NUMERICAL SIMULATION OF TSUNAMI CURRENTS AROUND MOVING STRUCTURES

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The paper aims to simulate Tsunami currents around moving and fixed structures using the moving-particle semi-implicit method. An open channel with four different sets of structures is employed in the numerical model. The simulation results for the case with one structure indicate that the flow around the moving structure is faster than that around the fixed structure. The flow becomes more complex for cases with additional structures.

Keywords: numerical simulation; Tsunami currents; bore; moving structures

INTRODUCTION

Tsunami is a well known phenomenon that often strike coastal areas and drowned various types of structures. The height and distance of swashed debris from the coast as well as the strength and run-up height of tsunamis are usually estimated by researchers. Estimating the tsunami-induced currents around structures and as a consequence, the moving patterns of the structures are very complex. The estimation of such complex currents and behaviors of drowned structures are important for designing coastal structures with the view of making countermeasures against tsunami attacks. In order to clarify such complex currents around moving three-dimensional structures as well as the interactions between the currents and the moving structures, the moving-particle semi-implicit method (MPSM) is introduced herein.

MPSM

The moving particle semi-implicit method (MPSM) is a modified particle method developed by Koshizuka and Oka (1996) for solving an incompressible flow. This method is suitable for simulation of complex free surface motion because the method does not use grids. Furthermore, since this method is a Lagrangian method, the calculation of advection terms is not required. The MPSM has been successfully applied to wave breaking (Koshizuka et al. 1998), shipping water on the deck of a ship (Shibata et al. 2009), and validating pressure (Khayyer and Gotoh 2008) as coastal engineering problems. The MPSM can be described as follows.

Discretization Method

Weight function. The MPSM uses a model of interaction among particles for discretizing a differential operator. The interaction between particle i and its neighboring particle j involves a weight function w, as follows:

$$w(r) = \begin{cases} \dfrac{r_e}{r} - 1 & r \le r_e \\ 0 & r_e < r \end{cases} \tag{1}$$

In Eq. (1), r_{ij} is the distance between particles i and j, and the radius of the interaction area is represented by parameter r_e. The particle number density is defined as

$$\langle n \rangle_i = \sum_{j \ne i} w\left(\left|\vec{r}_j - \vec{r}_i\right|\right) \tag{2}$$

which is the sum of the weight function of neighboring particle j. In Eq. (2), the contribution from particle i is not considered. The initial particle number density n^0 is calculated for the initial particle positions, which are usually given as a square lattice.

Gradient model in the MPS method. A gradient vector at particle i that has scalar quantity ϕ_i is calculated using the following equation:

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$$\langle \nabla \phi \rangle_i = \frac{d}{n^0} \sum_{j \neq i} \left[\frac{\phi_j - \phi_i}{\left| \vec{r}_j - \vec{r}_i \right|^2} \left(\vec{r}_j - \vec{r}_i \right) w\left(\left| \vec{r}_j - \vec{r}_i \right| \right) \right] \tag{3}$$

where ϕ_i is an arbitrary physical quantity, d is the number of dimensions, n^0 is the initial particle number density, and w is the weight function.

Laplacian model in the MPSM. Physical quantities of particle i are distributed to neighboring particle j using the weight function in the following equation:

$$\langle \nabla^2 \phi \rangle_i = \frac{2d}{\lambda n^0} \sum_{j \neq i} \left[\left(\phi_j - \phi_i \right) w\left(\left| \vec{r}_j - \vec{r}_i \right| \right) \right] \tag{4}$$

where λ is a coefficient introduced to control the increase in variance to agree with that of the analytic solution, given as follows:

$$\lambda = \frac{\sum_{j \neq i} \left| r_j - r_i \right|^2 w\left(\left| r_j - r_i \right|^2 \right)}{\sum_{j \neq i} w\left(\left| r_j - r_i \right| \right)} \tag{5}$$

For this problem, statistics indicate that the variance increases linearly with time.

Calculation algorithm

A semi-implicit algorithm is applied to the incompressible Navier-Stokes equation:

$$\frac{\partial \vec{u}}{\partial t} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \vec{u} + \vec{F} \tag{6}$$

where ρ is the fluid density and ν is the kinematic viscosity. In a time step, the external force, viscosity, and pressure gradient terms are calculated explicitly. The Poisson equation of pressure is calculated implicitly using an iteration solver. First, the external force and viscosity terms of the Navier-Stokes equation are calculated explicitly, and the temporary velocity $\vec{u}^*$ is obtained as follows:

$$\vec{u}_i^{\,*} = \vec{u}_i^{\,k} + \nu \nabla^2 \vec{u}_i^{\,k} dt + \vec{F} dt \tag{7}$$

where dt is the time increment. The temporary particle position $\vec{r}^*$ is calculated as follows:

$$\vec{r}_i^{\,*} = \vec{r}_i^{\,k} + \vec{u}_i^{\,*} dt \tag{8}$$

The temporary particle number density n^* is evaluated from the temporary position and deviates from the initial particle number density n^0. In this case, the fluid density is not constant. Therefore, the pressures of the particles are calculated such that they return to the initial particle number density n^0.

$$\frac{n^0 - n_i^{\,*}}{n^0} = -dt \nabla \cdot \vec{u}' \tag{9}$$

The correction velocity $\vec{u}'$ is calculated using the pressure gradient term:

$$\vec{u}_i' = -\frac{1}{\rho} \nabla P_i^{k+1} dt \tag{10}$$

Substituting Eq. (10) into Eq. (9), we obtain the Poisson equation for pressure:

$$\nabla^2 P_i^{k+1} = \frac{\rho}{dt^2} \frac{n^0 - n_i^{\,*}}{n^0} \tag{11}$$

The new time pressure p^{k+1} is obtained by solving Eq. (11). Substituting p^{k+1} into Eq. (10), we obtain the correction velocity. This correction velocity is then added to the temporary velocity:

$$\vec{u}_i^{\,k+1} = \vec{u}_i^{\,*} + \vec{u}_i' \tag{12}$$

In the end, the correction displacement is added to the temporary position:

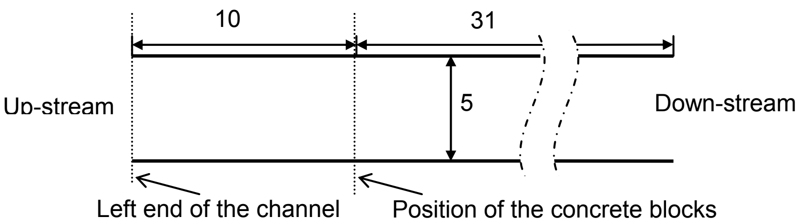
$$\vec{r}_i^{k+1} = \vec{r}_i^{*} + \vec{u}_i^{'} dt \quad (13)$$

NUMERICAL SIMULATION

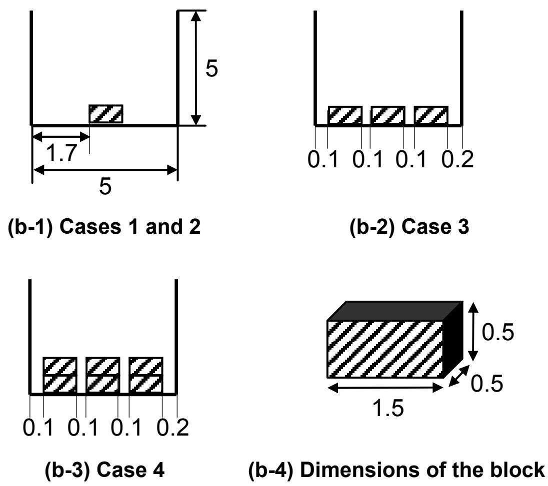
As a numerical simulation, the MPSM has been applied to simulate the current with structures on a channel. These simulations deal with both fixed and moving rigid bodies. The current is assumed to be tsunami bore and tsunami run-up, and the rigid bodies are assumed to be a broken coastal structure, a car, and rubble.

Numerical model

Plane and cross-sectional views of the channel model used herein as a numerical model are shown in Fig. 1.



(a) Plane view (length: m)



(b) Cross-sectional view and dimensions of the block (length: m)

Figure 1. Plane and cross-sectional views of the model

Fig. 1(a) shows a plane view of the channel. The width of the channel is 5.0 m, and the total length is 41 m. Concrete blocks are placed on the position of 10 m downward from the left end of the channel. Fig. 1(b) shows a cross-sectional view and the arrangements of the concrete blocks. Four cases with different arrangements of concrete blocks were examined (density: 2,300 kg/m^3, static friction: 0.4, dynamic friction: 0.3). In the first case (Case 1), a single concrete block is fixed. In Case 2, a single moveable concrete block is placed in the channel. In Case 3, three blocks that can be moved by the current are placed in the channel. Finally, in Case 4, six blocks stacked two blocks high are placed in the channel. The arrangements of Cases 1 through 4 are shown in Figs. 1(b-1) through 1(b-3). The dimensions of the blocks are shown in Fig. 1(b-4).

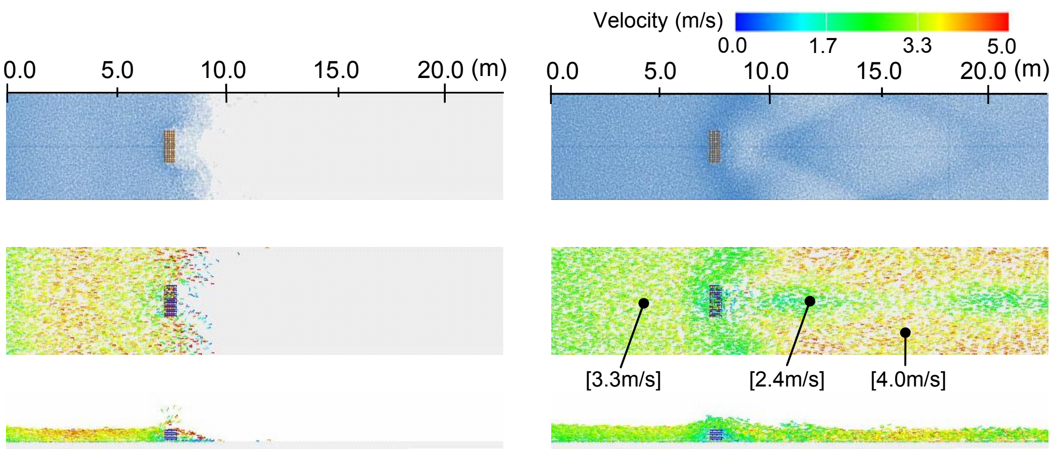
Table 1 shows the computational variables and the boundary condition. The initial bore height is 1 m, and the velocity is 2.5 m/s. The material of the bore is water. The boundary condition of the wall is the non-slip condition.

Table 1. Computational variables and boundary condition.

Case	1	2	3	4
Initial water level	0.1m			
Initial bore height	1m			
Initial velocity of bore	2.5m/s			
Coefficient of viscosity	0.001Pa・s			
Wall boundary condition	Non-slip			
Density of fluid	1,000kg/m^3			
Density of block	2,300kg/m^3			
Friction condition between Wall and block	Fix	Coefficient of static friction 0.4 Coefficient of dynamic friction 0.3		
Diameter of particle	0.1m			
Time increment	0.005s			

Simulation results

The behavior of the structures and the tsunami currents are shown in Figs. 2 through 6. In Case 1, the bore jumps up due to collision with the block, as shown in the bottom panel of Fig. 2(a). Backwater appears in front of the structure after 5.5 seconds of simulation time, and the velocity is found to be low along the center line behind the structure and high along the sidewalls, as shown in the middle panel of Fig. 2(b). In Case 2, the velocity is very high around the sides of the structure, but very low behind the structure (Fig. 3). The velocity was low around the fixed block of Case 1, but high around the moving block of Case 2. These results indicate that interaction between the fluid and structure creates several types of flow around structures. This is a very important consideration when designing structures to withstand tsunami bore. Increased interaction of the blocks with currents results more complex current patterns in Cases 3 and 4. In Case 3, the water level is higher than in Case 2 because the structure obstructs the progress of the bore, as shown in the bottom panel of Fig. 4(a). In this case, the flow direction is changed by the rotation of the structure, as shown in the middle layer of Fig. 4(b). In Case 4, the stacks of blocks move faster (Fig. 5) than the single blocks of Case 3 because the structures in Case 4 obstruct the progress of the bore and significantly increase the velocity around the structure. A close-up view of the results for Case 4 (Fig. 6) indicates that the upper part of the stored blocks have fallen down in front of the base one second after the tsunami. These results indicate that MPSM is a useful tool for understanding complex three-dimensional phenomena.



(a) Time = 1.0s **(b) Time = 5.5s**

Figure 2. Result for Case 1

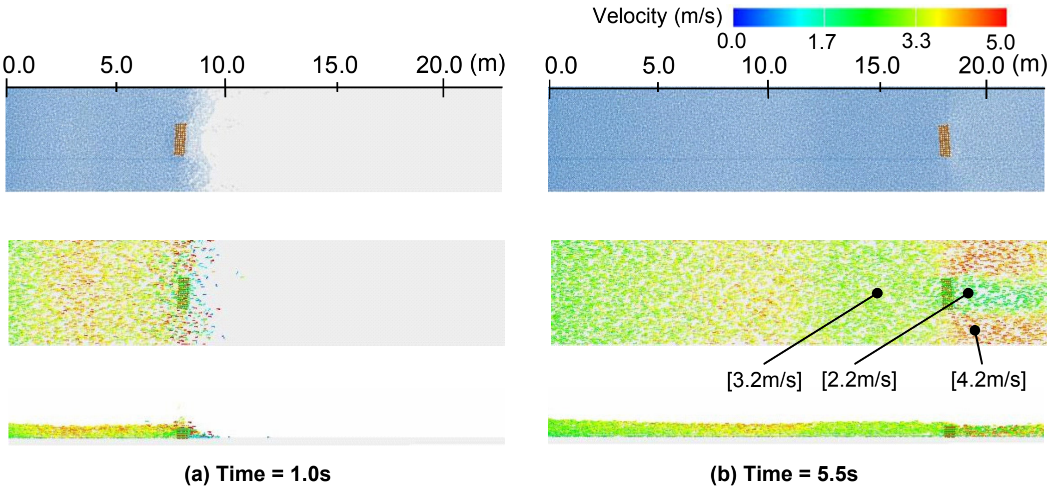


Figure 3. Result for Case 2

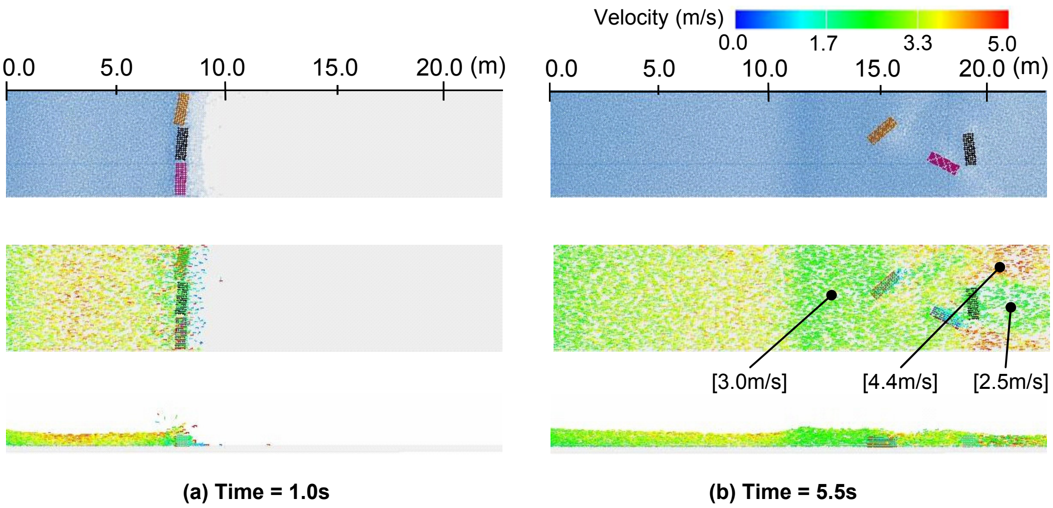


Figure 4. Result for Case 3

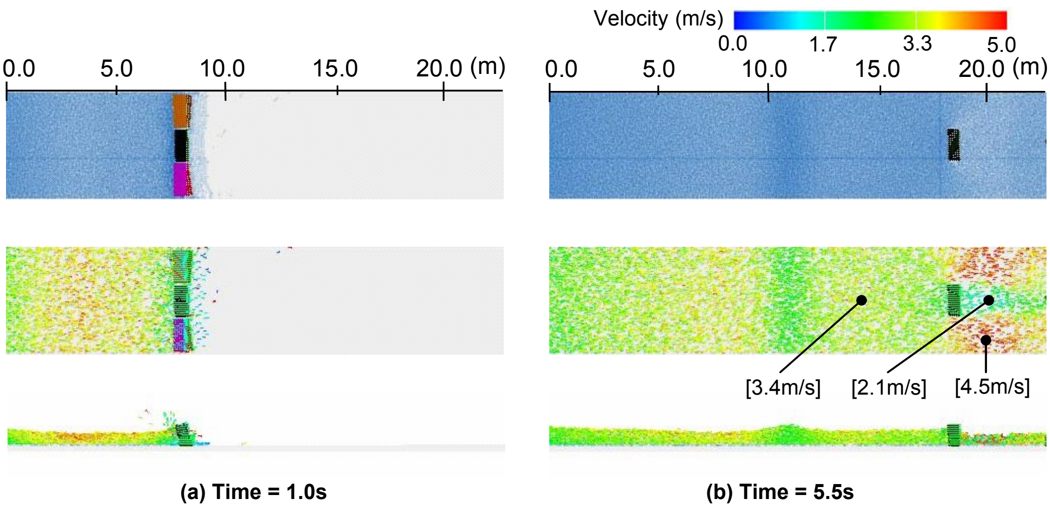
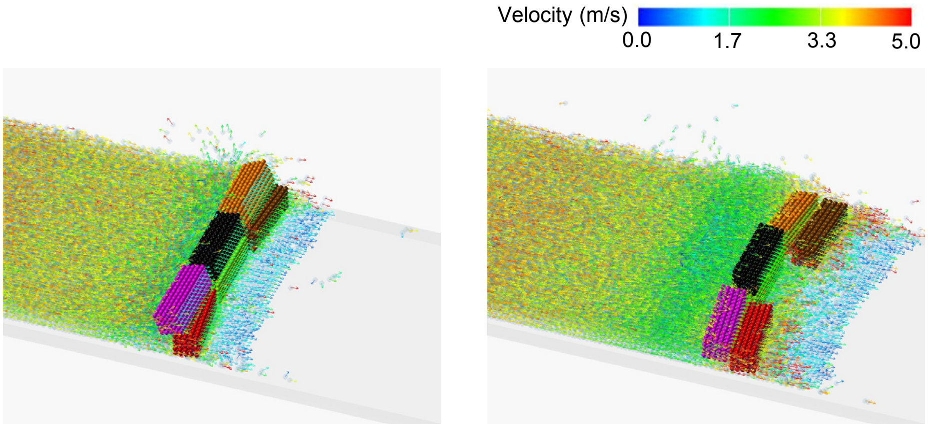


Figure 5. Result for case 4



(a) Time = 0.5s

(b) Time = 1.0s

Figure 6. Close-up of the results for Case 4

CONCLUSION

The present study clarifies the complex current patterns around moving three-dimensional structures using the MPSM. The simulation study revealed the following.

1. The flow around the moving structure is faster than flow around the fixed structure.
2. Additional structures and their positions would make the flow more complex.
3. The MPSM is a very useful tool to estimate such a complex current pattern.

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