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A smoothed particle hydrodynamics method for modelling soil-water interaction

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Abstract

Soil-water interaction, accompanied by large deformation of materials and fluctuation of free surface, is a vital process in landslide induced surge or submarine landslide problems. A great challenge is posed for numerical simulation to deal with free surface, dynamic interface and large deformations. Two typical approaches in the Smoothed Particle Hydrodynamics (SPH) framework for modelling soil-water interaction were proposed: 1. water and soil are simulated as different layers considering permeability and porosity; 2. water and soil are modeled as viscous fluid with different constitutive model in the same layer. However, the former is limited to seepage problems while the latter could not describe the elastic-plastic behavior of soil. An improved SPH based method which could overcome those defects is developed in this paper. Two typical tests of soil-water interaction including back-to-back extrution and face-to-face impact have been presented. The calculations are stable and the results appear acceptable throughout, which shows that the extremely large deformation and the dynamic interface can be handled well by the proposed SPH method. After that, a landslide-generated waves experiment by Heller (2007) is used to verify the accuracy of this method, and a good agreement is obtained in reproducing the soil-water dynamic interface and their respective profiles. The complete process including soil deformation, propagation of water waves, and soil-water interaction can be simulated satisfactorily, which overcomes the defects in the previous methods. This suggests the presented method is capable to deal with soil-water-coupled problems.

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Keywords: Soil-water interaction; large deformation; free surface; dynamic interface; Smoothed Particle Hydrodynamics (SPH)

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1. Introduction

Soil-water interaction is a vital process in landslide induced surge or submarine landslide problems. Numerical predictions for such interactions in the case of large deformations and free surface could provide useful knowledge for engineering practice and design. Some traditional numerical methods, such as finite element method (FEM) and finite difference method (FDM), always suffer from excessive mesh distortions for these problems. The smoothed particle hydrodynamics (SPH) method avoid these numerical instabilities due to its Lagrange and meshless features. Two typical SPH approaches for modelling soil-water interaction were proposed: 1. water and soil are simulated as different layers considering permeability and porosity [1]; 2. water and soil are modeled as viscous fluid with different constitutive model in the same layer [2]. However, both of them still have some flaws, the former is limited to seepage problems while the latter could not describe the soil elastic-plastic behavior. A novel SPH-based method which could overcome those defects is developed in this paper.

The paper is organized as follows. The next section concisely describes the implementation of SPH method for soil-water interactions. Then, two selected examples are presented and a landslide-generated waves experiment by Heller (2007) is used to verify the accuracy of this method. Conclusions are finally presented and discussed.

Nomenclature

α, β	Greek superscripts denoting Einstein's notation
i, j	Latin subscripts denoting individual particles
$f_g, \delta^{\alpha\beta}$	gravitational acceleration and the Dirac delta function, respectively
m, ρ, v, x	mass, density, velocity and position of a soil particle, respectively
σ, ε	the total stress and strain tensor, respectively
c, φ	the Coulomb's material constants: cohesion and internal friction angle
ψ	the dilatancy angle
α_φ, k_c	the Drucker-Prager's constants.
f, g	the yield and plastic potential function, respectively
E, υ	Young's modulus and Poisson's ratio, respectively
G, K	the shear modulus and the elastic bulk modulus, respectively
I_1, J_2	the first and second invariants of the stress tensor, respectively
W	the cubic spline kernel function
SPw, SPs	water particles and soil particles within smoothed kernel, respectively

2. SPH Formulations

2.1. Continuity and momentum equations

The governing equations including continuity and momentum equation in SPH can be expressed as

$$\frac{D\rho_i}{Dt} = \sum_{j=1}^{N} m_j (v_i^{\alpha} - v_j^{\alpha}) \frac{\partial W_{ij}}{\partial x_i^{\alpha}} \tag{1}$$

$$\frac{Dv_i^{\alpha}}{Dt} = \sum_{j=1}^{N} m_j \left(\frac{\sigma_i^{\alpha\beta} + \sigma_j^{\alpha\beta}}{\rho_i \rho_j} - \Pi_{ij} \delta^{\alpha\beta} + F_{ij}^{\ n} R_{ij}^{\alpha\beta} \right) \frac{\partial W_{ij}}{\partial x_i^{\beta}} + f_g^{\ \alpha} \tag{2}$$

The artificial viscosity term Π is used to stabilize the numerical system. The artificial stress method refer to the term $F_{ij}^{\ n} R_{ij}^{\alpha\beta}$ is applied to reduce tensile instabilities.

2.2. The Drucker-Prager soil model

For elastic-plastic materials, the strain rate tensor normally consists of the elastic $\dot{\varepsilon}_e^{\alpha\beta}$ and plastic $\dot{\varepsilon}_p^{\alpha\beta}$ two parts:

$$\dot{\varepsilon}^{\alpha\beta} = \dot{\varepsilon}_e^{\alpha\beta} + \dot{\varepsilon}_p^{\alpha\beta} \tag{3}$$

According to the generalized Hooke's law and plastic flow rule respectively:

$$\dot{\varepsilon}_e^{\alpha\beta} = \frac{\dot{s}^{\alpha\beta}}{2G} + \frac{1-2\upsilon}{3E}\dot{\sigma}^{\gamma\gamma}\delta^{\alpha\beta} \text{ and } \dot{\varepsilon}_p^{\alpha\beta} = \dot{\lambda}\frac{\partial g}{\partial \sigma^{\alpha\beta}} \tag{4}$$

The Drucker-Prager yield condition is applied here to determine the soil plastic flow regime.

$$f(I_1, J_2) = \sqrt{J_2} + \alpha_\varphi I_1 - k_c = 0 \tag{5}$$

The non-associated plastic flow rule specifies the plastic potential function by

$$g(I_1, J_2) = \sqrt{J_2} + \alpha_\psi I_1 - \text{constant} \tag{7}$$

The rate of change of the plastic multiplier λ is obtained by solving

$$\dot{\lambda}_i = \frac{3\alpha_\phi K \dot{\boldsymbol{\varepsilon}}_i^{\gamma\gamma} + (G/\sqrt{J_2})\mathbf{s}_i^{\alpha\beta}\dot{\boldsymbol{\varepsilon}}_i^{\alpha\beta}}{9\alpha_\phi\alpha_\psi K + G} \tag{8}$$

Finally, the stress-strain relationship, in particle approximation form, is given by

$$\frac{D\boldsymbol{\sigma}_i^{\alpha\beta}}{Dt} = \boldsymbol{\sigma}_i^{\alpha\gamma}\dot{\boldsymbol{\omega}}^{\beta\gamma} + \boldsymbol{\sigma}_i^{\gamma\beta}\dot{\boldsymbol{\omega}}_i^{\alpha\gamma} + 2G\dot{\mathbf{e}}_i^{\alpha\beta} + K\boldsymbol{\varepsilon}_i^{\gamma\gamma}\delta_i^{\alpha\beta} - \dot{\lambda}_i\left[3\alpha_\psi K\delta^{\alpha\beta} + \frac{G}{\sqrt{J_2}}\mathbf{s}_i^{\alpha\beta}\right] \tag{9}$$

2.3. Soil-water interaction

In our method, liquid and granular materials were simulated individually in the same layer with their respective physical properties (Fig.1). The brown triangles and blue dots stand for soil and water particles respectively. Water is represented as weakly compressible viscous fluids and soil is modeled as elastic-plastic geo-materials. Both fluid and solid phases are governed by the continuity and momentum equations. Remarkably, the water hydrostatic pressure results from the weakly compressible model by solving the equation of state, while the soil hydrostatic pressure is obtained directly from the constitutive equation by the standard definition of mean stress. The Drucker-Prager model with non-associated plastic flow rules is implemented into the SPH formulations to describe the elastic-plastic behavior of geo-materials. Soil and water particles interact with each other by supplying virtual properties to opposite side of the dynamic interface, and the interaction force is calculated according to the liquid phase. The soil stress state around the interface is corrected in accordance with the local hydrostatic pressure. The virtual properties can be obtained from:

$$\vec{f}_i = \sum_j \frac{m_j}{\rho_j}\vec{f}_j W_{ij} \Big/ \sum_j \frac{m_j}{\rho_j} W_{ij} \tag{10}$$

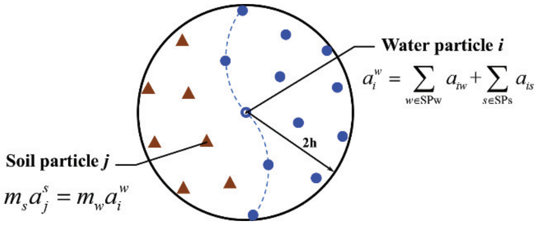

Fig.1 Sketch of soil-water interaction

Table 1. Soil parameters for numerical tests

No.	Soil parameters	Test 1	Test 2
1	Density ρ	2100 kg/m^3	2745 kg/m^3
2	Elastic modulus E	100 MPa	20 MPa
3	Poisson ratio υ	0.30	0.30
4	Cohesion c	10 kPa	0.02 kPa
5	Friction angle ϕ	20°	34°
6	Dilatancy angle ψ	9°	0°

3. Numerical Tests and Discussions

3.1. Test 1: two numerical examples

In order to understand the capability of our SPH code to deal with soil-water interaction, two typical examples of soil-water mass collapsing including back-to-back extrusion and face-to-face impact are tested. The initial arrangement is depicted in Fig. 2 (*t*=0 s). The numerical tests are conducted in a rectangular reservoir with 40 m long and 10 m wide. The soil sample is the same size of 10m×8m square as the water sample, with parameters in Table 1 (Test 1). The strength reduction technique (*SRF*=1.4) is applied here, where c_r and φ_r can be expressed as:

$$c_r = \frac{c}{SRF} \text{ and } \varphi_r = \arctan(\frac{\tan\varphi}{SRF}) \tag{14}$$

We simulated the gravitational flow following soil and water mass collapse. The simulations take up a total of 1280 particles regularly on each phase with an initial spacing of 0.5 m. Fig.2 shows the soil elastic-plastic behavior and the interaction between soil and water at representative times. In these simulations, whether it is back-to-back extrusion or face-to-face impact, the dynamic interface between soil and water is well presented. The soil particles near the boundary are stable during the calculation process and few particles at the interface between the two phases are permeated into each other, which shows a great potential of the proposed method to simulate the soil-water interaction.

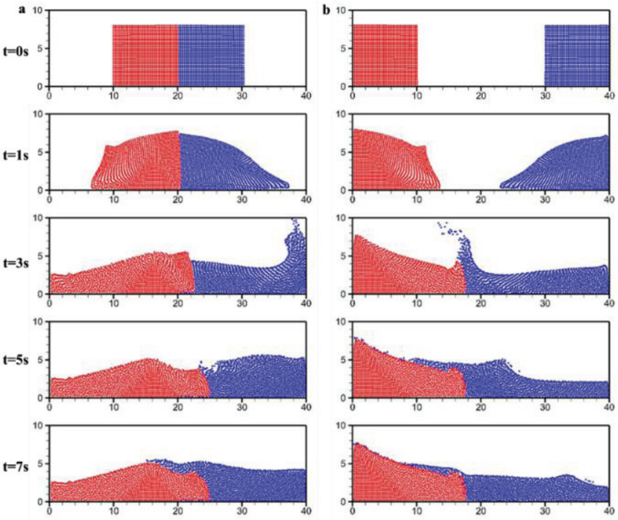

Fig. 2. (a) Back-to-back extrusion; (b) Face-to-face impact.

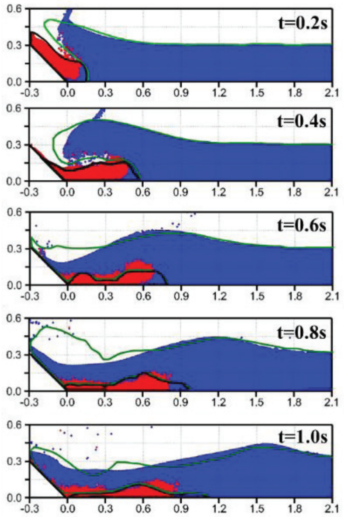

Fig. 5. Profile comparison between the calculated and the observed.

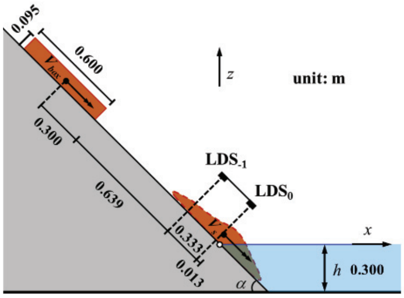

Fig. 3. sketch of landslide induced surge

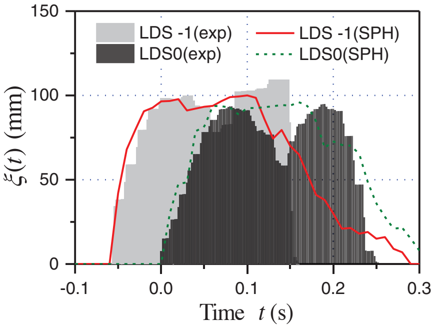

Fig. 4. Slide profile comparing to experimental data.

3.2. Test 2: landslide induced surge

In order to evaluate proposed SPH model for soil-water interaction, a model simulation of landslide induced surge presented by Heller [3] has been carried out. The simulation consists of 61859 water particles, 2299 soil particles, and 15966 boundary particles. The results include the granular slide deformation prior and during impact into the water body and the wave profiles from generation to propagation.

Fig.3 shows a sketch of the geometrical arrangement. A rectangular slide box was filled with granular slide material of dimensions 0.600 m × 0.118 m × 0.472 m and accelerated by a pneumatic landslide generator from the initial centroid position at −2.200 m above the coordinate origin along the hillslope ramp. At −1.285 m above the coordinate origin in the ramp direction, the slide box reached the maximum velocity of $V_{box} = 3.25$ m/s and its front flap opened. The granular slide material left the slide box and accelerated further down the ramp to generate impulse waves in the wave channel. The slide properties are listed in Table 1 (Test 2).

Fig.4 shows the comparison of the slide profiles $\xi(\tau)$ versus time t between experimental data and numerical results at LDS-1(grey region VS red solid line) and during impact at LDS0 (black region VS green dotted line). The agreement between numerical results and observed slide deformation is satisfactory, even if there are some differences in the latter half, especially at the ending of slide profile. These differences can be due to the influences of the wall boundary conditions and viscosity values.

Fig.5 presents the comparison of configration between the calculated and the experimental at representative times. The red region stands for slide material, and the blue part denotes water body. The black and green lines present the observed slide and wave profiles respectively. The results of this simulation seem reasonable for both soil and water behavior. Fig.5 demonstrates that the numerical results are in well agreement with the observation at the stage of generation. Although they are not so much in agreement at the stage of propagation especially at slide front, the SPH simulated results are still exciting and appear acceptable throughout.

4. Conclusions

The soil-water-coupled SPH method for simulating the behavior of soil-water interaction has been described through this paper. Water is represented as weakly compressible viscous fluids while soil is modeled as an elastic-perfectly plastic material. Soil and water particles interact with each other by supplying virtual properties to opposite side of the dynamic interface, and the interaction force is calculated according to the liquid phase.

Two typical examples of soil-water interaction including back-to-back extrution and face-to-face impact have been presented. The calculations are stable and the results appear acceptable throughout, which shows that the extremely large deformation and the dynamic interface can be handled well by the proposed SPH method. After that, a landslide-generated waves experiment by Heller [3] is used to verify the accuracy of this method. The numerical results correspond satisfactorily with the physical model test results in both the observed slide and wave profiles, which shows the implemented model can be capable to reproduce correctly the kinematics of both the soil and water body and their interaction.

Acknowledgements

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