Simulation of Behavior of Mooring Vessels in Tsunamis Using the 3-D MPS Method Considers Leading Wave and Backwash

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Background

Tsunami …

It will bring serious damage to lives, Properties and environment.

It has little observation data and prediction of damage is difficult.

When the tsunami attacks in harbors, the vessels were moored in the wharf suffers big damage.
Purpose

Damage of mooring vessel by tsunami

Leading wave effects:
- The breaking of a mooring tether
- The collision of vessels and floating structures
- Grounding on a wharf and the collision to architectures of the coast legion

Backwash effects:
- The outflow to the ocean space of floating body
- People which were rescued from the leading wave, but it fell victim to the backwash.

Chain of disaster
Purpose

Chain of disaster

This research was develop the numerical calculation method to be able to analyze fully nonlinear problems of the chain of disaster by tsunamis.

- I created the MPS method program code for the prediction of the chain of disaster by tsunami, and have examined the applicability and usefulness.

- In this research, I tried to express the leading wave and the backwash using the simulation method of the chain of disaster by the MPS method.
MPS method
(Moving Particle Semi-implicit method)
**MPS Method (Moving Particle Semi-implicit Method)**

- The MPS method calculates movement for fluid as an aggregate of particles.
- The MPS method does not need a lattice like a finite difference method or the finite element method.
Governing equations of MPS method

Continuity equation:

\[
\frac{D\rho}{Dt} = 0
\]

Navier-Stokes equation:

\[
\frac{D\tilde{u}}{Dt} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \tilde{u} + g
\]

- Incompressible fluid
- The fluid density is constant in terms of time
- Lagrange differential to velocity vector
- First term: pressure gradient term, Second term: viscosity term, Third term: gravitational term
Calculation algorithm of MPS method

Start

Input of calculation parameters

Input of configuration of particles \( r^0, u^0, p^0 \)

Explicit

\( r^k, u^k, p^k \)

Calculation of diffusion and source terms \( u_i^* \)

Calculation of particle motions \( r^* = r^k + \Delta tu^* \)

Solving pressure Poisson equation

\[ \nabla^2 p^{k+1} = \frac{\rho}{\Delta t^2} \frac{n^* - n'}{n^0} \]

Calculation of pressure gradient terms and modification of particle motions

\[ u' = -\frac{\Delta t}{\rho} \nabla p^{k+1} \]
\[ u^{k+1} = u^* + u' \]
\[ r^{k+1} = r^* + \Delta tu' \]

Check of output

Check of termination

Time step is advanced.

END

Output of Configuration of particles

Explicit

Implicit

Input of calculation parameters

Input of configuration of particles \( r^0, u^0, p^0 \)
Modeling of motion behavior of floating body
Motion behavior of floating body

- The floating body is expressed as a continuous body of the particle.

The solid body is expressed by \( N \) particles.

The center of gravity and the moment of inertia of the solid body are calculated first.

\[
\begin{align*}
    r_g &= \frac{1}{N} \sum_{i=1}^{N} r_i \\
    I &= \sum_{i=1}^{N} m \left| r_i - r_g \right|^2
\end{align*}
\]
Motion behavior of floating body

- The floating body is expressed as a continuous body of the particle.

The fluid particle and the floating body particle are calculated together.

(The calculation time interval is not large. Therefore, the change in a relative position is not so large.)

\[
\hat{u}_{i}^{k+1} = u_{i}^{k} + \Delta t \hat{a}_{i}^{k}
\]

\[
\hat{r}_{i}^{k+1} = r_{i}^{k} + \Delta t \hat{u}_{i}^{k+1}
\]

\[
a_{g}^{k} = \frac{1}{N} \sum_{i=1}^{N} \hat{a}_{i}^{k}
\]
The floating body is expressed as a continuous body of the particle.

The relative position between solid body particles is returned to former shape.

(At this time, the amount of a positional change of center of gravity and the rotation corner are kept.)

\[
\begin{align*}
  u_{i}^{k+1} &= \frac{r_{i}'}{\Delta t} \\
  r_{i}^{k+1} &= r_{i}^{k} + r_{i}'
\end{align*}
\]
Motion behavior of floating body
(in the regular waves)
Motion behavior of floating body
(in the large wave by water pillar collapse)
Modeling of mooring force on calculation
Algorithm of mooring force on calculation

Directly adding mooring conditions to the motion equation of a particle

Mooring force
(linear spring or nonlinear spring)

\[ F_r = kx \]
\[ F_r = k(r \pm \beta r^3) \]

\[ F_x = F_r \cos \theta \]
\[ F_y = F_r \tan \theta \]
\[ F_z = F_r \sin \theta \]

A mooring force \( F \) is added to the velocity correction value \( u' \) generated by the semi-implicit algorithm in the implicit pressure gradient term \( \nabla P^{k+1} \).
Experiment of tensile spring
(Conditions of experiment)

<table>
<thead>
<tr>
<th>Experimental conditions</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
</tr>
</thead>
</table>
## Simulation of tensile spring  
*(Conditions of calculation)*

### Particle distance: 0.01m

Compared with the results of...

- Linear spring condition
- Nonlinear spring condition

### Calculation conditions

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Object mass [kg]</strong></td>
<td>0.101</td>
<td>0.122</td>
<td>0.143</td>
<td>0.163</td>
<td>0.184</td>
<td>0.204</td>
</tr>
<tr>
<td><strong>Spring constant [N/m]</strong></td>
<td>149.7198</td>
<td>142.6422</td>
<td>135.9338</td>
<td>132.9715</td>
<td>129.7939</td>
<td>127.3591</td>
</tr>
<tr>
<td><strong>Particle number density [kg/m^3]</strong></td>
<td>1258.909</td>
<td>1510.691</td>
<td>1762.472</td>
<td>2014.254</td>
<td>2266.036</td>
<td>2517.818</td>
</tr>
</tbody>
</table>
Simulation of tensile spring
(Simulation result)
Validation of tensile load to tensile length

![Graph showing the relationship between tensile load (N) and tensile length (m). The graph includes data points for experiment, MPS (linear), and MPS (nonlinear), with a linear trend line.]
Validation of the motion behavior of floating body and collision force
Water tank experiment

Location:
Nihon University, Techno Place 15, Two dimensional Water tank

- Incident wave: Solitary Wave
- Wave height: 0.06m
Water tank experiment

Location: Nihon University, Techno Place 15, Two dimensional Water tank

H1~H7: Wave meter
V1: Electromagnetic current meter
P1: Pressure sensor
F1: Load cell

Solitary Wave

Wave generator
Calculation conditions

- **Particle distance:**
  \[ Pt = 0.01 \text{m} \]

- **Number of particle:**
  \[ Pn = 507,694 \]

- **Simulation time:** 6.0 sec.

- **Distance of wharf edge to architecture** \( x \): 0.25m, 0.30m, 0.35m
Verification of wave shape and maximum water elevation
Results
(Incident wave)

Wave height of H3

Wave generator

Experiment
MPS

Wave height (m)

Time (sec)

Wave height of H3
Results
(Maximum water elevation)

Water elevation of H4~H7

Experiment
MPS

$\eta_{\text{max}}/\eta_0$

$D/h$

H4, H5, H6, H7

$0 \quad 0.5 \quad 1.0 \quad 1.5$

$0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0$
Results
(Water elevation)

Water elevation of H4
Results
(Water elevation)

Water elevation of H5

Water elevation (m)

Time (sec)

Experiment
MPS

Water elevation of H5
Results
(Water elevation)

Water elevation of H6

Experiment
MPS
Results
(Water elevation)

Water elevation of H7

Experiment
MPS

Water elevation (m)

Time (sec)

Water elevation of H7
Verification of fluid pressure
Results
(Fluid pressure)

Comparison of time history of dynamic pressure at P1
Verification of motion behavior of floating model and collision force
Results
(Motion of floating model)

Comparison of horizontal displacement

Experiment
MPS

Motion of floating model
Results
(Motion of floating model)

Comparison of vertical displacement
Results
(Collision force)

Experiment

MPS Method
Time = 3.76 sec.

Time = 4.08 sec.

Time = 4.38 sec.
Results
(Collision force)

Comparison of collision force (x = 0.25m)
Results
(Collision force)

Comparison of collision force (x = 0.30m)
Results
(Collision force)

Comparison of collision force (x = 0.35m)
Conclusions

1) Water elevation in front of wharf was a good agreement. However, water elevation in on the wharf was a little difference. This problem is necessary to adjust the number of particles.

2) From the comparisons and discussions of present paper, it is confirmed that the present MPS program code is usefulness and applicability in the estimation of behavior of drifting vessel and maximum value of collision force on the facility by tsunami.

3) It is possible to clarify the characteristic of collision force and the collision mechanism by using the present method of simulation and the water tank experiments.
Simulation of leading wave and backwash
Calculation conditions (Leading wave and Backwash)

- Water depth: 11.0m
- Number of particle: 615,681
- Particle distance: 1.0 m
- Simulation time: 240 sec.
- Inundation height: 11.0m
- Wave condition: Bore wave (5 waves)
Incident wave height (Bore wave: 5 waves)

Incident wave height (bore wave)
Incident flow velocity

Incident flow velocity (bore wave)
Wave height of leading wave at wharf edge
Flow velocity of leading wave at wharf edge

Flow velocity (bore wave)
Water elevation (Wharf edge to -50m)

(Example of 3.11 Tohoku Earthquake)
Onagawa Fishing harbour: H=14.8m

Wave elevation (bore wave)
Flow velocity
(Wharf edge to -50m)

Flow velocity (bore wave)
Simulation results (Leading wave)

Time = 44 sec.
Simulation results (Leading wave)

Time = 48 sec.
Simulation results (Leading wave)

Time = 56 sec.
Simulation results (Leading wave)

Time = 65 sec.
Simulation results (Leading wave)

Time = 120 sec.
Water elevation on the wharf of backwash (Wharf edge to -50m)

As for backwash, a water level falls quickly. In 2 minutes, it falls to about 2.0 m.
Flow velocity on the wharf of backwash (Wharf edge to -50m)
Simulation results (Backwash)

Time = 120 sec.
Simulation results (Backwash)

Time = 135 sec.
Simulation results (Backwash)

Time = 155 sec.
Simulation results (Backwash)

Time = 240 sec.
Simulation of chain of disaster considers leading wave and backwash
Simulation of hazard chain
Calculation conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DWT</td>
<td>3,000 [t]</td>
</tr>
<tr>
<td>Displacement</td>
<td>2,937.2 [t]</td>
</tr>
<tr>
<td>Particle numbers</td>
<td>645,233</td>
</tr>
<tr>
<td>Particle numbers of structure</td>
<td>10,429</td>
</tr>
<tr>
<td>Density of structure's particles</td>
<td>474.5 [kg/m³]</td>
</tr>
<tr>
<td>Particle distance</td>
<td>1.0 [m]</td>
</tr>
<tr>
<td>Structure length [L]</td>
<td>88.0 [m]</td>
</tr>
<tr>
<td>Structure breadth [B]</td>
<td>13.0 [m]</td>
</tr>
<tr>
<td>Structure depth [D]</td>
<td>11.0 [m]</td>
</tr>
<tr>
<td>Structure draft [d]</td>
<td>5.0 [m]</td>
</tr>
<tr>
<td>Water depth [h]</td>
<td>11.0 [m]</td>
</tr>
<tr>
<td>Crown height [H]</td>
<td>2.0 [m]</td>
</tr>
<tr>
<td>Clearance [b]</td>
<td>1.0 [m]</td>
</tr>
</tbody>
</table>
Calculation conditions

Calculation arrangement \([x-z]\)
Mooring conditions

head line, Stern line: 4 lines

aft spring, Fore spring: 2 lines
### Mooring conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic point of vessel ([n])</td>
<td>1.0 [m]</td>
</tr>
<tr>
<td>Basic point of wharf ([a])</td>
<td>1.0 [m]</td>
</tr>
<tr>
<td>Length of mooring point ([x_1])</td>
<td>9.0 [m]</td>
</tr>
<tr>
<td>Length of mooring point ([x_2])</td>
<td>4.0 [m]</td>
</tr>
<tr>
<td>Breadth of mooring point ([y_1])</td>
<td>4.0 [m]</td>
</tr>
<tr>
<td>Breadth of mooring point ([y_2])</td>
<td>3.0 [m]</td>
</tr>
<tr>
<td>Depth of mooring point ([z_1])</td>
<td>4.0 [m]</td>
</tr>
<tr>
<td>Depth of mooring point ([z_2])</td>
<td>4.0 [m]</td>
</tr>
<tr>
<td>Mooring tether ([r_1])</td>
<td>11.53 [m]</td>
</tr>
<tr>
<td>Mooring tether ([r_2])</td>
<td>6.4 [m]</td>
</tr>
<tr>
<td>Tether type</td>
<td>Nylon</td>
</tr>
<tr>
<td>Tether diameter</td>
<td>35 [m/m]</td>
</tr>
<tr>
<td>Spring constant</td>
<td>34.3 [kN/m]</td>
</tr>
<tr>
<td>Line 1, Line 4</td>
<td>4</td>
</tr>
<tr>
<td>Line 2, Line 3</td>
<td>2</td>
</tr>
<tr>
<td>Breaking force</td>
<td>161.7 [kN]</td>
</tr>
<tr>
<td>Stretch rate</td>
<td>20 [%]</td>
</tr>
</tbody>
</table>
Calculation conditions

• Object vessel: 3,000 DWT (displacement tonnage: 2,937.2t)
• Water depth: 11.0m
• Number of particle: 623,671
• Particle distance: 1.0 m
• Simulation time: 240 sec.

On the wharf:

Object group (Truck) 20 sets
Simulation results (Leading wave)

Time = 44 sec.
Simulation results (Leading wave)

Time = 48 sec.
Simulation results (Leading wave)

Time = 56 sec.
Simulation results (Leading wave)

Time = 65 sec.
Simulation results (Leading wave)

Time = 85 sec.
Simulation results (Leading wave)

Time = 120 sec.
Simulation results (Backwash)

Time = 120 sec.
Simulation results (Backwash)

Time = 135 sec.
Simulation results (Backwash)

Time = 145 sec.
Simulation results (Backwash)

Time = 155 sec.
Simulation results (Backwash)

Time = 240 sec.
Simulation of the chain of disaster
Animation (Leading wave)

Animation of numerical calculation
Conclusions

1. From the comparison with the experiment and the linear spring condition, the usefulness of the model of mooring tether using a nonlinear spring condition in the MPS method was examined. As a result, the usefulness of nonlinear spring conditions was shown.

2. From the simulation results of the tsunami considering the leading wave and the backwash, it can be understood the usefulness of the MPS method. And, the wave making method of the leading wave and the backwash by the MPS method was shown.
3. From the simulation results of the chain of disaster considering the leading wave and the backwash, it can be understood the usefulness of the MPS method. The mooring tether is fractured by the leading wave over 10m. The vessel flowed out the wharf edge like basin under a waterfall by the backwash. And, the vehicles are falling down to basin under a waterfall.