Two-phase flow simulation of water infiltration into layered natural slopes inducing soil deformation

L. Stadler & R. Hinkelmann
Department of Civil Engineering, Water Resources Management and Modeling of Hydrosystems, TU Berlin, Germany

E. Zehe
Institute of Water and Environment, Hydrology and River Basin Management, TU München, Germany

ABSTRACT: The fast infiltration of rainwater into layered natural slopes can induce high water pressures and buoyancy effects, especially if the water flows beneath low permeable layers. In this contribution, we investigate the influence of soil layers on the resulting water pressure during infiltration. Field investigations on the Heumoes slope (Ebnit, Austria) indicated that the deformation of the slope results from the high water pressures during infiltration. In the first part of this contribution we present a numerical study concerning the high water pressures. In the second part we examine if the macropores in the upper part of the slope accelerate the infiltration.

1 INTRODUCTION

1.1 Motivation

The prediction of slow-moving landslides is a complex process (van Asch et al., 2007). Experiments of this topic range from lab-scale to field-scale (Lourerico et al., 2006). Since every natural slope is different, also the processes leading to a failure can differ. For that reason, detailed investigations of the slope structure and geometry are necessary. In this context, one has to mention the role of macropores for landslides (Uchida et. al. 2001). Macropores are large pores that allow preferential flow and the bypassing of the soil-matrix. Macropores are for example root channels, soil cracks, fissures and earthworm borrows (Beven & German, 1982, Jarvis 2007).

The aim of the DFG Research Unit “Coupling of flow and deformation processes for modeling the deformation of natural slopes” is to understand and predict the failure of natural slopes. Therefore, the simulation of infiltration processes is a crucial part. The resulting saturation and pressure distributions are required for the geomechanical models to simulate the deformation.

The Research Unit executes a multitude of measurements on Heumoes slope to understand the failure processes. It is assumed that the layering of the Heumoes slope creates high pore water pressures during infiltration which initiate the deformation of the slope. Tracer experiments showed that the macropores in the upper part of the slope accelerate the infiltration which leads to a fast pressure reaction. A detailed overview of the Heumoes slope is given in Lindenmaier (2008).

Prior a numerical simulation of the whole slope, a couple of smaller experiments, principle studies and numerical simulations have to be carried out to understand the single failure processes. Therefore the Research Unit executes controlled lab experiments for macropore infiltration and soil deformation (Germer et al., 2008a, Germer et al., 2008b).

1.2 Objectives

In this study we investigate the effect of soil layers on the pore pressure generation. For the numerical simulation we use an idealized cut through the layered upper part of the Heumoes slope. Since the leakage of air is inhibited in layered systems, the soil air influences the speed of infiltration fronts. As a consequence, we use a two-phase flow model for the study.

In the first setup of the study we investigate the influence of soil layers for the water pressure during infiltration. Therefore we compare the water pressure of two different layered systems with the pressure of a non-layered system. In the second setup we use a two-phase dual-permeability model to examine how macropores influence the infiltration.

2 MODEL CONCEPT

2.1 Model Equations

It is important to emphasize that the here presented two-phase flow model concept assumes a fixed soil-
matrix and does not include soil processes like deformation, erosion or swelling and shrinking. The main equation for the simulation of two-phase flow in porous media is the conservation of mass. The following equation is the mass balance for water ($\alpha = w$) and air ($\alpha = n$):

$$\frac{\partial (\phi \rho_a S_a)}{\partial t} + \text{div}(\rho_a \nabla_a) - \rho_a q_a = 0$$

(1)

The porosity $\phi$ is defined as

$$\phi = \frac{V_w + V_n}{V_{total}}$$

(2)

and describes the available pore volume ($V_w, V_n$) for the two phases. $V_{total}$ is the total volume of the REV. $S_a$ is the saturation, $\rho_a$ the density of the phase $\alpha$. The saturation is defined as:

$$S_a = \frac{V_a}{V_{pore}}$$

(3)

$V_{pore}$ is the available pore volume. Using this definition we can formulate the following supplementary constraint, assuming that the available pore volume is completely filled with the two phases:

$$S_w + S_n = 1$$

(4)

The effective saturation is defined as:

$$S_e = \frac{(S_w - S_{wr})}{(1 - S_w - S_{wr})}$$

(5)

$S_w$ is the residual saturation of the wetting phase and $S_{wr}$ is the residual saturation of the non-wetting phase. Between both phases acts the capillary pressure:

$$p_c = p_n - p_w$$

(6)

The capillary pressure is mainly a function of the saturation and can be formulated after the relationship from Brooks & Corey (1964) which uses the entry pressure $p_d$ and the shape parameter $\lambda$ for the parameterization:

$$p_c = p_d S_e^{-1/\lambda}$$

(7)

Both parameters depend on the soil. The velocity in equation (Eq. 1) is computed using the extended Darcy’s law.

$$\nabla_a = -K \frac{k_{ra}}{\mu_a} (\text{grad} p - \rho_a g)$$

(8)

$K$ is the tensor of the intrinsic permeability. The fraction of the relative permeability $k_{ra}$ and the viscosity $\mu_a$ is called mobility $\lambda_a$ of the phase. The relative permeabilities for the two phases can be computed with the Brooks & Corey relationship:

$$k_{ra} = S_e^{2+\frac{\lambda}{\lambda}}$$

(9)

$$k_{ra} = (1 - S_e)^2 (1 - S_e^{2+\frac{\lambda}{\lambda}})$$

(10)

For the dual-permeability model the soil is separated into a matrix and a macropore domain. This implies that the macropores form a well connected network which can be described as own domain. For both domains, separate mass balance equations for water and air are formulated. The exchange between both domains is computed over the macropore surface. The following pressure formulation with the exchange parameter $\beta$ is used to compute the scalar flux between both domains:

$$f_\alpha = \beta (p^\text{matrix}_\alpha - p^\text{macropore}_\alpha)$$

(11)

The exchange parameter $\beta$ describes the permeability of the macropore/matrix interface. In literature similar approaches are common (Simunek et al., 2002). For field simulations the parameter will strongly depend on the origin of the macropores. The exchange of mass $E_\alpha$ over the macropore surface is given as:

$$E_\alpha = f_\alpha \rho^\alpha \lambda^\alpha S$$

(12)

$S$ is the representative surface of the macropores in the considered volume and can be easily computed using the macropore properties (length, diameter). The parameter $\beta$ is often combined with the exchange parameter $\beta$ to reduce the number of fitting parameters. For the dual-permeability model we use the relationship after van Genuchten with the two parameters $VG^{\beta}$ and $VG^{n}$ for the capillary pressure and the relative permeabilities $k_{ra}$ (van Genuchten 1980, Mualem 1976).

### 2.2 Numerical Software MUFTE-UG

The study presented here was carried out with the software package MUFTE-UG (Breiting et al., 2000). MUFTE stands for MULTiphase Flow, Transport and Energy and UG for Unstructured Grids. The MUFTE package contains different discretization methods and the physical part of the model concepts. The software UG handles the mesh and provides fast numerical solvers. The equations for two-phase flow in porous media are leading to a complex system of non-linear coupled equations. The Newton-Raphson method and a fully implicit time discretization are used for the solution. The package MUFTE-UG provides different discretization types. We applied a vertex-centered finite volume method (also called box-method). The box-method assures the local and global conservation of mass and can be used for structured and unstructured grids. The mobility at the integration points is computed with the fully upwinding method. A detailed description of the meth-
ods can be found in Bastian (1997) and Helmig (1997).

3 INFLUENCE OF SOIL LAYERS

3.1 Setup 1

The first setup represents an idealized cut through the upper part of the Heumoes slope (Fig. 1). The setup demonstrates the influence of different soil layers for the pressure reaction during infiltration. The low permeable top layer and the layer above have a thickness of about 2 m. The soil properties are given in the following table.

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Fine sand</th>
<th>Coarse sand</th>
<th>Macropores</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_w$ [-]</td>
<td>0.18</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>$S_n$ [-]</td>
<td>0.01</td>
<td>0.01</td>
<td>0.15</td>
</tr>
<tr>
<td>$K$ [m²]</td>
<td>9.05E-15</td>
<td>3.1E-11</td>
<td>1.0E-10</td>
</tr>
<tr>
<td>$\lambda$ [-]</td>
<td>3.5</td>
<td>2.3</td>
<td>-</td>
</tr>
<tr>
<td>$p_d$ [Pa]</td>
<td>2400</td>
<td>700</td>
<td>-</td>
</tr>
<tr>
<td>$\phi$ [-]</td>
<td>0.43</td>
<td>0.36</td>
<td>0.06</td>
</tr>
<tr>
<td>$S$ [m³]</td>
<td>4.0</td>
<td>4.0</td>
<td>-</td>
</tr>
<tr>
<td>$V G_n$ [-]</td>
<td>5.5</td>
<td>7.5</td>
<td>4.7</td>
</tr>
<tr>
<td>$V G_\alpha$ [Pa⁻¹]</td>
<td>0.00045</td>
<td>0.0011</td>
<td>0.0037</td>
</tr>
<tr>
<td>$\beta$ [m]</td>
<td>1.0E-11</td>
<td>1.0E-9</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 1. Setup idealized slope.

Beside the low permeable top layer, the boundary conditions and geometries are important to create a pressure reaction. At the top of the slope a fixed Dirichlet boundary condition with a fixed water pressure $p_w = p_{atm} + \rho gh$ with $h = 1$ cm and a saturation of $S_w = 0.9$ is defined to guarantee a fast infiltration. The same Dirichlet boundary conditions are applied for domain 3. The fixed Dirichlet boundary condition overestimate the inflow compared to natural rainfall. However, in this setup we focus only on the prediction of the maximum water pressure. As initial condition the saturation of the wetting phase is set to $S_w = 0.2$ in all domains. With a higher initial saturation the infiltration will be faster. At the bottom of the domain, a Neumann no flow boundary condition describes a non permeable rock layer. To emphasize the influence of soil properties (layers), three different setups at the points A, B, C (Fig.1) are compared. Setup 1a represents a reference case of a non-layered system. Therefore, domain 1 and 2 consist of coarse sand, domain 3 contains fine sand. For setup 1b the soil in domain 2 is replaced by a fine sand to represent a low permeable top-layer. The last setup, setup 1c shows the same layered system as Setup 1b. However, the soil of domain 3 is replaced by the coarse sand and the high permeable layer is not longer closed by a low permeable top-layer at the bottom.

![Figure 1. Setup idealized slope.](image1)

![Figure 2. Pressures at points A, B, C during the infiltration.](image2)

3.2 Results Setup 1

To investigate the infiltration processes for the three different cases, the pressure after 18 hours of infiltration is compared at the three points A, B and C in Figure 2. The results show that for an increasing pressure it is not necessary that the higher permeable layer on the bottom is completely closed by the above laying low-permeable layer (Fig. 2, point A,
B). However, the increase of pressure with a lower permeable material in domain 3 is considerably higher. For setup 1b the water pressure reaches about the excepted pressure for hydrostatic conditions (point A = 186 kPa, point B = 215 kPa). Setup 1c suggests that for large inhomogeneous natural slopes various possibilities exist to create higher local pressures than expected for homogeneous slopes. The investigations also show that for a system with dry initial conditions the infiltration time is long, and the amount of water to fill the pore space and create a pressure reaction is high. The soil air additionally influences the speed of the infiltration front. The discharge of air in setup 1b is limited by the wetting front and the low permeable layer. The utilization of a two-phase flow model concept is therefore important.

3.3 Setup 2

To examine the influence of macropores, a macro-porous domain was added in the upper left part (x < 12m) of the layered slope of setup 1c. For the solution we applied the dual-permeability model. The exchange of water and air between matrix and macropores is driven by the pressure difference. This means that for soils with high capillary suction an almost saturated matrix is needed before water flow in the macropore domain occurs. However, if the water infiltrates directly into the macropores and the exchange to the matrix is inhibited, a fast infiltration and bypassing of low permeable matrix layers is possible (Stadler et al., 2008).

The same boundary conditions from setup 1 are applied for the matrix domain of setup 2 to describe a matrix infiltration. Assuming that no water infiltrates directly into the macropores, the boundary conditions $p_n = p_{atm}$, $S_w = 0.3$ for the macropore domain can be defined. The soil parameters of the additional macropore domain are given in Table 1.

3.4 Results Setup 2

After the saturation in the matrix domain has increased the water begins to flow from the matrix into the macropores (Fig. 3). Thus, the infiltration becomes significantly faster compared to the domain without macropores (Fig. 4). Although the rainwater flows not directly into the macropores, the results show the strong influence of macropores.
CONCLUSIONS

The presented study supports the hypothesis of the appearance of high water pressures in layered slope systems during infiltration. The highest pressures occur when a low permeable layer surrounds the high permeable layer at the lower part of the slope completely. The study also shows that macropores are essential for a fast infiltration and pressure reaction.

The presented dual-permeability model reproduces the complex interactions between matrix and macropores. In general, the dual-permeability model provides the possibility to model the infiltration processes more accurate than common model concepts which account for macropores with the addition of internal source terms or small high permeable soil tubes. However, the computational effort for the dual-permeability model can be high, depending on the nonlinearities.

Since the velocities in the macropores are high it is planned to use a non-linear Forchheimer-type filter law for further studies. Additionally we will use macropore distributions from field measurements and geostatistical investigations for the description of the macropore domain.

From literature it is known, that the gas phase can transmit the pressure during the infiltration (Hartge & Horn, 1999). It is envisaged to investigate this effect for the Heumoes slope with more complex slope sections. When the model is able to reproduce the piezometer heads measured at the Heumoes slope, we will couple the model with geomechanical models to be able to simulate the deformation of the Heumoes slope.

REFERENCES


