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A quasi two-dimensional friction-thermo-hydro-mechanical model for high-speed landslides

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ABSTRACT

For deep-seated landslides, thermal pressurization in shear zone has been considered an important cause of high-speed collapse. To quantify this mechanism, this study proposed a quasi two-dimensional friction-thermo-hydro-mechanical (FTHM) model, concerning the mechanisms of material frictional softening and thermo-hydro-mechanical softening during the start-up phase of high-speed landslides. In this model, the intact slide mass was divided into a lot of small slide blocks. The dynamic equations of each block, and the heat equations, pore pressure equations of each shear band were established respectively. The model fully considered the morphological characteristics of landslides, and variables such as velocity, temperature, excess pore pressure varied along both the normal and the tangential direction of the whole shear band during the slide mass movement. The model was applied to back-analyze the Vaiont landslide and the results were compared with existing one-dimensional models. It can be concluded that the irregular spatial shape of slide mass makes a difference on mechanism of thermo-hydro-mechanical softening which promotes the collapse, and that the quasi two-dimensional model is valid.

1. Introduction

The dynamic mechanics of high-speed landslide failures are still poorly understood (Cecinato et al. 2011b). Some catastrophic landslides move so fast and so far that they cannot be explained by conventional methods. For example, the 1963 Vaiont landslide occurring in Italy involved a volume of $2.7 \times 10^8\,m^3$ rock slide into the Vaiont reservoir at a speed of 20 to 30 m/s, killing > 2000 people (Genevois and Ghirotti 2005; Jr and Patton 1987). However, frictional heating in the shear band was identified as a possible cause of the unexpected velocity of some catastrophic landslides (Habib 1975; Vardoulakis 2000; Vardoulakis 2002; Voight and Faust 1982). Rapid movement of the slide occurs due to the generation of excess pore water pressure which is explained by expansion of water as a result of frictional heat production in the shear band at the bottom of the slide (Hueckel and Baldi 1990; Modaressi and Laloui 1997).

Based on the conservation laws of mass, momentum and energy, Vardoulakis (2000) first established the one-dimensional mathematical FTHM model, considering frictional heating and thermal pressurization in the shear band; this model was validated by applying it to the Vaiont landslide, and subsequently was developed in some degree (Alonso et al. 2016; Gerolymos et al. 2007; Goren and Aharonov 2007; Goren and Aharonov 2009; Pinyol and Alonso 2010b; Pinyol and Alonso 2010c; Vardoulakis 2001, 2002; Veveakis et al. 2007; Zervos et al. 2017). Based on the existing work of Vardoulakis and his co-workers, the modified friction-thermo-hydro-mechanical models taking into account the thermo-elasto-plastic constitutive of soil in the shear band were proposed by Cecinato, Vinayagamoorthy and their co-workers (Cecinato 2009; Cecinato and Zervos 2012; Cecinato et al. 2011a; Cecinato et al. 2008; Vinayagamoorthy 2014; Vinayagamoorthy and Zervos 2015). The above models are governed by a set of coupled diffusion-generation partial differential equations for pore pressure and temperature inside the thin shear band at the base of the coherent mass sliding. The considered time window is the acceleration phase of the landslide, which starts at the initial failure and ends after a few seconds; when certain displacement and velocity are reached, the coherent slide begins to break up. The problem variables vary only with the shear band thickness, assuming that they are constant along the direction of the landslide movement. Thus, the total normal stress anywhere at the bottom of the slide, which has a significant impact on the diffusion-generation of pore pressure and temperature inside the shear band, is simplified to a constant, irrespective of the change in thickness of the whole slide body and the morphology of the ground surface. Of course, this is far from the actual situation, in which the total normal stress on the upper boundary of the shear band applied by the upper slide may significantly vary along the direction of movement. The above

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simplification will inevitably lead to an incorrect distribution of pore pressure and temperature in the shear zone along the sliding direction. As a result, the movement process of the landslide will be another case. Therefore, it is necessary to consider the uneven distribution of the normal stress at the contact surface between the upper slide and the bottom shear band along the sliding direction.

In this paper, a quasi two-dimensional FTHM model for the dynamic failure of high-speed landslides was established based on Vardoulakis' models, considering the irregularity of landslide morphology. The mechanisms of material frictional softening and thermo-hydro-mechanical softening were taken into account. In the model, the intact slide mass was divided into a lot of small slide blocks using the slice method. The dynamic equations of each block, and the heat equations, pore pressure equations of each shear band were established respectively. The movement of each slide block brought about shear deformation within the corresponding shear band, generating heat and excess pore water pressure, which in turn affected the motion of the overlying slide blocks. Furthermore, adjacent slide blocks or shear bands would affect each other directly or indirectly. As long as the number of small slide blocks and shear bands was large enough, it could be approximated as a two-dimensional model. Finally, the model was applied to back-analyze the Vaiont case to assess its validity.

2. Problem formulation

The problem studied in this paper can be summarized as: a deep-seated slide mass slid on a thin shear band consisting of clayey layer, before it disintegrated. The motion of slide mass which was solved by the momentum equation resulted in material frictional softening and thermo-hydro-mechanical softening inside the shear band, that governed by the heat equation and pore pressure equation. The interaction between the slide mass and the shear band affected the movement of the landslide. This problem will be elaborated as follows.

2.1. Simplified physical model for landslide

In Vardoulakis' model (Vardoulakis 2000; Vardoulakis 2002), an extended landslide with constant base slope angle α and height h was assumed (Fig. 1(a)). The system consisted of slide mass with thickness h and shear band with thickness d. The shearing deformation was assumed to be localized at the bottom of the landslide, within the shear band. The thickness of the overlying slide h was much larger than the thickness of the shear band d. For example, the Vaiont landslide had $d \approx 1.4$ mm according to Vardoulakis (2002) and the average thickness of the slide mass $h \approx 145$ m, leading to a geometric scaling factor of $h/d \approx 10^5$ between the two substructures. As a result, the analysis was 1D, and accordingly all variables within the shear band evolved only in z-direction, which was normal to the long direction of the slide. As mentioned above, this model had a large discrepancy with the actual landslide model having a non-uniform spatial shape.

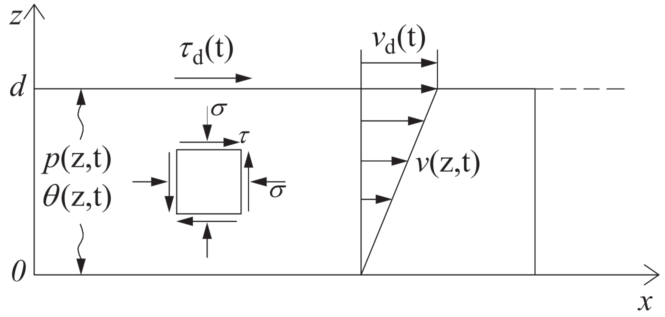

Fig. 2. The individual shear band, including the stress state, pore pressure, temperature and velocity (after Vardoulakis 2002).

However, the huge difference in thickness between the shear band and the overlying slide block made it very difficult to establish the two-dimensional friction-thermo-hydro-mechanical model in the shear band. In order to solve this problem, the slice method was used to divide the coherent slide mass into n small slide blocks with width b_i and thickness h_i (Fig. 1(b)). The bottom of each small slide block corresponded to a shear band with thickness d and slope angle α_i. The slide blocks, which were assumed to be elastic, moved along the shear bands, undergoing shear deformation. In this modified model, the total normal stress, shear stress, and velocity on each interface between the small slide block and the shear band were different. As a result, the velocity, pore water pressure and temperature between individual shear bands were also different. However, limited by the big difference in dimension between the two structures, these variables inside each individual shear band were still assumed to evolve only along the direction perpendicular to the movement. As long as n is large enough, it can be regarded as an approximate two-dimensional friction-thermo- hydro-mechanical model.

The individual shear band (Fig. 2) consisted of water-saturated clayey soil, in which the shear stress was given by Coulomb's friction law and Terzaghi's effective stress principle (compression was taken as positive):

$$\tau = \sigma'_n \bullet \mu = \sigma'_n \bullet \tan\varphi \tag{1}$$

where σ'_n is the effective normal stress, acting in a direction normal to the shear band; μ denotes the friction coefficient; and φ denotes the Coulomb friction angle.

$$\sigma'_n = (\sigma'_n)_0 - p(z,t) \quad (p > 0) \tag{2}$$

where $(\sigma'_n)_0$ is the initial effective stress, normal to the shear band, and $p(z, t)$ is the excess pore water pressure generated by heat, which is produced by shearing inside the shear band. The generation mechanism of heat and excess pore pressure will be elaborated in the next section.

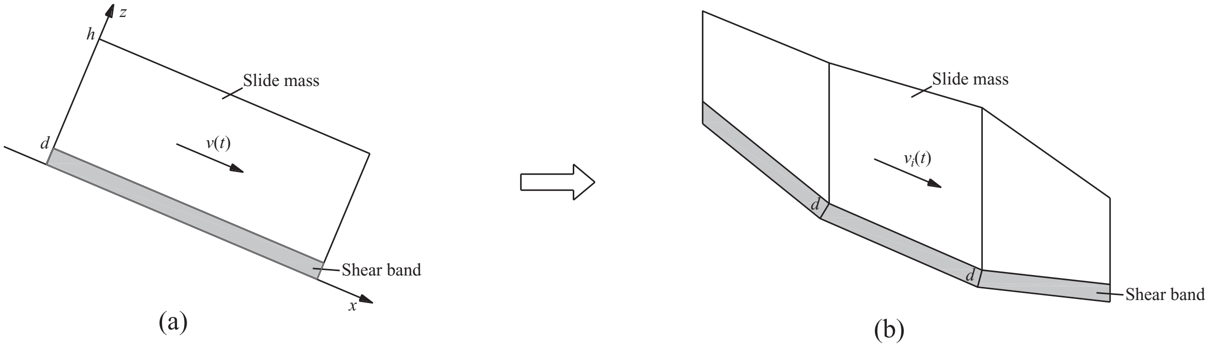

Fig. 1. The simplified physical model for landslide: (a) Vardoulakis model; (b) modified model.