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Post-failure simulations of a large slope failure using 3DEC: The Hsien-du-shan slope

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ABSTRACT

The goal of this paper is to evaluate the post-failure behavior of the Hsien-du-shan rock avalanche, which was triggered by Typhoon Morakot in 2009, using a three-dimensional (3D) discrete element program, namely, 3DEC. The 3D slope topography and local joint sets are explicitly considered in the calculations, and the joint sets cut the sliding rock mass into blocks with arbitrary shapes. The modeled blocks exhibit the elastic behavior of the local rocks. The analysis successfully simulates the wedge failure at the initiation of the landslide. Additionally, the 3DEC results clarify the local rock sliding phenomena at the boundaries of the source area. The simulated depositional area correlates well with the actual area affected by the Hsien-du-shan rock avalanche. In addition, the erosion of a ridge by the sliding rock near the southwestern margin of the area at an elevation of 590 m has a significant influence on the shape and size of the impacted area. The interlocking effect between blocks is also considered.

1. Introduction

In 2009, the heavy rainfall of Typhoon Morakot triggered the Hsien-du-shan rock avalanche (Fig. 1), which killed > 400 local residents in the nearby Hsiaolin Village in Taiwan. The tragedy emphasized the insufficient technologies available to warn residents of large slope failures and to evacuate residents affected by rainfall-induced rock avalanches.

A rock avalanche is an extremely rapid, flow-like movement of fragmented rock from a large rock slide or rock fall (Hungr et al., 2001). Devastating damage and a short warning time are two major challenges in mitigating such a disaster, especially when a mountain village is nearby (Lee et al., 2009; Chen and Wu, 2018). Identifying the area impacted by a large landslide is an economic countermeasure that is useful in planning the future development of mountain villages.

Dynamic behavior, large displacement, and block contacts are three essential aspects in post-failure behavior analysis. Many discrete numerical approaches can be applied to simulate the post-failure behavior of a large slope, such as the distinct element method (DEM) (Cundall and Strack, 1979; Wu et al., 2017b), discontinuous deformation analysis (DDA) (Wu et al., 2009; Wu and Chen, 2011; Wu et al., 2017a), numerical manifold method (NMM) (Shi, 1991), general particle dynamics (GPD) (Zhou et al., 2015), and peridynamics (PD) (Silling, 2000) Local residents can easily visualize the possible slope movement and determine the hazard potential from the simulation results.

The open arrow in Fig. 1 is the sliding path of the Hsien-du-shan rock avalanche from the source area to the depositional area. After the rock avalanche occurred, the sliding rocks/soils moved downward from the source area via the transitional area. When the flow reached the area known as the “590-m height” at the elevation of 590 m, the flow directions of many sliding rocks/soils shifted northward, and the avalanche divided into 3 flow paths, refer to as Routes A, B, and C. The scar of the landslide dam on the west bank of the Chishan River is evidence of the three-dimensional (3D) movements of the blocks because the arrangement of the source area, the area at 590-m, and the landslide dam is not rectilinear. In addition, a large volume of rocks moved along Route B down to the Chishan River. The 3D movement shows the complicated interaction between local topography and sliding rocks, especially at the 590-m height. A 3D numerical simulation technique is required to simulate the post-failure behavior.

The post-failure behavior of the Hsien-du-shan rock avalanche was simulated using a 3D sphere distinct element model, PFC 3D (Tang et al., 2009; Lo et al., 2011). However, PFC 3D did not appropriately simulate the in situ elastic rocks and the contacts between blocks with planar joints. When a polyhedron (Fig. 2a) is simplified as an assemblage of bonded particles (Fig. 2c), the block surface changes from a planar surface to one with bumpy discontinuities. The particle size and packing govern the block surface roughness and affect the block sliding distance (Donze et al., 2009). Therefore, the simplification of a polyhedron as a particle or an assemblage of particles reduces the reality of

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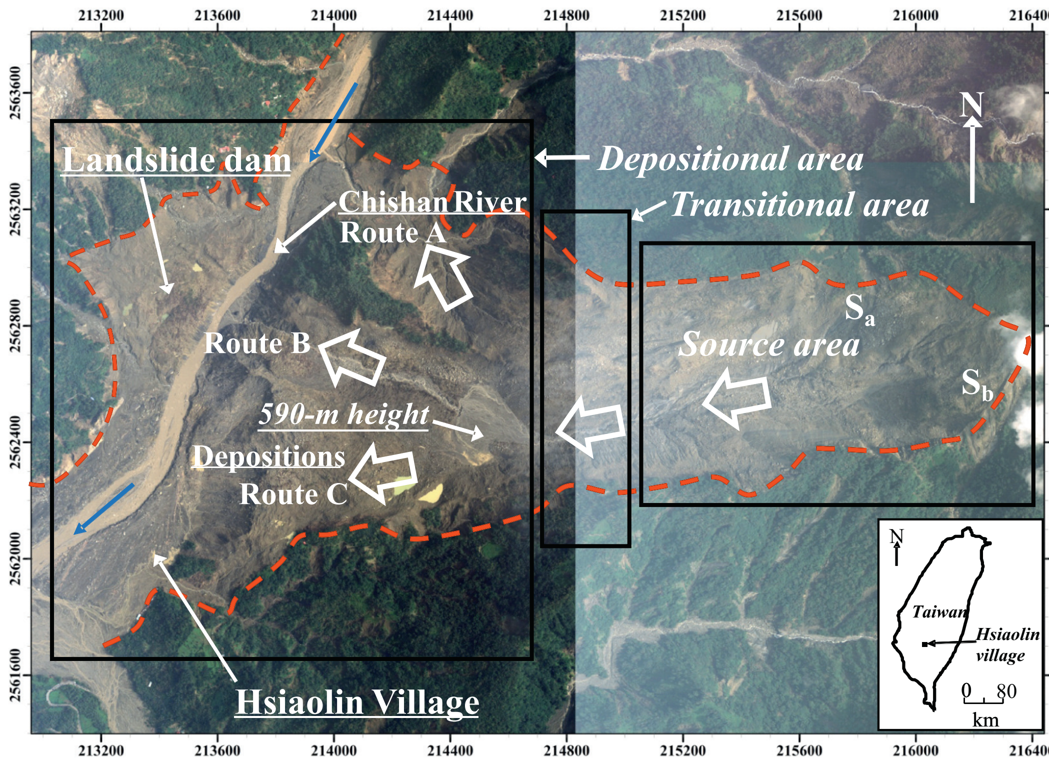
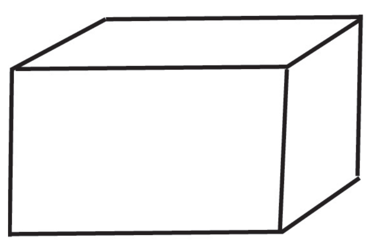
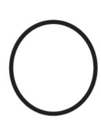


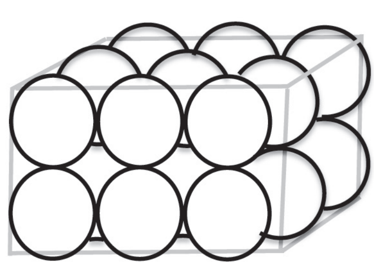
Fig. 1. The aerial photo of the Hsien-du-shan rock avalanche.



(a) Polyhedron with planar surfaces



(b) Simplification to a sphere



(c) Simplification to an assemblage of spheres

Fig. 2. Simplification polyhedrons to spheres.

the block deformability, shape, contact patterns, sliding movement, and topography of a blocky rock mass (Lisjak and Grasselli, 2014). The same issues arise in other numerical analysis methods with particle assumptions, such as GPD and PD.

Therefore, the DEM, DDA, and NMM with polyhedral blocks are considered discrete numerical methods that can potentially simulate the Hsien-du-shan landslide. Theoretically, the DEM uses an explicit time integration approach (Cundall and Strack, 1979), but the DDA (Wu et al., 2009) and the NMM (Shi, 1991) use implicit time integration. The unnecessary global matrix generation in each calculation step in explicit time integration increases the calculation speed in DEM relative to DDA and NMM, especially when there are numerous blocks. In this study, the 3D DEM software called 3DEC (Itasca Consulting Group, Inc, 2007a, 2007b), which explicitly describes the local 3D topography and the geometry of discontinuities in a sliding rock mass, is applied to simulate the post-failure behavior of the Hsien-du-shan rock avalanche. In addition, the rocks are assumed to be elastic. The accuracy of the computational landslide impact area is assessed through a comparison with a local aerial photograph.

2. Outline of the Hsien-du-shan slope

Fig. 3 shows the topographic change in the Hsien-du-shan slope before and after the landslide. The red line in Fig. 3 indicates the boundary of the rock avalanche. In Fig. 3b, based on a comparison with Fig. 1, images of the vegetated zone A in the upper part of the source area were not updated in 2010 by Google Earth. In Fig. 3, P1 is at the toe of the resource area, P2 is at the downhill end of the 590-m height, and P3 is at the intersection of Route B and the Chishan River at the north end of the original Hsiaolin Village (Fig. 3a). Fig. 3a shows that the creek channel of P1-P2-P3 existed before the Hsien-du-shan slope failure.

2.1. Local geology

The geological maps proposed by Lee et al. (2009) and Tsou et al.

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