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Investigation of the Hsien-du-Shan rock avalanche caused by typhoon Morakot in 2009 at Kaohsiung county, Taiwan

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ABSTRACT

The Hsien-du-shan rock avalanche at Kaohsiung County, Taiwan, was triggered by heavy rainfall brought by Typhoon Morakot in 2009. Heavy rainfall began on the day of August 6, and continued to the morning of August 9 when the slope failure and landslide occurred. In this post-event investigation, physical, mechanical, and hydraulic properties of the rocks/soils at this large landslide site are evaluated. The *in situ* hydraulic conductivity of the soils at the source area was found to be too low ($k=1.48\times10^{-6}$ m/s) for rainfall to vertically infiltrate to the deep sliding surface, which was found to have a maximum depth of 85.6 m. The post-failure simulations using discontinuous deformation analysis (DDA) suggest that the geometry of the sliding surface governs the failure behavior, and two continuous progressing failures likely occurred at the beginning of the Hsien-du-shan rock avalanche.

Slope deformation was observed by the local residents before the Hsien-du-shan rock avalanche occurred as a geomorphologic precursor. In addition, water accumulation along the sliding surface governs the behavior of the sliding surface. Therefore, in the future, an early warning system of a rock avalanche can be developed by simultaneously applying high-resolution airborne LiDAR to detect slope deformation and using geo-electric measurements to image the infiltration of surface water to the sliding surface.

1. Introduction

Rock avalanche is defined as an extremely rapid, massive, flow-like motion of fragmented rock from a large rock slide or rock fall [1] and severely threats the people living in the mountainous areas. The Duraham Fatal Landslide Database shows that increasing intensity of typhoons is a governing factor of a rainfall-induced rock avalanche [2] and highlights the importance to investigate the behavior of the rainfall-induced rock avalanche. The case studies of rock avalanches indicate that rainfall duration governs the depth of the slope failure: long duration rainfall causes deep landslide, while, high intensity and short duration rainfall triggers shallow slides [3,4]. Additionally, strongly weathered and highly fractured rock mass is the inherent factor to the rock avalanche [4,5]. The initiation of a rock avalanche can be in the damaged zone of a geological structure [6]. The rainfall infiltrating through the highly fractured rock mass saturates and increases the pore pressure of the rocks/soils near the sliding surface to trigger the large landslide [5,7]. Moreover, slope deformation is a geomorphologic precursor of rock avalanches [8]. Additionally, the behavior of a rainfall-induced rock avalanche can be simulated by a schematic model [9] and numerical simulations [8,10].

On August 9, 2009, the Hsien-du-shan rock avalanche at Hsiaolin village, Kaohsiung County was triggered by the rainfall of Typhoon Morakot and killed more than 400 local residents. The rock avalanche at Hsiaolin village is unique because the historical landslide records are unavailable. The slid volume of the Hsien-du-shan rock avalanche was approximately 27.718×10^6 m^3, and the maximum sliding thickness was 85.6 m [11]. The sliding slope can be divided into a source area, a transitional area, and a depositional area from east to west, as shown in Fig. 1(a). The pre-failure, fluvial generated wide valley bottom became the depositional area in its western part. Fig. 1(b) shows an image of the flat ground, the depositions, and the valley of the Chishan River.

Fig. 2 shows the rainfall record at Chiahsien rainfall station, which is located 10 km southwest of Hsiaolin village from August 6 to 11. The maximum hourly rainfall was 94.5 mm at 18:00 on August 8. The cumulative rainfall exceeded 2000 mm. The rock avalanche occurred at 6:09 a.m. on August 9, 2009, which was 12 h after the maximum hourly rainfall was detected [12].

Regarding the studies of the mechanism of the rock avalanche, the loose thick colluvium at the source area provided suitable conditions for water infiltration and caused the unstable wedge to be easily saturated [13]. The depositional pattern of the Hsien-du-shan rock avalanche was simulated using a three-dimensional distinct element model, PFC 3D [14,15], and a new continuum shallow-water model [16]. The computational results by 3D PFC suggested that the maximum velocity of the slid rocks was 50 m/s

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[14] to 70 m/s [15]. The landslide occurred on a dip slope overlying late Miocene to early Pliocene sedimentary rocks consisting of silty shale, massive mudstone, and sandstone. The apparent frictional angle of the landslide was 14° [17]. The landslide was preceded by gravitational deformation, which appeared as hummocky landforms before the landslide and as exposed buckle folds after the event.

However, the physical, mechanical, and hydraulic properties of the rocks/soils are still unavailable. Additionally, in the study of Lu et al. [18] it was argued that the failure process was a single or progressing failure to the Hsien-du-shan rock avalanche based on slope stability analysis.

Therefore, this study attempts to investigate the physical, mechanical, and hydraulic properties of the local rocks/soils. Additionally, the failure behavior of the Hsien-du-shan rock avalanche is simulated by a discrete numerical analysis method since the conventional continuum approaching models, such as Finite Element Method (FEM), neglect the contact between rocks, making it impossible to trace the position of an individual rock during a landslide.

2. Geological and geographical features outlining instable slope conditions

2.1. Geological outline

Fig. 3 shows the geological and tectonic outline near Hsiaolin before the rock avalanche. The landslide is also plotted in Fig. 3.

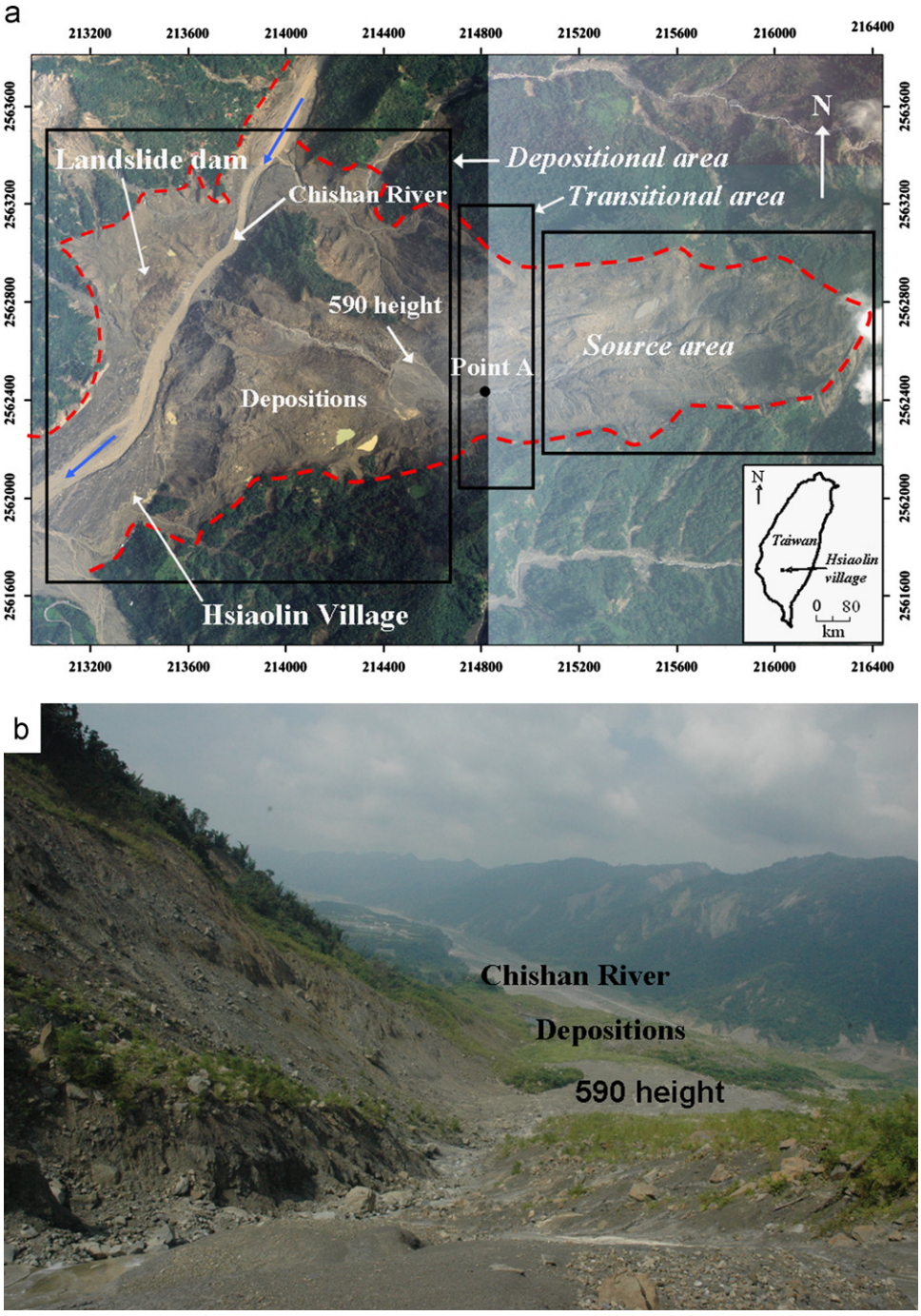

Fig. 1. Rock avalanche at the Hsiaolin village. (a) Aerial photo, (b) local picture.