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Coupling a 1D dual-permeability model with an infinite slope stability approach to quantify the influence of preferential flow on slope stability

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Abstract

In this study, a 1D hydro-mechanical model was developed by coupling a dual-permeability model with an infinite slope stability approach to investigate the influence of preferential flow on pressure propagation and slope stability. The dual-permeability model used two modified Darcy-Richards equations to simultaneously simulate the matrix flow and preferential flow in a slope. The simulated pressure head was sequentially coupled with the soil mechanics model. The newly-developed numerical model was codified with the Python programming language, and benchmarked against the HYDRUS-1D software. The benchmark example showedthat the proposed model is able to simulate the non-equilibrium phenomenon in a heterogeneous soil. We further implemented the model to conduct a synthetic experiment designing a slope with heterogeneous soil overlying an impermeable bedrock as a combined analysis of hydrology and slope stability, the results shows that the occurrence of preferential flow can reducing the time and rainfall amount required for slope failure. The proposed model provides a relatively simple and straightforward way to quantify the effect of preferential flow on the pressure propagation and landslide-triggering in heterogeneous hillslope.

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1. Introduction

Rainfall-induced shallow landslides are among one of the most frequent natural hazards in mountainous areas[1-3]. Slope instability is often initiated by a fast pore-water pressure response to precipitation or snow-melt events that reduces the suction stress and shear strength of the slope[3-4]. Therefore, quantification of pore pressure propagation in a subsurface hydrological system is critical to simulate the timing and location of rainfall-triggered landslides[4-6].

In response to rain-pulses, the pressure propagation in a saturated soil is nearly-instant due to a low compressibility of the saturated soil[5-6]. While, in an unsaturated soil, fast pore water response might be related with preferential flow bypassing the adjacent soil matrix, directly reaching the groundwater table[7-10]. Preferential flow paths, such as cracks, macropores, fissures, pipes, etc., are common features in slopes[6-11]. Increasingly sophisticated models have been developed for simulating preferential flow in various environmental systems[12-14]. The widely-used dual-permeability models conceptualize the soil as two porous domains that interact hydrologically: the more permeable domain with associated larger porosity represents the macropores, fractures, fissures, and cracks; and the less permeable domain with lower porosity represents the soil matrix[14-17].

Yet, most of the hydro-mechanical models calculate the pore water pressure based on a single-permeability assumption[18], and the effects of preferential flow on pressure wave propagation and landslide-triggering under high-intensity rainstorms are rarely quantified. Therefore, the objective of this paper is to describe a hydro-mechanical model, which couples a 1D dual-permeability model simulating infiltration and lateral flow along a slope gradient with an infinite slope stability approach. Such direct coupling of dual-permeability hillslope hydrological model and slope stability calculation allows to quantify the influence of preferential flow on slope stability under different boundary conditions. First we present the model set up, then we use a synthetic numerical experiment for model validation. Thereafter, we investigate pressure propagation and landslide-triggering under the influence of preferential flow in a pre-defined heterogeneous hillslope.

2. Model description and numerical implementation

2.1. Steady initial pressure distribution

In a conceptualized 2D hillslope, the groundwater table at lower part of the slope is higher, which is therefore highly correlated with the slope failure. Here, we adopt a widely-used approach to estimate the groundwater table at the lower part of the slope that further can assist in specifying an initial pressure distribution along a vertical profile of the slope. Considering a long-term lateral steady flow parallel to the slope (Fig.1), the water table height at the slope bottom h_G can be expressed as[3]:

$$h_G = \frac{L(R-E)-Q_{leak}}{K\sin\alpha} \quad (1)$$

Where α (deg) is the slope angle, K (LT^{-1}) is the hydraulic conductivity of the soil material, L(L) is the length of a slope, R and E (LT^{-1}) are the flow rate of rainfall andevaporation,and Q_{leak} (L^2T^{-1}) is the groundwater leakage.

Assuming a leakage flow q_{leak} (LT^{-1}) normal to the bottom boundary of the slope, the specific discharge $q$in the normal direction (Z) of the slope can be expressed by Darcy's Law[5]:

$$q(Z)\big|_{Z<h_G} = -K_s\left(\frac{\partial h}{\partial Z}+\cos\alpha\right) = -q_{leak} \quad (2)$$

where$h$ (L) is the pressure head, K_s(LT^{-1}) is the saturated hydraulic conductivity.Equation (2) implies that an extra elevation head of gravitational gradient (sinαin Eq.1) drives a parallel saturated flow in the hillslope (cosαin Eq.2). As a result, the water pressure head distributioncan be derived as:

$$h(Z)\big|_{Z<d_G} = (d_G - Z)\left[\cos\alpha - \frac{q_{leak}}{K_s}\right] \quad (3)$$