DEVELOPMENT AND APPLICATION OF A NEW NUMERICAL SIMULATION METHOD FOR DEBRIS FLOW WITH LARGE BOULDERS BY COUPLING 3D DDA

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論 文 名　: DEVELOPMENT AND APPLICATION OF A NEW NUMERICAL SIMULATION METHOD FOR DEBRIS FLOW WITH LARGE BOULDERS BY COUPLING 3D DDA
(3 次元 DDA との連成による巨礫を有する土石流シミュレーション手法の開発と適用)

区　　分　: 甲

論 文 内 容 の 要 旨

Debris flow is a geo-hazard frequently occurred in mountainous regions. Due to the sudden occurrence, high-speed motion and large volume of sediment, debris flow can cause serious disaster and is one of the major threats to residents and structures in susceptible areas. For example, the 1999 Venezuela debris flow killed about 15,000 lives and destroyed or damaged more than 88,000 buildings. Various kinds of countermeasures, such as check dams and concrete canals, have been developed for disaster mitigation. In order to design proper countermeasure structures, it is important and necessary to estimate the kinematic and mechanic behaviors of a potential debris flow as well as impact forces on structures in risk.

In recent decades, many studies on debris flows have been conducted by using numerical methods, analytical methods, empirical approaches based on in-situ investigations and laboratory experiments. With advancement of computer technique, numerical methods become more and more attracting in researchers in this field. Among them, conventional debris flow simulation (DFS) with a depth-integrated model based on Navier-Stokes equations has been widely used because it can be easily applied to simulate evolution of debris flow with bed-sediment erosion as well as estimate kinematic behaviors such as flowing velocity, depth and volume of debris flow and inundated area with high efficiency. However, since DFS is based on two-phase fluid of water and solid, called pure debris flow here, using the so-called volume concentration for different ratio of solid to water, there are seldom debris flows of two-phase fluid in nature. In fact, large boulders and driftwoods are often involved in debris flows, called boulder debris flow here, according to a large number of past events. It is obvious that the behaviors and impact force of boulder debris flow cannot be correctly estimated by DFS with two-phase fluid model. How to simulate boulder debris flows still remains unsolved problem.

This study aims at developing a new numeric technique for simulating boulder debris flows by coupling Discontinuous Deformation Analysis (DDA) with conventional DFS. DDA is a powerful numerical method for modelling dynamic behaviors of a rock mass system involving discontinuities, and it has been well used for rock-fall analysis and landslide simulation. Thus, the dynamic behavior and impact force of the transported boulders in debris flow can be estimated by three-dimensional DDA while the kinematic and mechanic behaviors of two-phase fluid are estimated by conventional DFS. To this end, the existing 3D DDA is firstly improved by incorporating a damped contact model to simulate inelastic collisions. And then, a coupled method of improved DDA and DFS (3D DDA-DFS) is developed for simulating boulder debris flows. Subsequently, the impact force of large boulders on check dam are investigated and discussed through a series of conceptual examples. Finally, a case study is carried out using the developed 3D DDA-DFS method to discuss the kinematic and mechanic behaviors of a boulder debris flow based on a real catchment.

The contents of the thesis are organized as follows:

Chapter 1 introduces the background, the scope and objectives of the research. Previous studies on debris flow and the transported large boulders are reviewed. The existing methods are briefly discussed.

Chapter 2 reviews the state-of-the-arts of 3D DDA and DFS. The basic theories and equations are introduced together with their advantages and applications. The above-mentioned unsolved problems are also clarified.

Chapter 3 improves 3D DDA by incorporating a damped contact model for inelastic collision. Original DDA is based on perfectly elastic collision, but energy dissipation occurs almost in any real collisions in nature. If energy loss is not addressed, the collisions between large boulders, slope surface and structure could be inaccurate. In order to make DDA applicable to real collisions, a damped contact model based on linear spring-dashpot assumption is incorporated into 3D DDA. How to determine the control parameter viscous damping coefficient of dashpots is discussed and clarified using a predefined coefficient of restitution (COR). Inelastic collisions with unconstrained and fixed targets are carefully investigated. Rebound of a freefall block assembly is analyzed for demonstrating viscous damping effect. The results show that the damping effect is significant and should be properly addressed.

Chapter 4 develops a fluid-solid coupling method called 3D DDA-DFS by coupling 3D DDA with DFS for simulating boulder debris flows. First, a framework for flow-solid interaction is proposed. Then, an interactive module is incorporated for evaluating the interactive forces between DFS flow and DDA solid blocks through the synchronization of the 3D DDA module and DFS module since time steps in both methods are quite different. Thirdly, the flow force on solid blocks, including static pressure, buoyancy and drag force, are incorporated for arbitrarily shaped polyhedral blocks on complex 3D terrain. In addition, the drag effect between adjacent blocks is addressed so that the calculated drag force is more realistic. Fourthly, since direct implementing of force from DDA blocks on DFS flow is not easy, which involves large deformed boundary condition in the flow governing equation, an equivalent solution is proposed by taking the action of blocks on flow as time-varying elevation of terrain node. Finally, the coupling scheme as well as the calculations of the interaction forces are validated by a number of examples.

Chapter 5 clarifies the behaviors of large boulders and driftwoods in debris flow. At first, a series of simulations are carried out on debris flows with boulders in a channel model with a downstream check dam. The impact forces and deformations that the dam suffers from are analyzed under different kinds of debris flows. The results show that (1) A boulder debris flow can destroy the check dam that cannot be destroyed by the corresponding pure debris flow, and the impact force of the boulder debris flow can be about 15 times larger in an example than that of the pure debris flow; (2) The impact forces and deformations are related to the size, distribution and shape of the boulders very much. The dam can be deformed slightly or largely and even destroyed totally under different boulders. Larger size, higher initial altitude, subcircular shape of the boulders are capable of causing more damages to the dam. And then, the behaviors of driftwoods in debris flow are also investigated. The movement looks reasonable, and the impact force is larger than that of pure debris flow but smaller than that of the boulder with the same volume. The driftwoods can either be stopped by the dam or pass over the dam when overflowing occurs. The example shows that the driftwoods in debris flow can also be simulated by developed 3D DDA-DFS method.

Chapter 6 performs a case study by using the 3D DDA-DFS method to simulate potential debris flow with large boulders based on a real catchment located in Amami Oshima, Japan, where the 2010 Yohutagawa debris-flow event occurred. The same source area of the debris flow is used, and a number of boulders are distributed in the valley path. When debris flow passes by, the boulders are driven and move along with debris flow. The simulation results show that the transported boulders can break the dam, and more area will be affected by the alluvial fan although the dam was not destroyed under the real debris flows due to no large boulders involved. The dam safety is further analyzed by a number of dam properties and the results suggest that the strength of the dam should be much higher if boulders are involved in a potential debris rather than a pure debris flow. Therefore, the developed 3D DDA-DFS method is applicable to simulation of debris flow with large boulders. The 3D DDA-DFS can be used to check whether the check dam is safe under boulder debris flow, and the critical strength of check dam can also be determined by 3D DDA-DFS simulation.

Chapter 7 summarizes the conclusions and recommends the problems to be solved in future studies.