

ADVANCED SIMULATION OF DEBRIS FLOWS BASED ON A MULTI-PHASE SMOOTHED PARTICLE HYDRODYNAMICS

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論 文 名 : ADVANCED SIMULATION OF DEBRIS FLOWS BASED ON A MULTI-PHASE
SMOOTHED PARTICLE HYDRODYNAMICS
(多相粒子法による先進的な土石流シミュレーション)

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論 文 内 容 の 要 旨

Catastrophic debris flows are characterized as rapid, gravity-driven heterogeneous mixtures of viscous fluids and solids that are complex in terms of material composition and exhibit unpredictable spatiotemporal evolution. These phenomena pose one of the greatest threats to human society due to their high flow velocity, extreme impact force, and extensive run-out distances. Due to their complex and dynamic nature, the prediction, modelling, and theoretical description of debris flow physical processes remain acknowledged as open and multidisciplinary challenges in earth science. This thesis addresses the major unresolved issues in the numerical analysis of debris flows by developing and applying advanced numerical simulation methods.

Smoothed particle hydrodynamics (SPH) is widely used in hydrodynamic problems and geotechnical engineering due to its superior ability to handle large deformations, free surface flows, and post-failure scenarios. The discrete element method (DEM), on the other hand, offers unparalleled insight into the discontinuous and heterogeneous nature of granular materials. These particle-type simulation models have great potential to solve several open questions in numerical soil flow analysis. The first major issue is the modeling of erosion, entrainment, and deposition, which are the primary processes in debris flows. These processes exhibit morphological changes, phase changes from solid to fluid, and vice versa. Erodible bed can then increase the total mass and momentum of debris. This phenomenon is referred to as positive feedback of debris flow and can be negative in the case of dry sediments. Positive and negative feedbacks of debris flow are secondary major issues. By solving the open questions in modeling debris flows, this thesis proposes a two-layer multiphase smoothed particle hydrodynamics (TLMP-SPH) model for simulating viscous debris flows. In addition, a coupled SPH-DCDEM scheme is also developed by combining the DEM for boulder-rich debris flows. Finally, the application of these advanced simulation models to field-scale disaster prediction is discussed.

The contents of this study are organized as follows:

Chapter 1 presents the background, scope, and objectives of the study, along with an outline of the thesis organization. It details the classification and triggers of debris flows and emphasizes the threats posed by debris flows and the associated disaster chains. Additionally, it briefly discusses the methodologies available for analyzing these disasters.

Chapter 2 offers a detailed review of debris flow prediction and numerical simulation methods. It then concentrates on the research frontiers, engineering application, and existing

issues of SPH and DEM. Furthermore, it introduces the fundamental theories of the SPH and SPH-DEM coupled methods utilized in this study.

Chapter 3 develops a Two-Layer, Multi-Phase SPH (TLMP-SPH) model to simulate the rheological characteristics and dynamic processes of viscous debris flows, including erosion, entrainment, and deposition. It begins with a comprehensive introduction to various rheological models of debris flows and their implementation in the SPH scheme. The Herschel-Bulkley-Papanastasiou (HBP) rheological model is integrated with different yield criteria to capture complex processes such as erosion and entrainment. To ensure stable phase transitions on steep terrains, a specific phase transition model is developed. Finally, several numerical tests are conducted for verification. This study offers an innovative paradigm based on multiphase flow particle modeling, potentially informing better analysis and prediction.

Chapter 4 pioneers a hydro-poro-mechanics-based pore water pressure algorithm embedded within the TLMP-SPH scheme to simulate the pore pressure response and flow momentum growth of debris flows on beds with varying wetness. To address scale effects, this method is rigorously tested and validated through a series of large-scale flume experiments conducted by the United States Geological Survey (USGS). The findings reveal that the model proficiently captures and replicates the intricate dynamics of flow momentum growth, reflected in erosion-induced variations in volume and mobility. Our methodology establishes a definitive link between volumetric water content and pore pressure response, further emphasizing its ability to characterize levee-channel and deposition morphology. This study represents the first attempt to model debris flow on beds of varying wetness from a particulate perspective.

Chapter 5 constructs a two-way, resolved SPH-DCDEM coupling scheme for dynamic simulation of boulder-rich debris flows. In this approach, fine-grained materials and viscous fluid are generalized to a viscoplastic flow following the HBP non-Newtonian flow dynamics. The DCDEM represents irregular boulders with much larger particle scales, explicitly defining the interaction forces between fluid and solids, and among solid particles. Similarly, numerical tests on the collapse of multi-layered aluminum columns and debris-flow impacting on varying sloping bed are conducted. The results indicate the capability of the applied approach in both solid-solid and solid-fluid systems.

Chapter 6 extends the proposed method to field-scale hazard prediction, applying it to real-world cases, including the 2010 Yohutagawa debris-flow event in Japan and the 2010 Hongchun Gully debris-flow event in China. The first example is simulated using TLMP-SPH for the viscous-type debris flow, while the second simulation utilizes the two-way resolved SPH-DCDEM. These simulation results successfully reproduce the dynamic processes of both events, particularly depicting the deposition morphology on the alluvial fan. By adjusting the water content of the bed sediment, the entrainment volume in the Yohutagawa event is calibrated. This study demonstrates the potential of the proposed TLMP-SPH for practical engineering applications.

Chapter 7 summarizes the conclusions and proposes recommendations for future research.