Modeling of Landslide Inducing Groundwater Table Surges in Residual Soils due to Rainfall

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ABSTRACT: Rainfall triggered landslides associated with residual soils are a major natural hazard in the hilly terrain of Sri Lanka. With heavy precipitation within a limited time, the groundwater table in such soils would surge, resulting in reduction of strength along with an increase of stresses within the soil, thus creating favorable conditions for slope failures. Hence, reliable and accurate methods of estimating the rainfall intensities and durations that generate critical rates of groundwater level surges in landslide prone areas would be invaluable. Currently, there are several empirical models which can be employed to predict the surge in groundwater table due to rainfall. However, an empirical model can be of limited applicability if it cannot be calibrated for soil and groundwater conditions of any given region. To address this problem, a groundwater model based on fundamental fluid flow principles which can also be calibrated for given soil and groundwater characteristics, is developed. Of a variety of fundamental modeling methods available, this research specifically focuses on a numerical model based on the Navier-Stokes formulation. A preliminary parametric study was performed to produce useful prediction curves and their applications are illustrated with a numerical example.

1 INTRODUCTION

Landslides triggered by rainfall is currently a major cause for loss of lives and property damage in Sri Lanka. Heavy precipitation that occur within a limited time has resulted in major destructions in past. Rainfall results in a surge of groundwater table, which causes a reduction in strength along with an increase in the weight of soil. This creates favorable conditions for slope failure. Hence, it is of utmost importance to forecast the fluctuations in groundwater table due to rainfall, in order to predict the occurrence of landslides, so that the devastating impact can be minimized.

There are many empirical models developed in the past to forecast the fluctuations in groundwater table due to rainfall. One such model is the one developed by Hong et.al (2010), which utilizes the Darcy's law along with continuity equation, in order to forecast the groundwater table fluctuations. However, such an empirical model lacks the flexibility to be calibrated based on the conditions of any specific region. To address this problem, a groundwater flow model based on fundamental fluid flow principles is developed. The fluid flow model presented in this paper uses a finite difference approach based on Navier-Stokes equations to model the fluid flow through soil.

An empirical model also lacks the ability to incorporate the randomness in soil particle size distribution encountered in a given region. On the other hand, the fluid flow model presented in this paper accounts for the randomness in soil particle size distribution.

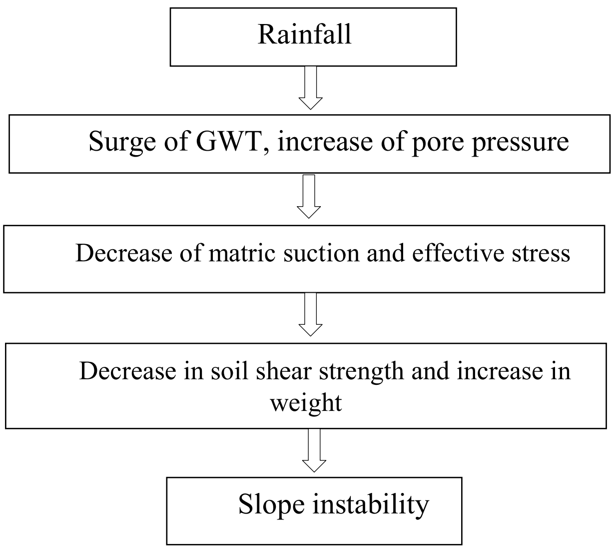

Fig. 1 Sequence of events leading to a landslide

2 OBJECTIVES

Objectives of this paper are twofold:

1. To develop a groundwater flow model based on fundamental fluid flow principles that can be calibrated for soil and groundwater conditions of any given region, addressing a notable deficiency in existing generic empirical models.
2. To incorporate the randomness of soil grain size distribution at a site in the analysis.

3 METHODOLOGY

This research uses the two Navier-Stokes equations to model one dimensional water flow through the unsaturated zone. The first equation is based on the principle of conservation of mass. The second equation is based on the principle of conservation of momentum.

First equation:

$$\frac{\partial(sv)}{\partial z} = -\frac{\partial s}{\partial t} \quad (1)$$

Second equation:

$$\frac{n\partial(sv)}{\partial t} = -\frac{n\partial(sP)}{\partial z} - \frac{D}{\rho} + gns.. \quad (2)$$

Where s is the degree of saturation, v is the water velocity, z is the direction of water flow, t is time, n is the soil porosity, p is water pressure, ρ is the density of water and D is the drag force.

The drag force is quantified using the semi-empirical relationship shown below (Jeyisanker, 2008):

$$D = \frac{150\mu\,(1 - ns)^2\, v}{(ns)^2\, d^2} \quad (3)$$

with the assumption that each sand layer consists of uniform sized spherical particles of diameter d. µ is the dynamic viscosity of water.

Soil water characteristic curve (SWCC) is employed to determine the variation of suction in the unsaturated zone with the degree of saturation (Fredlund, 1994). The SWCC is represented by the following equation:

$$s=\left\{\left[\frac{-\ln\left(1+\frac{P}{\mathrm{Pr}}\right)}{\ln\left(1+\frac{10^6}{\mathrm{Pr}}\right)}+1\right]\left[\frac{1}{\left\{\ln\left[e+\left(\frac{P}{a}\right)^n\right]\right\}^m}\right]\right\} \quad (4)$$

Where P is the suction in soil (kPa), P_r is the residual suction (kPa) corresponding to the residual water content, a,m and n are soil constants.

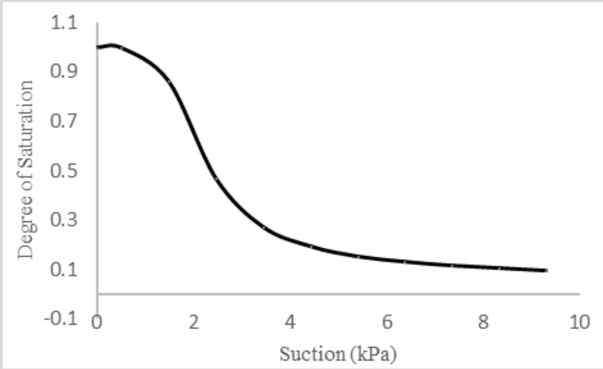

Fig. 2 Soil water characteristic curve

In figure 2, the residual suction P_r is considered as 3000kPa, a is 1.799, n is 4.524 and m is 1.157.

The randomness in soil particle size was incorporated in the model by performing a Monte-Carlo simulation using the soil particle size distribution. It will be explained further in the case study.

3.1 *Case Study*

A site with a sandy soil was selected in a case study to apply this methodology. An assumed vadose zone of 1 meter thickness was discretized in to 10 elements as shown in Figure 3:

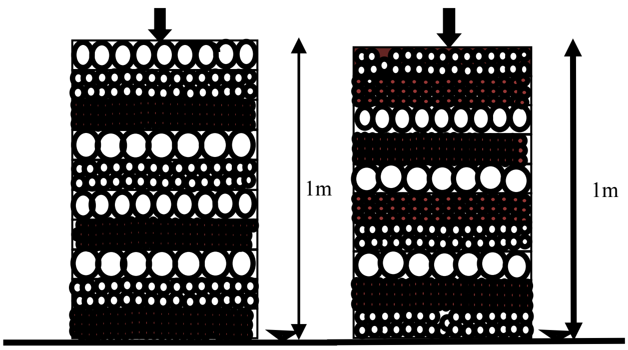

Fig. 3 Two out of many different soil packing configurations for same PSD

The uniform-sized particle packing each element was selected based on the particle size distribution (PSD) shown in Figure 4 (Fredlund, 2000). By selecting a random percentage passing between 0 and 100 on the y axis, the corresponding particle size could be obtained from the x axis. The soil column could be filled with particles from gravel to fine sand in this manner. This type of a simulation is known as 'Monte-Carlo' simulation. The initial pore pressure/suction distribution prior to rainfall was determined applying the Bernoulli's equation over the vadose zone.The corresponding degree of saturations for the suctions determined above were determined from SWCC.

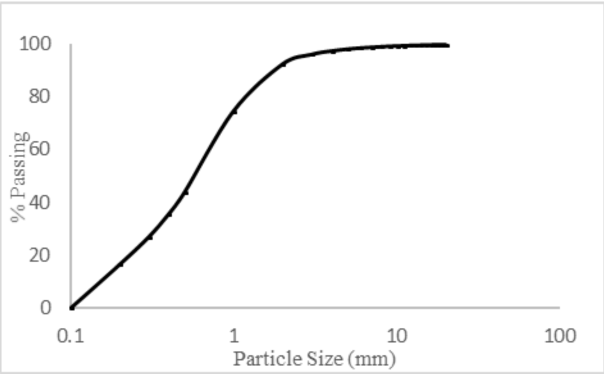

Fig. 4 Representative soil particle size distribution for the site

The soil column was subjected to a constant rainfall of an intensity of 0.75 inches/hour. Navier-Stokes second equation was used to determine the water velocities at every node while Navier-Stokes first equation was used to determine the corresponding changes to the degree of saturation. Finally, the SWCC was used to determine the pore pressures of every element.

The time taken for the entire soil column to saturate under the given rainfall was determined. The analysis was performed repeatedly with different random soil packing arrangements to simulate the randomness in particle size distribution within the considered soil layer and finally determine the frequency distribution of the time required for saturation.

4 RESULTS

From the above analysis, the depth wise variation of degree of saturation of the soil column was determined. Figure 5 shows the increase of the degree of saturation with time, along the depth of the column.

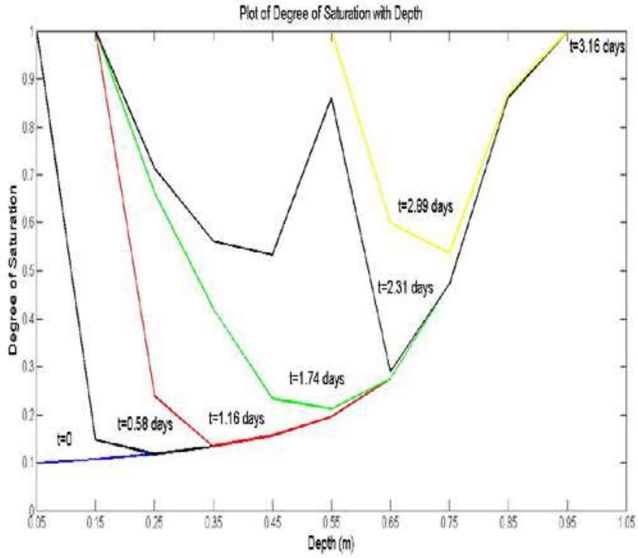

Fig. 5 Variation of the degree of saturation with depth

The variation of water velocities along the depth of the soil column was also determined. Figure 6 shows the increase of velocities with time, along the depth of the soil column.

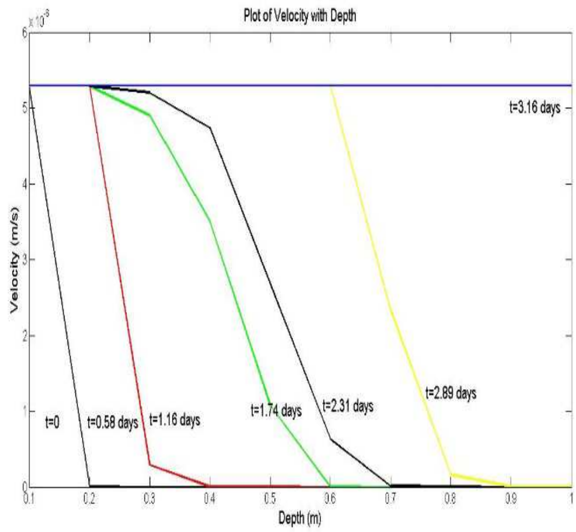

Fig. 6 Variation of water velocities along the depth of the soil column

When the randomness of the particle distribution is taken into account by considering different particle packing arrangements, the time required for saturation of the soil column considered in this case study could be represented by a normal distribution having a mean of 3.13 days and a standard deviation of 0.1 days as shown in figure 7:

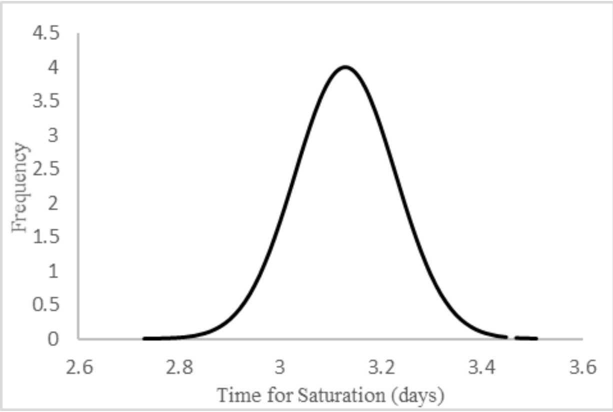

Fig. 7 Frequency distribution of the time required for saturation of the soil column represented by a normal distribution

5 CONCLUSIONS

The time taken for the saturation of and the water table surge in any granular soil due to a given rainfall intensity and duration can be predicted with this model. These predictions would aid the timely identification of GWT fluctuations that could cause landslides.

The model can be calibrated for groundwater and soil conditions in any given region. Also, it accommodates the inherent randomness in soil grain distribution. All in all, this model can provide more reliable predictions for groundwater table surge compared to existing empirical models.

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