Fundamental study for seawall collapse simulation during Tsunami by using a particle method

***Toshihiro Morimoto[1], Mitsuteru Asai[2], and Yoshimi Sonoda[2]**

[1]Department of Civil and Structural Engineering, Graduate School of Engineering, Kyushu University, Japan.
[2]Department of Civil and Structural Engineering, Kyushu University, Japan.

*Corresponding author: asai@doc.kyushu-u.ac.jp

Abstract

In 2011, Tohoku-Kanto earthquake tsunami caused serious damage on the infrastructures. Soil scour and erosion behind the seawall had occurred during the overflow, and it may become one of the main reasons for the collapse of seawall. Fluid-Structure-Soil coupling simulation is desired for a systematic comprehension of seawall collapse mechanism, and it may help to develop next disaster prevention method. In this study, a new numerical simulation tool for the Fluid-Soil interactions problem is developed as a fundamental study related to the soil sour and erosion.

SPH Method has been selected as a basic numerical simulation method for Fluid-Soil interactions. In this research, soil is modeled by a Bingham flow model which is one of the Non-Newtonian fluids, and the Mohr-Coulomb criterion is utilized in the plastic yield judgment.

Finally, efficiency and adequacy of the proposed simulation technique has been validated through an application to one of experimental test.

Keywords: SPH, Soil erosion, Particle Method, Tsunami

Introduction

The interaction between water, soil and structures causes various problems to different areas of marine, geomechanics and hydraulic engineering. As an example of these problems, Tohoku-Kanto earthquake tsunami in 2011 is impressive incident. This tsunami hit the bridges and flowed away. On the other hand, tsunami overflowed seawalls and scoured behind the seawall. Soil scour and erosion may become one of the main reasons for the collapse of seawall.

Under these circumstances, Fluid-Structure-Soil coupling numerical simulation is desired for a systematic comprehension of multi-physics problems such as seawall collapse mechanism, and it may help to develop next disaster prevention method. There are some traditional numerical methods for deformation and failure of geomaterials in the framework of continuum mechanics, such as finite element method (FEM), finite difference method (FDM), and boundary element method (BEM). These methods have been successfully implemented. On the other hand, in the case of large deformation problems, several numerical methods have been introduced. SPH method and other Particle method have been developed for solving large deformation, crack propagation and post flow failure phenomenon of soil. In this study, focusing on the Fluid-Soil interaction, soil scouring simulation was carried out by using SPH method.

In the water-soil problem, many researchers have been proposed various soil models from different perspective. In this study, the fluid is modeled as a Newtonian fluid, and the soil model considers the granular material as a fluid with a variable viscosity, where a Bingham type constitutive model is proposed based on the Mohr-Coulomb yield-stress criterion.

Finally, efficiency and adequacy of the proposed simulation technique has been validated through an application to one of experimental test done by Yamamoto. These numerical results show a reasonable soil erosion behavior.

Smoothed particle hydrodynamics (SPH) formulation

In this paper, smoothed particle hydrodynamics (SPH) method[1),2)] was adopted. A basic concept in SPH method is that any function ϕ attached to particle "*i*" at a position r_i is written as a summation of contributions from neighbor particles

$$\phi(r_i) \approx \langle \phi_i \rangle = \sum_j \frac{m_j}{\rho_j} \phi_j W(r_{ij}, h) \tag{1}$$

Note that, the triangle bracket $\langle \phi_i \rangle$ means SPH approximation of a function ϕ. The divergence of a vector function can be assumed by using the above defined SPH approximation as follows

$$\nabla \cdot \bar{\phi}(r_i) \approx \langle \nabla \cdot \bar{\phi}_i \rangle = \frac{1}{\rho_i} \sum_j m_j (\bar{\phi}_j - \bar{\phi}) \cdot \nabla W(r_{ij}, h) \tag{2}$$

and the expression for the gradient can be represented by

$$\nabla \phi(r_i) \approx \langle \nabla \phi_i \rangle = \rho_i \sum_j m_j \left(\frac{\phi_j}{\rho_j^2} + \frac{\phi_i}{\rho_i^2} \right) \nabla W(r_{ij}, h) \tag{3}$$

In this study, Incompressible SPH (ISPH) method[3)] developed in the incompressible fluid analysis was adopted. In this method, the pressure is calculated implicitly and the velocity is calculated explicitly.

The Governing equation

In natural phenomenon, there is regularity and it is organized as continuum mechanics or discontinuity mechanics. Here, fluid and soil are written as the following equation by using Lagrange description.

$$\frac{D\boldsymbol{v}}{Dt} = \frac{1}{\rho} \nabla \cdot \boldsymbol{\sigma} + \boldsymbol{g} \tag{4}$$

In the case of solid mechanics, total stress tensor $\boldsymbol{\sigma}$ is evaluated following equation.

$$\sigma_{ij} = D_{ijkl} \varepsilon_{kl} \tag{5}$$

On the other hand, in the case of viscous fluid, total stress tensor $\boldsymbol{\sigma}$ is evaluated following equation.

$$\sigma_{ij} = -p\delta_{ij} + \tau_{ij} \tag{6}$$

Here, τ_{ij} is shear stress tensor. In the continuum mechanics, the difference between solid and fluid is only way to evaluate the total stress tensor.

Modeling of fluid

Fluid is generally modeled as Newtonian fluid. This fluid has a feature that shear stress and strain rate are linear relationship, and described below equation.

$$\tau_{ij} = \mu * \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \tag{7}$$

Where, μ^* is the effective dynamic viscosity and composed from a viscosity μ and an eddy viscosity μ_T as.

$$\mu^* = \mu + \mu_T \tag{8}$$

Substituting Eq.(6) and Eq.(7) to Eq.(4), Navier-Stokes equation can be derived.

$$\frac{D\boldsymbol{v}}{Dt} = -\frac{1}{\rho}\nabla P + \nabla^2 \boldsymbol{u} + \boldsymbol{g} \tag{9}$$

In addition to the above equation, law of conservation of mass equation was also used as governing equation.

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \boldsymbol{v} = 0 \tag{10}$$

Modeling of soil

At the field of soil mechanics, behavior of various type of soil is very complicated and its organized constitutive law is difficult to be derived. In the present circumstances, it is modeled in accordance with each types and phenomenon. In general, soil is modeled as solid and nonlinear elastic-plastic material. However, in this study, soil was modeled as Bingham fluid[4),5)] which is one of Non-Newtonian fluid because of expressing flow failure of ground. Bingham fluid has shear strength and can be written as following equation

$$\boldsymbol{\tau} = \mu_s^0 \dot{\gamma} + \tau_y \tag{11}$$

Here, τ_y is yield shear stress and μ_s^0 is viscosity after yield. Note, a Bingham fluid has behavior such as a rigid body and dose not deform but when the shear stress surpasses the yield stress, flow failure occurs resulting in large deformations. The Mohr-Coulomb criterion is introduced for the yield shear strength in the Bingham model for a given soil as

$$\tau_y = c + P \tan\varphi \tag{12}$$

Where, c is the cohesion, and φ is the internal friction angle. Then, the soil viscosity should be expressed in Bingham model[6)] as

$$\mu_s = \frac{\boldsymbol{\tau}}{\dot{\gamma}} = \begin{cases} \dfrac{c + p\tan\varphi}{\dot{\gamma}} (= \mu_E) & \dot{\gamma} \le \dot{\gamma}_y \\ \mu_s^0 (= \mu_P) + \dfrac{c + p\tan\varphi}{\dot{\gamma}} & \dot{\gamma} \succ \dot{\gamma}_y \end{cases} \tag{13}$$

Here, drawing the graph of above Eq.(12), relationship $\boldsymbol{\tau}$ and $\dot{\gamma}$ is expressed as

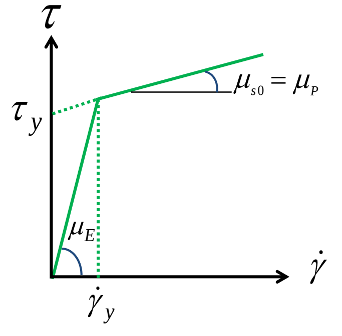

Figure1. Relationship $\boldsymbol{\tau}$ and $\dot{\gamma}$

Numerical validation test

In the following section, the numerical examples have been conducted to validate the current scheme. The hydraulic experiment[7)] done by Yamamoto was adopted. Fig.2. presents the schematic diagram for the experiment. This experiment is return flow scouring experiment and its scale is showing below. As for soil parameters, the density ratio between soil density ρ_s and water density ρ_w is taken as $\rho_s / \rho_w = 1.6$. The soil viscosity after yield is set to $\mu_s^0 = 5\text{Pa s}$. The internal angle and cohesion are taken as $\varphi = 3°$ and $c = 30kPa$.

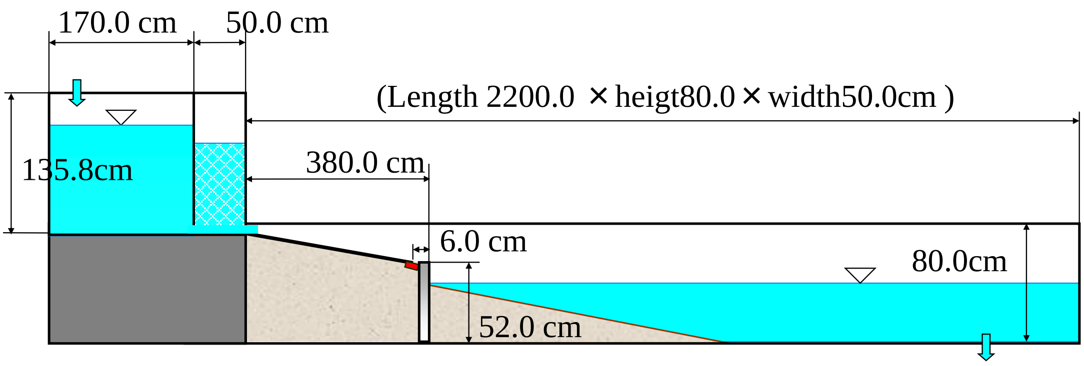

Figure2. Initial schematic diagram for hydraulic experiment

Here, gradient of sandy beach and slope is one-fifteenth, and there is a seawall at the front of sandy beach. There is a velocity meter away from the seawall by 6cm. Arrows in left side and right side are respectively water supply pipe and drainage pipe, and tank in right hand side is rectification tank. From above diagram, making a particle model as

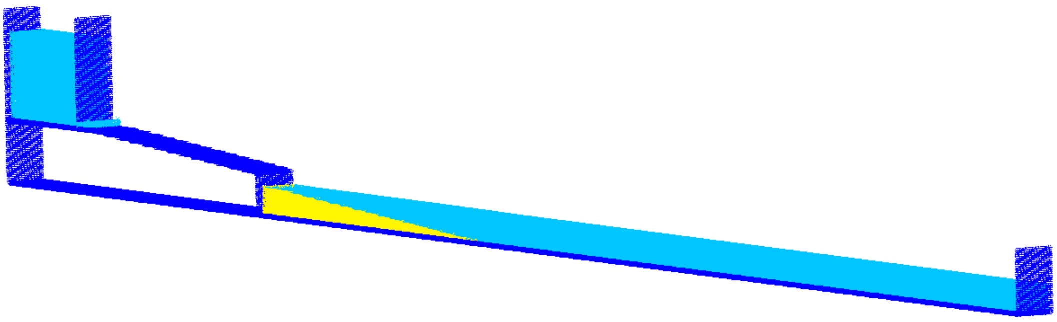

Figure3. Complete view of the particle model

Table1. Analysis option

Initial particle distance	Total particles	Time step	Real time	Analysis time
2cm	1371475	0.001s	25s	24h(16odes×16cores)

Table1 shows the analysis parameters. This numerical experiment was carried out by using super computer in Kyushu University, Fujitsu PRIMERGY CX400. Under these conditions, numerical experiment was carried out. It is shown that analysis result on the next page.

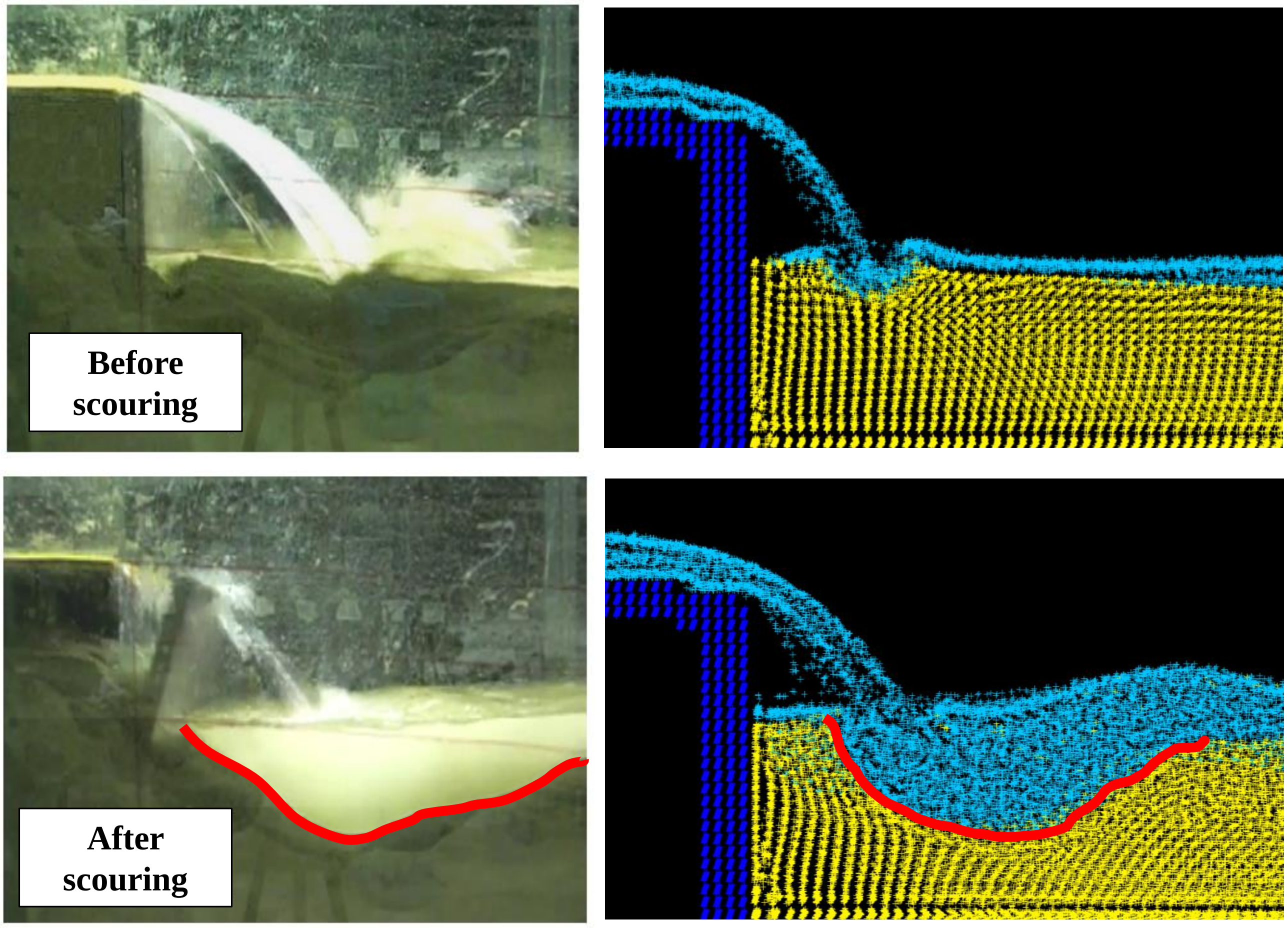

Figure4. Comparison between experiment and analysis result

Fiq.4. shows the analysis result compared to experimental result. Left hand side pictures are before and after scouring snap shot of hydraulic experiment and right hand side pictures are those of numerical experiment. In the right hand side pictures, the soil particles are transported by the flow. From these pictures, the predicted express soil erosion and scouring behaviors shows a good agreement with the hydraulic experiment test. However, the shape of soil erosion is slightly different. As for the reason, various factors are taken into account. One of them is not considering permeability of soil.

Conclusions

In this study, an improved ISPH algorithm has been used to simulate water and soil interactions. All of them are modeled by SPH method. The fluid is modeled as a Newtonian fluid, and the soil is modeled as a Bingham model. In this approach, the soil model considers the granular materials as a fluid, where a Bingham type constitutive model is proposed based on Mohr-Coulomb yield-stress criterion, and the viscosity is derived from the cohesion and friction angle. And in order to validate above scheme and modeling, numerical experiment was carried out. Through this experiment, it was confirmed that ISPH method and modeling soil as a Bingham flow can express soil erosion and scouring. However, its analysis result is good from qualitative perspective, but not so good from quantitative one.
Finally, as a future work, obtaining validated result from quantitative perspective is our goal, in order to achieve this goal, considering permeability of soil is important.

Acknowledgements

This work is partially supported by JSPS Grant-in-Aid for Young Scientists (B); Grant Number 24760365.

References

[1] S.J. Cummins and M. Rudman(1999), An SPH projection method, *Journal Computational Physics*, Vol.152(2), pp.584-607.

[2] E. S. Lee, C. Moulinec, R. Xu, D. Violeau, D. Laurence and P. Stansby(2008), Comparisons of weakly compressible and truly incompressible algorithms for the SPH mesh free particle method, *Journal of Computational Physics*, Vol.227(18), pp.8417-8436.

[3] A. Khayyer, H. Gotoh and S. Shao(2008), Corrected incompressible SPH method for accurate water-surface tracking in breaking waves, *Coastal Engineering*, Vol.55,pp. 236-250.

[4] S. Shao, E.Y.M. Lo(2003), Incompressible SPH method for simulating Newtonian and non-Newtonian ows with a free surface, *Advances in Water Resources*, Vol.26, pp.787-800.

[5] X.Y. Hu and N.A. Adams(2007), An incompressible multi-phase SPH method, *Journal of Computational Physics*, Vol.227, pp. 264-278.

[6] Christian Ulrich and Thomas Rung.(2010), Multiphysics SPH for harbor and ocean engineering hydrodynamics., V European Conference on Computational Fluid Dynamics ECCOMAS CFD 2010.

[7] Yoshimichi Yamamoto, Nunthawath CHARUSROJTHANADECH, Kenji NARIYOSHI(2011), Proposal of rational evaluation methods of structure damage by tsunami, Journal of Japan Society of Civil Engineers, Ser. B2(Coastal Engineering), Vol. 67, No.1 P72-91