{\Delta t} = 590kN \), with a reference collision time of 0.01s\(^5\).

(3) Trajectories of the center of automobiles

Because of the symmetry, we only focus on the trajectories of automobiles laid in front of the right half of tsunami evacuation tower. And for simplicity, only automobiles with odd numbers, namely the 1st, 3rd, 5th, 7th and 9th automobiles from the center of tsunami evacuation tower, are analyzed. The results are shown in Fig. 5. In the figure, the black solid circles and squares represent pillars of B-type and C-type respectively, and colors of green, red, blue and yellow are used to sign automobiles of Line 1 to Line 4 respectively. The wave propagates in the y-direction.
In Lattice Boltzmann Method (LBM), the macroscopic fluid can be represented by an aggregation of microscopic virtual particles moving on lattices, and the flow of fluid can be obtained through the calculation of time evolution of streaming and collision processes of these virtual particles. According to Ladd’s LBM model for particle suspension, the fluid-particle interaction can be simulated by the exchange of momentum, due to the application of link-bounce-back scheme for the movable solid particles in the fluid. The authors have extended Ladd’s LBM model for particle suspension with free surface and SGS turbulence model. In this paper, it is further modified to satisfy the rigid boundary conditions of automobiles with irregular shape.

D3Q19 lattice model is applied, as it is necessary to determine the macroscopic variables (density, velocity and momentum flux) from the velocity distribution function. The basic Boltzmann equation is given in

$$f_i(x + e_i \Delta t, t + \Delta t) = f_i(x, t) + \Delta f_i(x, t)$$ (1)

where $f_i(x, t)$ is the particle distribution function (DF), indicating the number of particles with a velocity vector of $i$ direction in the lattice of $x$ position at time $t$, and $e_i$ is the velocity vectors ($i=0, 2, ..., 18$) of each single particle.

The DF of a moving automobile can be shown as

$$f_i = \rho \left[ \frac{\mathbf{j} \cdot \mathbf{e}_i}{c_s^3} + \left( \rho \mathbf{u} \mathbf{u} + \Pi^{eq} \right) : \left( \mathbf{e}_i \mathbf{e}_i - c_s^2 \mathbf{1} \right) \right]$$ (2)

where $\rho$, $\mathbf{j}$ and $\rho \mathbf{u} \mathbf{u}$ are mass density, momentum density and momentum flux $\Pi$, respectively. $\Pi^{eq}$ is the post-collision non-equilibrium momentum flux, which is a function of the non-equilibrium momentum flux $\Pi^{eq} = \Pi - \Pi^{eq}$ with $\Pi^{eq} = p \mathbf{l} + \rho \mathbf{u} \mathbf{u}$. The pressure $p = \rho c_s^2$ takes the form of an ideal gas equation of state with adiabatic sound speed $c_s = \sqrt{\gamma k T}$ ($\gamma = \Delta v / \Delta t$).

Further details of parameters in the above equations together with free surface condition and turbulence term can be found in the authors’ paper.

Link-bounce-back scheme is applied for the moving boundary condition of a solid automobile. It is assumed that the surface boundary nodes (open square in Fig. 6) of an automobile locate in the center of the fluid nodes (solid circle in Fig. 6) and solid nodes (open circle in Fig. 6), and the velocities along links cutting the boundary surface are represented by arrows. Hence, the DFs of moving boundary node can be updated from

$$f_{b_i}(x, t + \Delta t) = f_{b_i}(x, t) - 2\alpha \rho \mathbf{u}_b \cdot \mathbf{e}_b$$ (3)

3. MODIFICATION OF LBM

It can be seen in Fig. 5a and Fig. 5b, trajectories of automobiles far away from the center of tsunami evacuation tower (No.4 and No.5 of all lines) are similar in both B-type and C-type cases, while trajectories of automobiles for No.1 to No.3 of all lines are quite different in those two cases. Automobiles of Y1 (abbreviate for No.1 of Line4 colored by yellow), Y2, B1, B2 curve slightly to the right and then drift straightly through B-type tsunami evacuation tower, while automobiles of R1, R2, B1, B2, Y1, Y2, Y3 bend significantly to the right and bypass C-type tsunami evacuation tower. For the case of B-type, automobiles drift through the tsunami evacuation tower immediately after colliding with its pillars. However, for the case of C-type, automobiles of Line 1 accumulate in front of the tsunami tower after colliding with its pillars and cause the following automobiles dammed one after another. As a result, the flow field changes, and the automobiles appear to significantly drift.
A series of numerical simulations has been performed to investigate the collision speed of automobiles to the tsunami evacuation tower by the change of submerged water depths and flow velocities.

In order to save computation time, a small computation domain of 140×1700×60mm is applied. With this limited computation domain, tsunami flooding current is generated by a dam-break in front of the automobiles (Fig. 7a). No-slip boundary condition, periodic boundary condition, transmission boundary condition and free surface boundary condition are used for the bottom, front and back, right and top sides respectively.

Figure 8 shows the behavior of partly submerged 8 drifting automobiles in front of two pillars located in the center of C-type tsunami evacuation tower. Figure 8a shows the initial position of the automobiles and pillars. Distances between the center of automobiles and the pillar are the same with the hydraulic experiment. The blue and white automobiles are set oppositely to the yellow and red ones, as in the experiment. After 0.17s, tsunami flooding current flows to the front of the yellow automobiles (Fig. 8b), which are then drifted by it and collide to the blue automobiles. Momentum from current flow is transferred to the blue automobiles and makes them drifting together (Fig. 8c). As the simulation goes on, all 8 automobiles are submerged in and drifted by the flooding current. These drifted automobiles collide with each other, and at the time period of 1.3s, the white and red automobiles bypassed the two pillars (Fig. 8d). All these automobiles drift to the pillars in y-direction but against the pillar in x-direction (perpendicular to the wave propagating direction), and have a tendency of bypassing the pillar (Fig.9), which is very similar to the experimental results.

4. SIMULATION RESULTS

A typical initialized automobile is constructed with 6,550 solid nodes, 2,160 surface solid nodes which are adjacent to fluid nodes. The inertia momentums of the automobiles are approximated to the 80×28×26mm polyhedron as shown in Fig. 7. The submerged volume for the calculation of buoyance force is simplified to a pyramid when only a corner of the automobile is submerged, but once one whole edge of the automobile is submerged, the volume is calculated with the length of the edge by its perpendicular submerged surface area of the automobile.
Study on the behaviors of tsunami drifted automobile debris is necessary in the design of tsunami evacuation tower, because automobile debris drifting in the tsunami current can block towers and cause damage to it. Using 80 automobile models, hydraulic experiments of automobiles colliding against both B-type and C-type tsunami evacuation towers are carried out. The results show B-type tsunami evacuation tower is more effective. Larger distances between pillars make more automobiles passing through and as a result, less collision between automobiles and automobiles against towers occur. The drag force caused by the tsunami flooding current decreases due to the less active area when few automobiles block tsunami evacuation towers.

Besides physical experiments, numerical experiments are conducted by using a 3D LBM model for particle suspension, modified for irregular surface boundary shape and extended with free surface part and SGS turbulence term. The numerical results for the B-type tower show that automobiles collide with each other but bypass the pillar of the tsunami evacuation tower. These drift behaviors are also observed in the physical experiment.

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