A Numerical Analysis of Violent Free Surface Flow on Flooded Car Deck using Particle Method

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SUMMARY

A numerical study concerning violent free surface flow is presented. The sloshing on large car deck, which is extremely non-linear and complicated free surface flow, is numerically analysed using the Particle Method. The long time free surface simulation of large amplitude forced roll oscillation is carried out. Time series of force and moment from fluid on the deck and free surface profiles are presented. In addition, simulated results of very large amplitude free oscillation of floating body with fragmentation of fluid are presented.

1. INTRODUCTION

After the accident of "ESTONIA", a lot of studies concerning damage stability are carried out. In these studies, it has always been pointed out that water invasion to large car deck is extremely dangerous. However it is difficult to analyse this problem by means of ordinary CFD tools. The reason of this is difficulty of complicated free surface dynamics such as fragmentation of fluid. In addition, it is necessary that very shallow water with breaking waves can be treated. Then SOLA-VOF has been used in several past studies for this problem. But long time violent free surface simulation was hardly carried out.
Another difficulty of this problem is the large amplitude floating body motion. Tanizawa[2] carried out BEM non-linear simulation of a floating body in waves. He shows simulations for large amplitude and liquid cargo. However it is difficult to simulate breaking waves and damaged hull's opening using BEM.

MPS (Moving Particle Semi-implicit) method based on macro and deterministic model, which is developed by Koshizuka, is a kind of the particle method. This has following advantages for the present problem.

- Strict conservation of mass
- No numerical diffusion of free surface
- Enough robustness

In order to carry out the long time and violent free surface simulation, these characteristics should not be lacking. The particle method requires enormous computational resources. Nowadays, increase of the computational performance gives availability of the particle method for 2 dimensional problems.

Table 1 : Assessment of Numerical Method.

	BEM	VOF	MPS
conservation of mass	A	B	A
clear surface	A	B	A
computation time	A	B	C
fragmentation of fluid	C	A	A
robustness	B	B	A

A : good B : normal C: no good

Table 1 shows characteristics of three methods for non-linear free surface simulation.
Validation of the computational code is shortly presented in the appendix of this paper.

2. Water on Flooded Large Car Deck

2.1 Numerical Modelling

Numerical simulations are carried out on following assumptions.

- The problem is considered as 2 dimensional one.
- Surface tension and air effects are neglected.

The governing equations for incompressible flow are as follows.

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\mathbf{u} + \mathbf{g} \qquad (1)$$

$$\frac{d\rho}{dt} = 0 \qquad (2)$$

ν Coefficient of viscosity
ρ Density of fluid
$\mathbf{g}$ Gravity acceleration vector
P Pressure
t Time
$\mathbf{u}$ Velocity vector

Equation (1) and (2) are solved using MPS method.
The details of algorithm of MPS method is presented by Koshizuka and Oka[1] (1996).

2.2 Forced Roll Oscillation

RORO ship has a large car deck inside of vessel. Considering sloshing on the car deck, one of important motions is the roll motion.
Figure 1 shows the co-ordinate system and arrangement of simulations. Fx is a force acting on both side of tank. Fy is a force acting on the deck and ceiling of the tank. M is a moment from fluid. The model rectangular tank (0.17x0.07m) is forcedly oscillated in simulations. The first resonance period of the tank, when it is filled with

water at depth h=0.01375(m), is T=0.93 (sec.). Rolling pivot is fixed at 0.02 m above the car deck. Simulations are carried out several patterns.

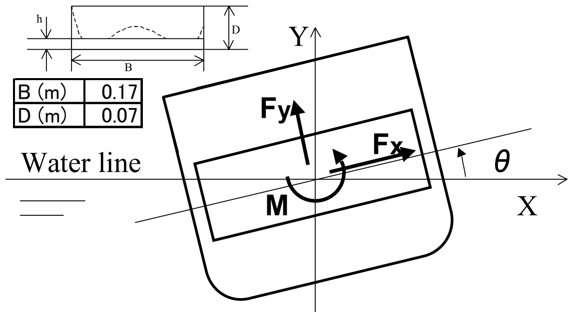


Figure 1: Co-ordinate system.

2.2 (a) Symmetrical Roll Motion

The tank is oscillated without heel angle. Symmetrical sinusoidal motion is given. Figure 2 shows particle configurations for 1.4 seconds. In spite of very large deformation, free surface of water is quite clear.

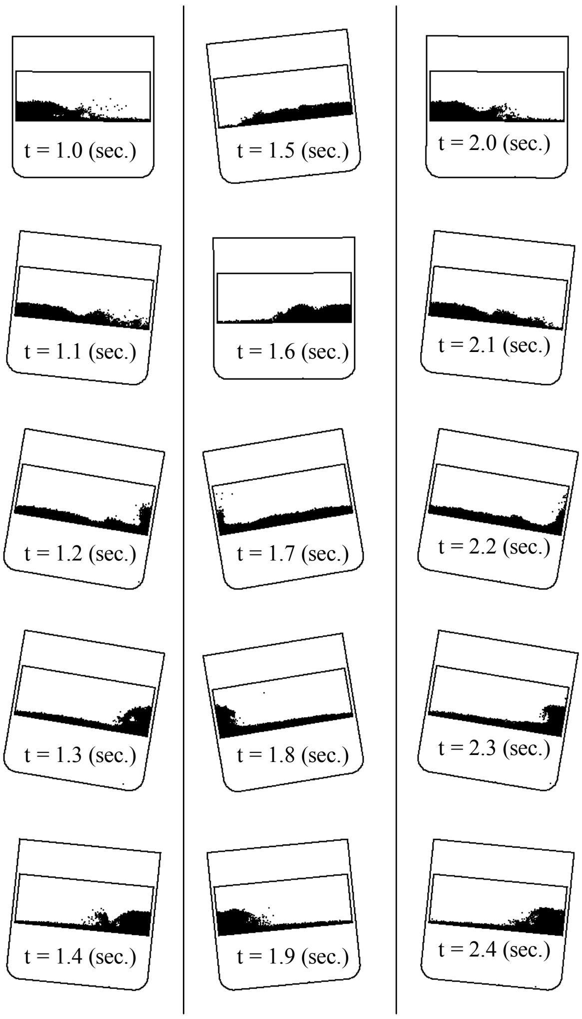


Figure 2: Particle Configurations for symmetric rolling oscillation every 0.1 seconds.

2.2 (b) Increase of Heel Angle as Time-marching

When ship is damaged, the motion of tank is not symmetrical one. Heel angle of the tank increases as time marching. Forced roll angle $\theta(t)$ is given as following equation (2).

$$\theta(t) = at + \theta_0 \sin(\omega\ t + \varepsilon) \qquad (2)$$

Parameters of motion are following, heel angle ratio a =3.0 (degree/sec.), rolling amplitude θ_0 =15.0 (degree) and phase ε =0.0. Figure 3 shows time series of force acting on the tank wall. The transition of sloshing mode as change of heel angle is presented.

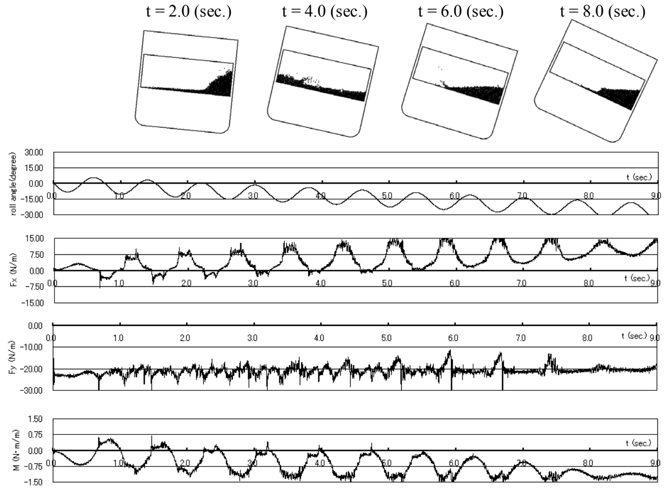


Figure 3: Time series of forces and moment by inner water (roll period 0.8 sec.) and transition of sloshing mode.

2.3 Trailers and Motorcars on the Deck (Example of Estonia)

When RORO ship operates, cargoes, which are mainly trailers and motorcars, usually exist on the car deck. These are fixed on the car deck using some of instruments, chock and harness. Then water on the deck encounters various obstacles. These are pressured by water. Then interaction between floating body and water should be considered on the situation, if binding instruments were broken or sabotaged. Trailers have almost same cross-sections along longitudinal line, and motorcars have usually 3 dimensional forms. However in this study, it is approximate that cargo is fixed and 3 dimensional effects are neglected.

When water invade on the car deck, the ship losses its speed. Fin stabilisers cannot work well on this situation. Then the ship oscillates with large amplitude in waves.

In the simulation, the flooded car deck is forcedly oscillated. Sinusoidal roll motion, whose amplitude is 7.5 degree and the period is 10.0 seconds, is given. The dimension of considered RORO ship's car deck is shown on Table 2. Rolling pivot is fixed at 2.0 m under the car deck. Actual numerical simulations are executed in 1/100 model scale (time scale is 1/10). Initial configuration of obstacles on the car deck is shown Figure 4. Cross sections of trailers and motorcars are simplified for 2 dimensional simulation. Three cases are simulated. In Case A, the car deck is empty. In case B, 8 numbers of fixed obstacles exist on the deck. In case C, one of obstacles on the deck is freely movable. Figure 5 shows particle configurations for case A, B and C.

Figure 5 shows time series of particle configurations every 0.2 seconds for case A, B and C. When car deck is empty, shallow water runs extremely wild. The turn over splash touches the ceiling of car deck. In case cargoes are fixed, they resist waves and water is well behaved.

Table 2: Dimension of RORO ship's car deck.

Bredth of car deck (m)	24.4
Height of car deck (m)	5.0
Initial level of water (m)	0.5

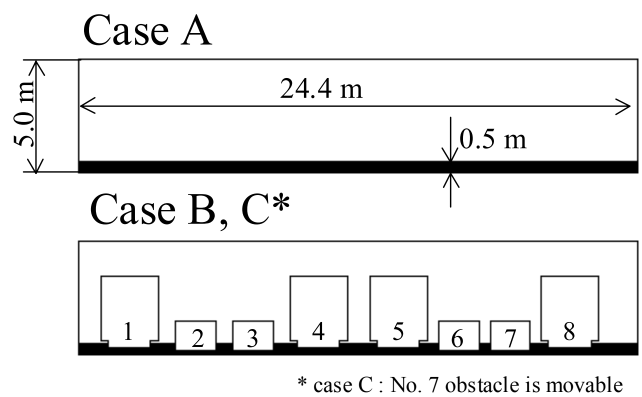


Figure 4: Particle configurations for initial time step of simulation of sloshing on RORO ship's car deck.

3. Interaction between Floating Body and Fluid

3 cases of demonstrations using the particle method are shown. Interaction problem between floating bodies and fluid is presented in the previous section too. However in present section, floating bodies, which are in larger water area, are considered. The first example is free rolling of 2D ship which has a flooded tank. Secondly, very large amplitude free oscillation of floating body is shown. Thirdly free oscillation of floating body with openings in waves is shown in a restricted water.

3.1 Free Oscillation of Floating Body with Deck Water

Coupled motion of heave, roll and sway are simulated in time domain. Complicated behaviour of floating body with shallow deck water is presented. Figure 6 shows initial configurations of particles. The initial heel angle of 2 dimensional cross section is 30 degrees and initial velocities of particle, which is arranged as a part of ship, are all zero. 24,611 particles are totally used. Tow cases of simulation are carried out. One is fixed solid cargo on the inner deck. Another is free liquid cargo on it.

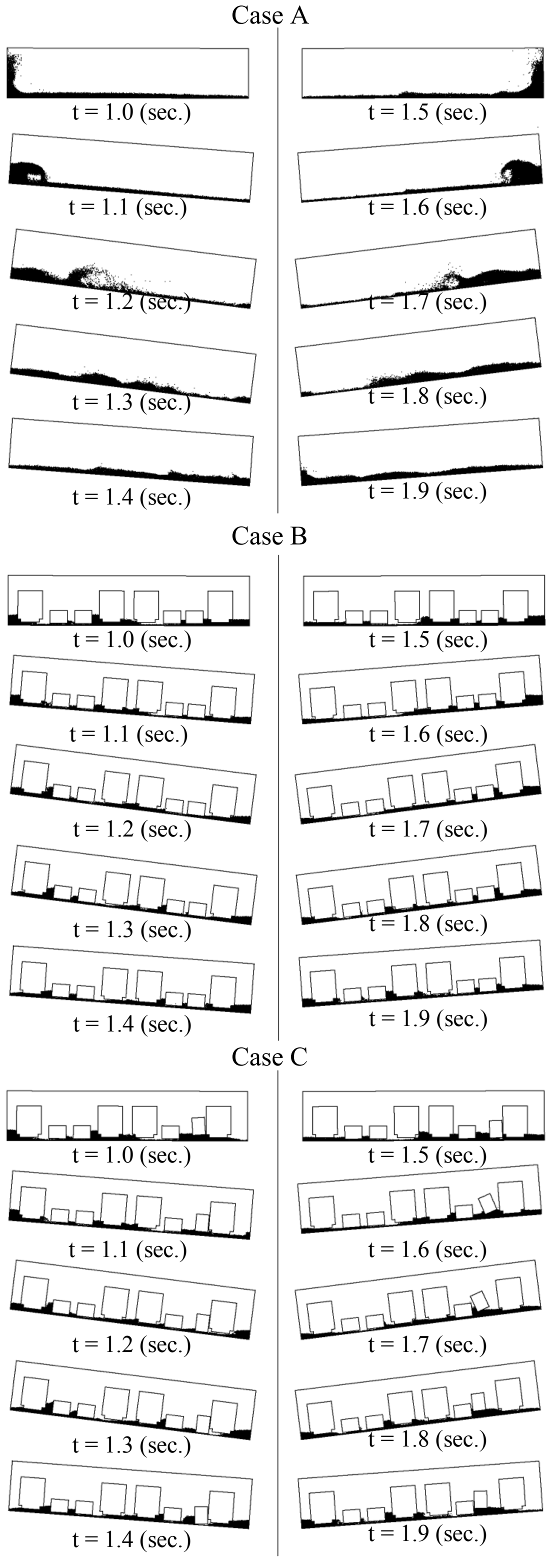


Figure 5: Particle configurations every 0.1 seconds (roll period: T=10.0 (sec.) roll amplitude: θ_0 =10 (degree)).

Figure 7 shows phase plot of simulated roll motion. Black circles on the trajectory are plotted every 1.0 seconds. Figure 8 shows the time series of roll angle. Figure 9 shows particle configurations for the liquid cargo case every 0.1 seconds and every 1.0 seconds. In the liquid cargo case, as first, the flooded water sloshes on deck. Finally, the flooded ship heels over and stabilises at the point.

3.2 Large Amplitude Free Oscillation of Floating Body

Free falling of floating body with inner free water and water mass is simulated. The floating body makes a touchdown on the free surface and oscillates freely. At the same time the water mass and water of tank unites and large amplitude waves are generated. Figure 10 shows particle configurations every 0.1 seconds.
7,717 particles are used in this simulation.

3.3 Free Oscillation of Floating Body with Opening in Waves

The Floating body has one opening, which is on the right side of hull above water. Inner deck is perfectly dry at initial time step. The right side of tank wall is movable, which play a role of wave generator. The period of generated wave is T=0.8 (sec.) and the amplitude of wave maker is 0.05 m. The left side of tank is fixed wall. Consequently the simulated result involves reflection of waves. 28,908 particles are used.

Figure 11 shows particle configurations for 7.5 seconds every 0.5 seconds. Water invades in floating body every collision with waves. Invading water sloshes on inner deck. Draft of the floating body increases and opening closes with water surface. As a result amount of invading water increases.

4. CONCLUSIONS

This study is aimed to obtain feature of shallow water sloshing using numerical method in time domain. In this study MPS method can be applied to these violent free surface problems successfully.
Various numerical simulations of 2 dimensional violent free surface flow are carried out. As a result, capability of the particle method for shallow water sloshing and large amplitude oscillation of floating body with fragmentation of fluid is presented.
As a next step, 3 dimensional expansion of computational code is required. It is not so difficult, because algorithm of particle method is simple one. A main difficulty for the expansion is limitation of computer performance.
In addition, a development of wave-absorbing zone for particle method should be developed. Especially it is necessary to simulate motion of floating body in the actual sea.

6. REFERENCES

[1] S. Koshizuka and Y. Oka, ‘Moving-Particle Semi-Implicit Method for Fragmentation of Incompressible Fluid’, Nuclear Science and Engeneering, 123, pp421-434, 1996.
[2] K. Tanizawa, ‘Nonlinear Simulation of Floating Body Motions in Waves’, ISOPE Proceeding of the 6th, pp414-420, 1996.
[3] A. Francescutto and V. Armenio, M. L. Rocca, ‘On the Roll Motion of a Ship with Partially Filled Unbaffled and Baffled Tanks: Numerical and Experimental Investigation’, ISOPE Proceeding of the 6th, pp377-386, 1996.
[4] K. AMAGI, N. KIMURA, K. UENO, ‘On the Practical Evaluation of Shallow Water Effect in Large Inclinations for Small Fishing Boats’, 5th International Conference on Stability of Ships and Ocean Vehicles Proceeding, 1994.

7. APPENDIX

MPS method code used in this paper is validated by comparison with two experiments. One is dam-break flow and another is tank sloshing. Both of them show good agreement between simulations and experiments. Figure 12 shows leading edge of dam-break. Figure 13 shows particle configurations and velocity vectors of tank sloshing. Both of them show pretty good agreements.

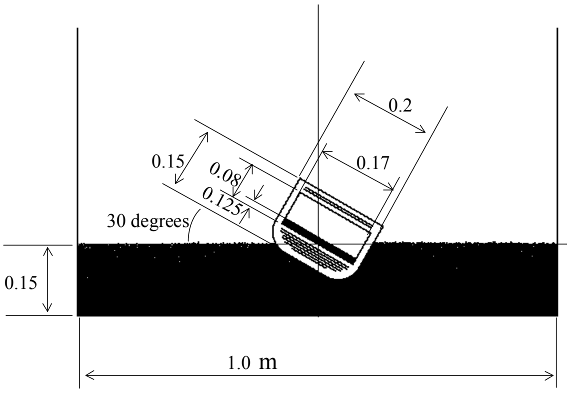


Figure 6: Particle configurations for initial time step.

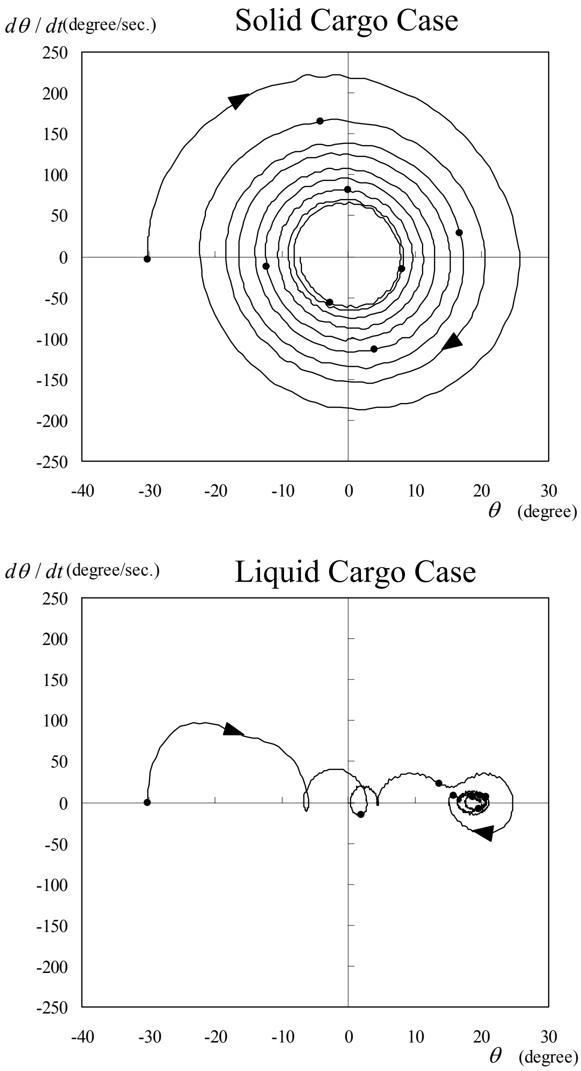


Figure 7: Phase plot of the simulated free roll motion.

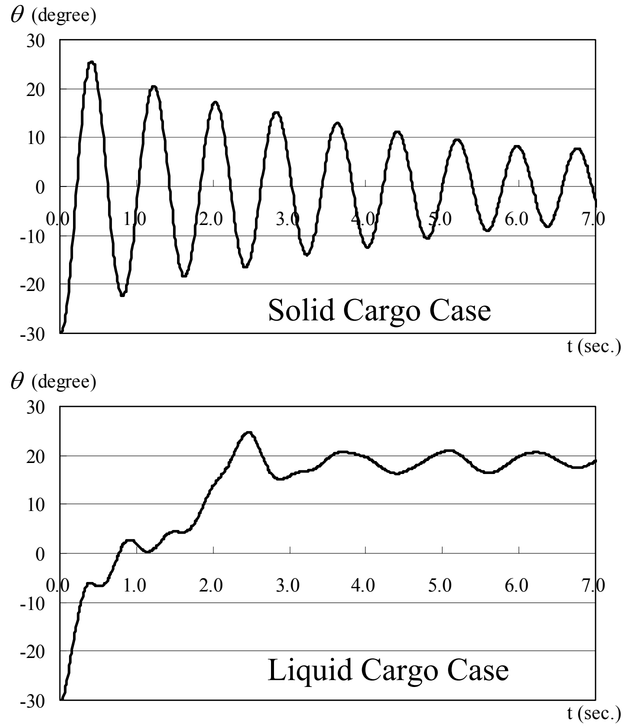
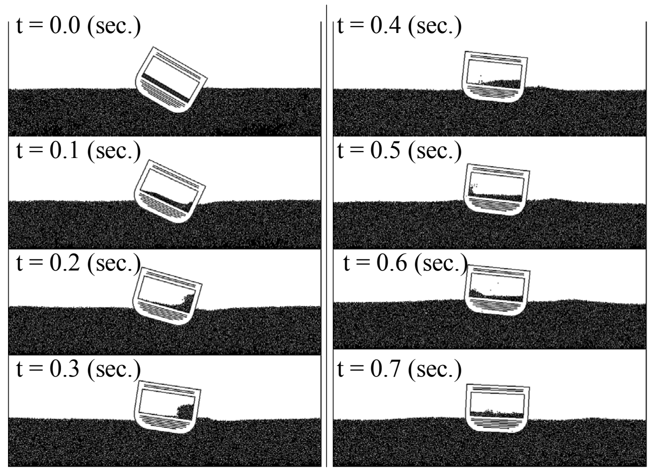
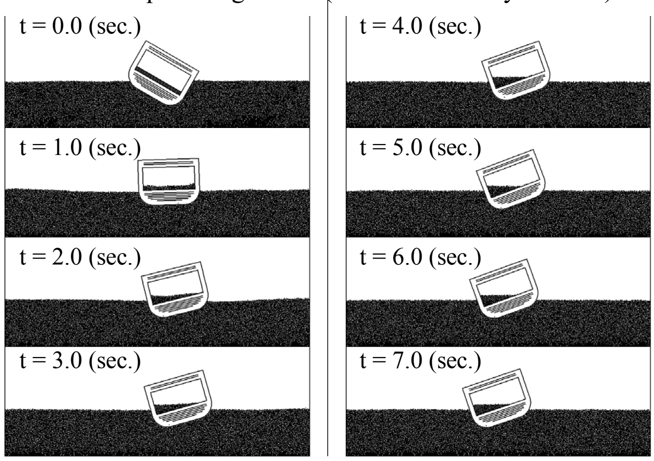


Figure 8: Time series of simulated rolling angle.



Liquid Cargo Case (for 0.7 sec. every 0.1 sec.)



Liquid Cargo Case (for 7.0 sec. every 1.0 sec.)

Figure 9: Particle configurations for free rolling of 2D ship with liquid cargo in channel tank.

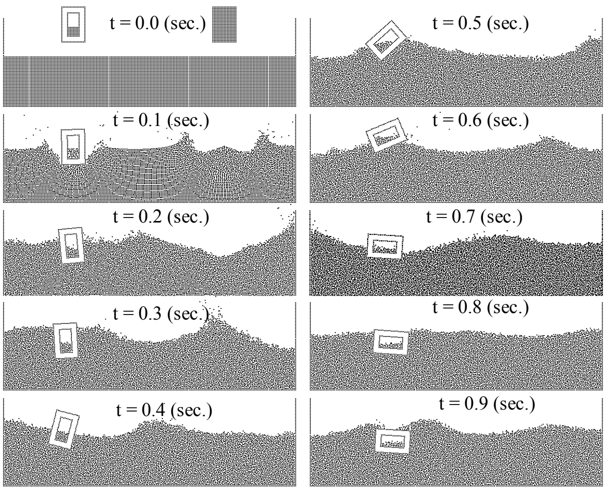


Figure 10: Particle Configurations for Large Amplitude Freedom Oscillation every 0.1 seconds.

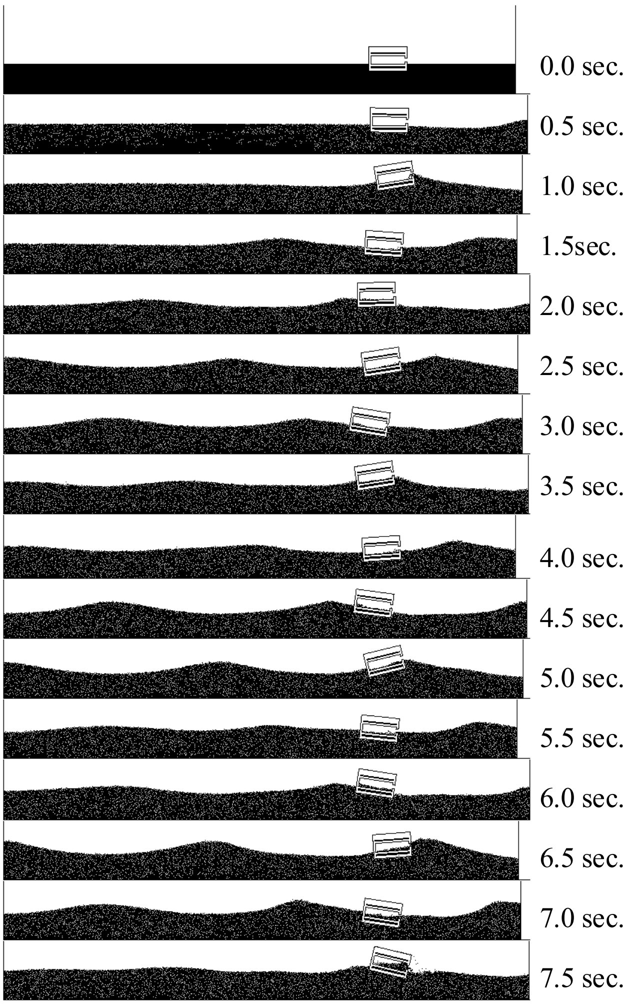


Figure 11: Particle Configurations for Freedom Oscillation of Floating Body with Openings in Waves every 0.5 seconds.

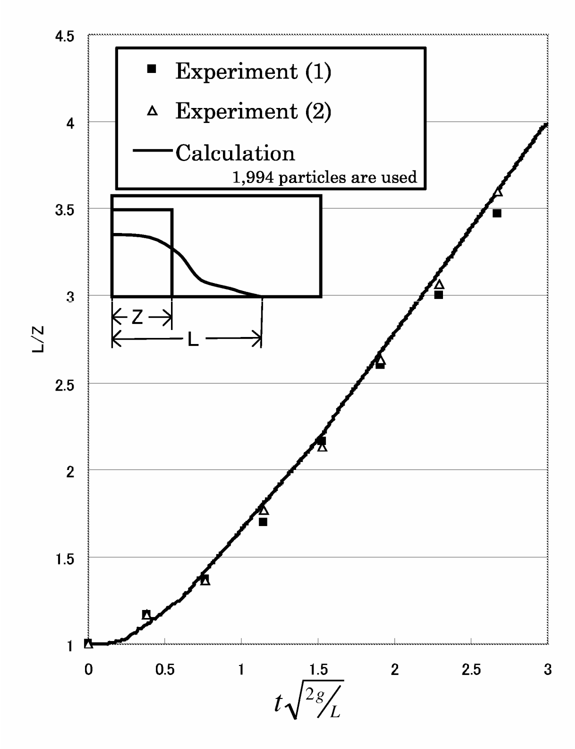


Figure 12: Comparison between experiments and simulations using particle method.

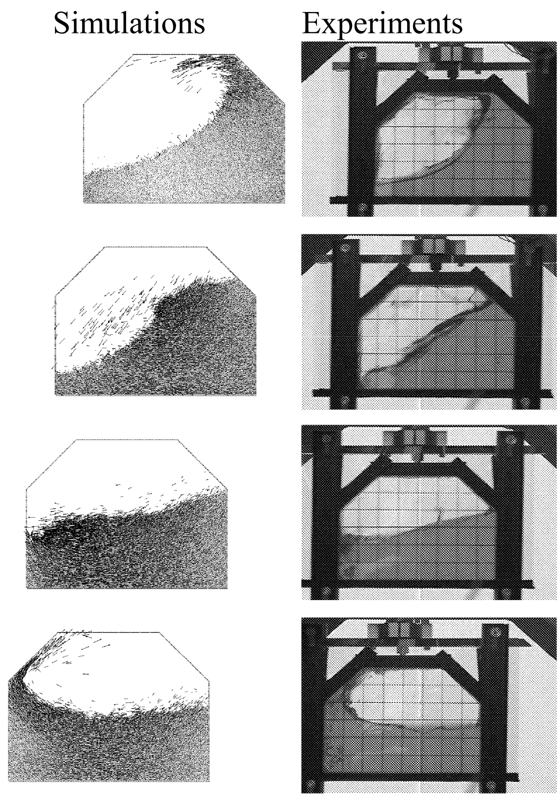


Figure 13: Comparison between experiments and simulations using particle method.