MODELING OF WATER-AIR-SOIL THREE-PHASE MATERIAL USING SMOOTHED PARTICLE HYDRODYNAMICS METHOD AND ITS APPLICATION TO SEEPAGE FAILURE DUE TO HEAVY RAINFALL

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URL http://doi.org/10.20602/00003224

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Extreme weather events caused by the climate change have triggered many natural disasters worldwide. Among these disasters, rainstorms or heavy rainfalls including the localized torrential downpours and the large-scale typhoon place the greatest threats to the people's lives and properties in the urban area for the triggering of river dike ruptures, floods and flow slides. There are some important factors that should be considered in the analysis of seepage failures due to heavy rainfall, such as the water-air-soil coupling, the unsaturated behavior, the large deformation, the surface infiltration, and so on.

The Smoothed Particle Hydrodynamics (SPH) method, has a unique advantage on the simulation of free surfaces, deformation boundaries and large deformations, therefore is suitable for the analysis of slope and dike failures under heavy rainfall. However, to date, few studies regarding SPH simulations of seepage failures under heavy rainfall that consider the water-soil-air coupling, large deformation, surface infiltration, and suction reduction have been presented in the literature. Therefore, this work conducted the study on the modeling of water-air-soil three-phase material using the SPH method, the verifying and validating of the
The proposed SPH method, and the application of it to seepage failure model tests.
In the proposed water-air-soil three-phase SPH model, the fluids and solid are simulated on different layers. The three-phase field theory was introduced and related quantities are derived.
Then, governing equations including the continuity equation and the momentum equation are transformed to SPH formulas for the water phase, air phase, and soil phase, respectively. The equation of state is used to calculate the pressure change of the water phase and the air phase.
After that, we introduce a novel unsaturated constitutive model to describe the behavior of the soil phase. Besides, the proposed SPH model adopts the frictional forces, with due consideration of the effects of the porosity and the coefficient of permeability, as interaction forces between different phases.
The B-spline function is selected as the smoothing kernel function to obtain high accuracy and efficiency. Based on the Linked-list searching algorithm, a highly effective searching algorithm has been proposed and applied in the SPH programs. Meanwhile, the critical section in OpenMP API and the atomicAdd in CUDA solved the incoherent issue of the parallel optimization. After that, using the C++ programming language, highly parallelized SPH programs are written, called the ZM-OP (OpenMP) SPH program and the ZM-CD (CUDA) SPH program.
From a dam break, a triaxial compression test and a water-air coupled case, SPH simulations of the water phase, air phase, soil phase, and furthermore the effect of the suction reduction are verified and validated. The coupling between the water phase and the soil phase was checked through the simulation of a falling head permeability test and a flowing test of liquefied soils.
After that, the proposed SPH method is proved to be a highly effective numerical method by simulating a three-dimensional dam break with different number of threads and GPUs.

The application of the proposed SPH method was extended to three seepage failure tests, the dike failure due to the water level up, the dike failure due to heavy rainfall, and the slope failure due to heavy rainfall. The SPH simulations reproduced the surface infiltration of shallow slope failures, the deformation process, the air blow, the suction reduction, and the Rayleigh–Taylor instability, corresponding with model tests. The proposed SPH method provided new insights and is a novel numerical tool for the analysis of seepage failures due to heavy rainfall.
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The doctoral thesis is excellent and adequate for the doctor degree.