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Development of time-variant landslide-prediction software considering three-dimensional subsurface unsaturated flow

Hyunuk An [a], Tran The Viet [b], Giha Lee [b], Yeonsu Kim [c], Minseok Kim [c], Seongjin Noh [d], Jaekyoung Noh [a, *]

[a] Dept. of Agricultural & Rural Eng., Chungnam National University, Daejeon, South Korea
[b] Dept. of Construction & Disaster Prevention Eng., Kyungpook National University, Sangju, South Korea
[c] International Water Resources Research Institute, Chungnam National University, Daejeon, South Korea
[d] Department of Civil Engineering, University of Texas at Arlington, Arlington, USA

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ABSTRACT

An accurate landslide-susceptibility assessment is fundamental for preventing landslides and minimizing damage. In this study, a new time-variant slope-stability (TiVaSS) model for landslide prediction is developed. A three-dimensional (3D) subsurface flow model is coupled with the infinite slope-stability model to consider the effect of horizontal water movement in the subsurface. A 3D Richards' equation is solved numerically for the subsurface flow. To overcome the massive computational requirements of the 3D subsurface flow module, partially implicit temporal discretization and the simplification of first-order spatial discretization are proposed and applied in TiVaSS. A graphical user interface and two-dimensional data visualization are supported in TiVaSS. The model is applied to a 2011 Mt. Umyeon landslide in the Republic of Korea, and its overall performance is satisfactory.

Software/data availability

Name of software TiVaSS
Developer's email address hyunuk@cnu.ac.kr
Tel +82-42-821-5797
Fax +82-42-821-5791
Year first available It will be open in public within this year
Software required windows OS, windows 7 or later
Program language C++
Program size 16.3 MB zip file
Download link https://sites.google.com/site/cnuaehelab/software/tivass/TiVaSS_release.zip?attredirects=0&d=1 User manual & tutorial is now in preparation.

1. Introduction

Landslides are common natural hazards in mountainous areas, causing significant damage and casualties worldwide every year. A high rainfall intensity or frequency can trigger landslides. An accurate landslide prediction is fundamental for preventing such disasters and minimizing casualties and property damage (Liao et al., 2011; Borga et al., 2002; Papathoma–Köhle et al., 2015; Pradhan and Lee, 2010; Ciabatta et al., 2016). Shallow landslide modeling falls into three categories: empirical (Sirangelo et al., 2003; Aleotti, 2004; Guzzetti et al., 2007, 2008; Bezak et al., 2016), statistical (Dickson and Perry, 2016; Guzzetti et al., 1999, 2005, 2006; Pham et al., 2016; Soeters and van Westen, 1996), and physically based models. Among these, physically based models are preferred because of their accuracy and ability to forecast the spatial and temporal occurrence of landslides (Raia et al., 2014). They describe the triggering processes of shallow landslides and provide spatially variable slope-stability information, often as a safety factor (*FS*), which is an index expressing the ratio between the local resisting and driving force. The infinite slope-stability model and simple infiltration-runoff process are commonly combined for computing the *FS* in physically based slope-stability models. Those models are

* Corresponding author.
E-mail address: jknoh3109@hanmail.net (J. Noh).

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widely used and packaged as computer programs such as SINMAP (Stability Index MAPping), SHALSTAB (Shallow Landsliding Stability Model), TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope stability), and GEOtop-FS.

SINMAP (Pack et al., 1999) and SHALSTAB (Dietrich and Montgomery, 1998; Montgomery and Dietrich, 1994) consider a simple steady-state hydrological process under constant rainfall. This means that both models are useful for producing a spatially distributed slope stability but are limited to the temporal prediction of the slope stability because of the steady-state description of hydrological fluxes. On the other hand, TRIGRS (Baum et al., 2008; Alvioli and Baum, 2016) computes the transient pore-water pressure using the solution of the one-dimensional (1D) Richards equation with the assumption of a simple exponential soil-water retention relationship (Gardner, 1958) and can produce a time-variant distribution under time-variant rainfall conditions. Thus, this model can forecast the timing and distribution of shallow landslides (Baum et al., 2010) and has been widely applied in the past decade (Baum et al., 2010; Liao et al., 2011; Liu and Wu, 2008; Luan et al., 2010; Montrasio et al., 2011; Saadatkhah et al., 2014; Peres and Cancelliere, 2016). In recent years, the predictive accuracy and computational efficiency of TRIGRS have been improved via the addition of a probabilistic approach (Raia et al., 2014) and the parallelization of the code (Alvioli and Baum, 2016). GEOtop-FS (Simoni et al., 2008) solves the three-dimensional (3D) subsurface flow numerically on the basis of the 3D Richards equation and considers the physical hydrological process for estimating the slope stability. GEOtop is also used for predicting soil erosion and deposition (Zi et al., 2016).

In the context of landslide early-warning systems, practical physically based slope-stability models are essential for determining the influence of rainfall recharge on the subsurface hydrological behavior and soil mechanics in triggering landslides. That is, advanced slope-stability tools should account for the time-varying subsurface water flow during a landslide event and consequently provide accurate spatio-temporal information about the slope failure (Apip et al., 2010).

This study aims to develop a new time-variant slope stability (TiVaSS) model, which combines a 3D subsurface flow model and an infinite slope stability model. An analytical solution is not available for the 3D subsurface flow, and a numerical technique is used to solve the problem. A numerical solver establishes the general soil-water retention relationships between the water content and the pore-water pressure such as van Genuchten model (1980) or Brooks-Corey model (1964). 3D subsurface flow usually requires a large amount of computational resources because fully implicit temporal discretization is essential for the numerical stability owing to the high nonlinearity of the Richards equation. The large computational requirement can hinder the practical application of landslide-occurrence assessment with the 3D subsurface flow. To reduce this requirement, the 3D subsurface flow is solved in a partially implicit manner in TiVaSS, with the assumption that the horizontal flow is far slower than the vertical flow. The vertical flow is solved implicitly, and the horizontal flow is solved explicitly with a low-order discretization. Further, TiVaSS supports a graphical user interface (GUI). The developed model is applied to the 2011 Mt. Umyeon landslides in Seoul, Korea for the evaluation of its performance and functions.

This paper is organized as follows. The infinite slope-stability model and 3D subsurface flow model, including the numerical scheme used in TiVaSS, are described in the next section. Details about the Mt. Umyeon landslide, including the data set, are provided in Section 3. The application results and discussion are also presented in Section 3. We draw our conclusions in Section 4.

2. Model description

2.1. Infinite slope-stability model

Fig. 1 shows a schematic of an infinite slope-stability model. Assuming an infinite slope and failure parallel to the slope surface yields the following shear and normal stress:

$$\tau = \frac{T}{b/\cos\phi} = \frac{W}{b}\cos\phi\,\sin\phi, \tag{1}$$

$$\sigma = \frac{P}{b/\cos\phi} = \frac{W}{b}\cos^2\phi, \tag{2}$$

where $W = \gamma_s Db$ is the soil weight (kg/m), T is the shear force (kg/m), P is the normal force (kg/m), D is the soil depth (m), b is the slope width (m), φ is the slope angle (rad), and γ_s is the unit weight of the soil (kg/m^3). According to Mohr–Coulomb theory, the shear strength of an infinite slope is

$$S = c + \sigma' \tan\varphi, \tag{3}$$

where c is the cohesion (kg/m^2), σ' is the effective stress (kg/m^2), which was expressed as $\sigma' = \sigma - u$ by Terzaghi (1943), u is the pore water pressure (kg/m^2), and φ is the angle of internal friction (rad). Then, the FS is defined as

$$FS = \frac{S}{\tau}. \tag{4}$$

Substituting Eqs. (1)–(3) into Eq. (4) yields the following equation:

$$FS = \frac{c + (\gamma_s D\cos^2\phi - u)\tan\varphi}{\gamma_s D\sin\phi\cos\phi}. \tag{5}$$

Substituting $u = \gamma_w\psi$ into Eq. (5) gives

$$FS = \frac{c + [D\gamma_s\cos^2\phi - \gamma_w\psi]\tan\varphi}{\gamma_s D\sin\phi\cos\phi}, \tag{6}$$

where γ_w is the unit weight of water (kg/m^3), and ψ is the pressure head of the subsurface water (m). Eq. (6) is rewritten by separating the time-variant term and steady terms as (Iverson, 2000)

$$FS = -\frac{\psi\gamma_w\tan\varphi}{\gamma_s D\sin\phi\cos\phi} + \frac{\tan\varphi}{\tan\phi} + \frac{c}{\gamma_s D\sin\phi\cos\phi}, \tag{7}$$

Eq. (7) is valid for saturated soil. However, Terzaghi's effective stress is unsatisfactory for unsaturated soil (Lu and Likos, 2006; Lu

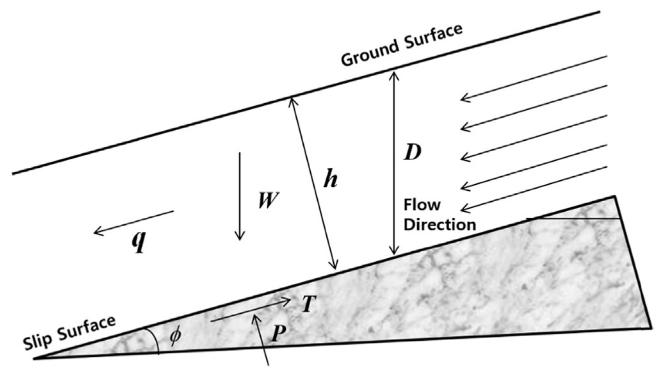

Fig. 1. Schematic of the infinite slope-stability model.