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Technical Paper

Numerical simulation for runout process of debris flow using depth-averaged material point method

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Abstract

Debris flows, i.e., combined flows of watery mud, chunks of boulders, trees, etc., can be extremely destructive to life and property and can exhibit complicated mechanical features. These complicated features of heterogeneous debris-flow surges can be rationally modeled by considering the rheological behaviors of solid, liquid, and interaction-force phases. Herein, we present the simulation results obtained using a numerical method for a runout process of debris flows based on the depth-averaged equation of motion implemented with the material point method. This method enabled us to describe the debris-flow behaviors in a more adequate manner than previous methods, by simulating debris flows using a depth-averaged model. The simulation results were verified by comparing them with the results of flume tests on dry and wet sand flows. The test results were calibrated to identify the key parameters for simulating the runout process of soil flows. In addition, a real debris-flow event was simulated, and important features of the simulated debris flow, i.e., the geographical dimensions of the depositional zones, conformed well to the observed dimensions of the real debris flow.

Keywords: Debris flow; Depth-averaged equation; Material point method; Rheological model

1. Introduction

Fast-moving flows of debris, which grow in volume with the addition of water, sand, mud, boulders, and trees, are among the most numerous and dangerous types of landslides and are extremely destructive to life and property. Debris flows vary in size, from watery mud to thick, rocky mud, and exhibit complicated mechanical features. Intense rainfall, glacial melting, or earthquakes at high-elevation sites, either alone or combined with each other, can result in deadly debris flows. The average speed and volume of a debris flow vary from 5.0 to 80 km/h and several tens of cubic meters to more than 100,000 m^3, respectively. The channel geometry, the presence of loose sediments, and forest-harvesting activities also influence debris-flow behaviors.

Recently, various forms of landslides have been reported worldwide. The Mid-Niigata Prefecture Earthquake jolted central Japan on October 23, 2004 and was followed by several aftershocks. The epicenter of the earthquake was in the low-raised Higashiyama mountainous terrain, which has a very clear active-folding geological structure. Numerous landslides occurred in the mountainous areas, particularly along the Imogawa River, where landslide masses stopped the waters of the Imogawa River and its tributaries. These landslides caused a serious threat in terms of the occurrence of a

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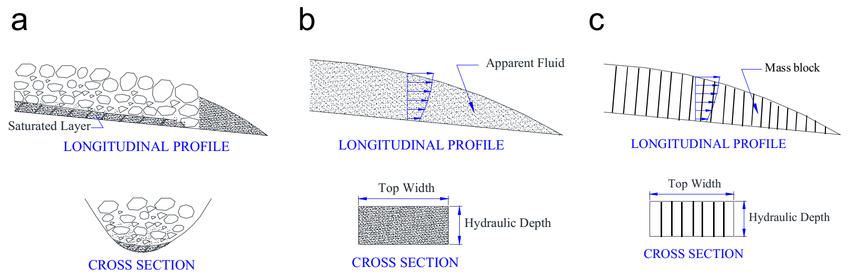

Fig. 1. Basic concept of the numerical model proposed by Hungr (1995).

debris flow to the people living along the lower reaches of the river (Marui and Yoshimatsu, 2007). In the 2005 magnitude-7.6 earthquake in Kashmir, Pakistan, a large landslide occurred 3.5 km upstream of the town of Hattian Bala. The landslide masses blocked two tributaries of the Karli branch of the Jhelum River, forming two lakes behind it. This landslide dam was breached on February 9, 2010, following five days of rain and snowfall, which triggered debris flows that eroded ~7.78 million m^3 of soil during the breaching event (Konagai and Sattar, 2012). In the 2008 Iwate-Miyagi earthquake, a large debris flow occurred at Dozou-sawa near the top of east Mt. Kurikoma. Its average speed and amount of soil were estimated to be 30 km/h and 650,000 m^3, respectively. The debris flow killed seven people and destroyed a hot-spa hotel called Komanoyu (Kazama et al., 2011). Moreover, the increased seismic activity after the March 11 Tohoku Earthquake off the Pacific coast of Japan in 2011 raised serious concerns about landslide risks nationwide. Thus, it is necessary to define countermeasures for mitigating debris-flow risks, particularly in mountainous areas.

These countermeasures should be considered from both “technical” and “non-technical” viewpoints. One typical technical measure is to construct check dams to reduce the speed of the debris flows, which reduces erosion and gullying in the flow channel and allows sediments and pollutants to settle. It is desirable to arrange check dams in a stepwise manner along a channel. However, it is always a matter of thorough discussion to assure maximum safety by means of a scientifically rational approach with minimal human, economic, and time resources, especially when the hazardous area is extremely wide. In particular, it is necessary to identify the point of origin, onset, and end of terminal deposition when planning the optimal arrangement of these check dams. This identification is also important for preparing a reliable hazard map to map out the “non-technical” measures.

A risk assessment of mountain slopes is mandatory for identifying debris-flow source areas. Okimura and Ichikawa (1985) proposed a method for estimating the landslide hazard potential by considering the groundwater movements and topographical features of mountain slopes. The source areas can be identified using such a method. There are two major difficulties in analyzing the rapid, large-mass movements and depositional processes of debris flows. The first is describing the history-dependent mechanical features of the combined flow of watery mud, chunks of boulders, trees, etc. The second is that strains are not accurately calculated when elements of the debris mass model are largely distorted. For dealing with the second difficulty, mesh-free methods, such as the material point method (MPM, Sulsky et al., 1994 and 1995) and smoothed-particle hydrodynamics (Lucy, 1977; Gingold and Monaghan, 1977), which employ a set of a finite number of particles that move around to represent the history-dependent mechanical features of a landslide mass and record their locations in a time-marching calculation scheme, are used.

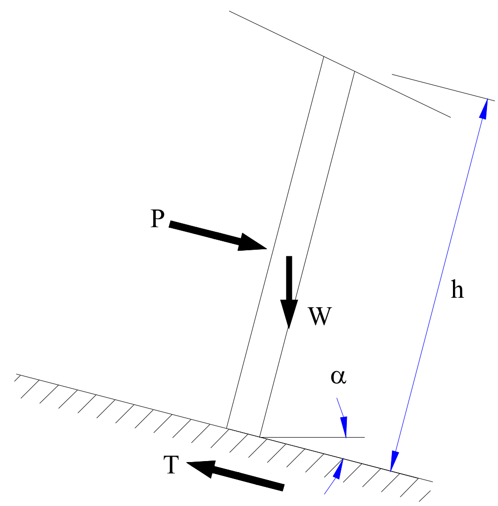

Fig. 2. Net driving forces acting on each boundary block in Hungr's model (Hungr, 1995).

Presently, with highly manipulative numerical solutions for problems of increasing complexity, three-dimensional (3D) mesh-free methods can be used for debris-flow analyses. However, given the first difficulty, it has been a long-continued practice to use the depth-averaged equations of motion to describe gravity-driven debris flows (Sassa, 1988; Savage and Hutter, 1989; Hungr, 1995; Iverson and Denlinger, 2001). In depth-averaged modeling, debris masses are replaced by a homogeneous apparent fluid and separated by mass blocks, as shown in Fig. 1. Then, the net driving force acting on each boundary block consists of a tangential component of weight $W \sin \alpha$, a basal resisting force T, and a tangential internal pressure resultant P, as shown in Fig. 2. An advantage of modeling debris flows with the depth-averaged equation of motion is the ability to describe complicated 3D geometries easily in pseudo-3D planes, significantly reducing the calculation task load. Another advantage is the ability to separate the complicated net driving force in the heterogeneous debris-flow surges into two forces: the resultant internal pressure P and the basal resisting force T. The rheological behavior of the solid phase can be modeled by the resultant internal pressure