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PAPER

Conceptualization of preferential flow for hillslope stability assessment

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Abstract This study uses two approaches to conceptualize preferential flow with the goal to investigate their influence on hillslope stability. Synthetic three-dimensional hydrogeological models using dual-permeability and discrete-fracture conceptualization were subsequently integrated into slope stability simulations. The slope stability simulations reveal significant differences in slope stability depending on the preferential flow conceptualization applied, despite similar small-scale hydrogeological responses of the system. This can be explained by a local-scale increase of pore-water pressures observed in the scenario with discrete fractures. The study illustrates the critical importance of correctly conceptualizing preferential flow for slope stability simulations. It further demonstrates that the combination of the latest generation of physically based hydrogeological models with slope stability simulations allows for improvement to current modeling approaches through more complex consideration of preferential flow paths.

Keywords Preferential flow · Numerical modeling · Landslides · Discrete fractures · Unsaturated zone

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Introduction

Landslide processes is a common topic in scientific studies, both in terms of environmental threats and from a geomorphological point of view (Kellerer-Pirklbauer et al. 2010; Knighton 1998). Long-term meteorological conditions affect the stability of hillslopes through changing their hydrogeological conditions. Increased precipitation rates are typically associated with high groundwater levels and an increased risk of landslides (Knighton 1998; Uchida et al. 2001; Fox and Wilson 2010).

The impact of groundwater on hillslope stability can be expressed through several physical mechanisms. Fox and Wilson (2010) describe the influence of pore-water pressure on soil shear resistance, hydraulic gradient forces developing in steep slopes, and slope internal erosion caused by seepage flow. There are several other effects on hillslope stability associated with groundwater, such as surcharge of soil weight due to water infiltration or negative pore-water pressure (Lu and Godt 2013). Lourenço et al. (2006) carried out several tests with artificial slopes in the laboratory. The results of their experimental study showed that increased pore-water pressure provokes more slope ruptures than internal erosion caused by seepage flow (Lourenço et al. 2006).

Preferential flow paths play an important role in hillslope hydrology and thus hillslope stability (McDonnell 1990; Pierson 1983; Shao et al. 2015; Krzeminska et al. 2012). Two main types of preferential flow paths in slopes are macropores and pipes (Lu and Godt 2013; Uchida et al. 2001). Macropores are relatively large pores in comparison to the encompassing soil matrix. They can be formed by biological activity (e.g. tree root growth and decay, animal caves etc.), or physical effects such as soil/rock cracking, variable hydraulic properties of the soil/rock, or caused by topographical forcings such as surface or subsurface layer topography (Bogaard and Greco 2016; Lu and Godt 2013). Large macropores are often called "pipes". Pipes evolve from macropores due to rapidly infiltrating water moving along a low-permeability layer and causing internal erosion (Pierson 1983) or dissolutional widening of fracture networks in karstic systems (Siemers and Dreybrodt 1998). Several recent studies have shown that preferential flow paths cause significant differences in the velocity and rate of subsurface flow that vary by several orders of magnitude within a very small area (Weiler and McDonnell 2007; Anderson et al. 2009; Uchida et al. 2001; Jones 2010).

Soil pipes and macropores can develop complex networks consisting of both tree-root-related features and bedrock fractures (Noguchi et al. 1999). Moreover, their characteristics change in space and time (Harp et al. 1990). Water can enter pipes through seepage from the surrounding soil matrix or through overland flow entering the pipe networks (Pierson 1983).

Several studies have illustrated that preferential flow has both positive and negative effects on slope stability (Mosely 1979; Pierson 1983; Uchida et al. 2001; Lu and Godt 2013). Results from a field study in New Zealand showed that large pipes (i.e., with diameter larger than 3 mm) can collect water preventing the formation of perched water tables above the less permeable layer (Mosely 1979). If pipes can conduct water without total saturation of the soil matrix, slope stability increases (Pierson 1983). Consequently, pipeflow can contribute to slope stability by draining adjacent soil and limiting the development of perched water tables (Pierson 1983). However, during high precipitation events or if pipes are blocked, parts of the network of pipes can become fully saturated. This increases the pore-water pressure in the hillslopes (Pierson 1983; Uchida et al. 2001), as the hydrostatic head of the water-filled pipes leads to a local increase of pore-water pressure. As a result, additional pressure potentials from water collected in the pipe are generated in the surrounding soil matrix (Pierson 1983). This phenomenon could cause ruptures of slopes which would be considered safe when using conventional single-permeability models.

Simulations of slope stability have been frequently used since the beginning of twentieth century allowing researchers to express slope stability with a safety factor (Lu and Godt 2013; Shao et al. 2015). This approach allows comparison of different slope stability scenarios, including groundwater conditions. Several recent studies have focused on the simulation of subsurface flow in the slope stability analysis (Shao et al. 2015, 2016; Lu et al. 2012). The latest advances in hydrogeological modeling allow using different approaches in dealing with preferential flow and their subsequent integration in slope stability simulations.

Models of preferential flow can be divided into two-dimensional (2D) (Barcelo and Nieber 1981) and 3D models (Barcelo and Nieber 1982; Nieber and Warner 1991). Simulation of only saturated (Nieber and Warner 1991) or saturated-unsaturated flow through the adjacent soil matrix is possible (Barcelo and Nieber 1981, 1982). There are various approaches for modeling the exchange between pipes and porous media. Pipes often have been treated as tile drains that do not interact with the surrounding matrix (Barcelo and Nieber 1981, 1982). In considering the water exchange between the pipes and the soil matrix, the surface of a pipe can be treated as a seepage face (Uchida et al. 2001). Nieber and Warner (1991) have applied a prescribed head boundary condition for the pipe, or even a zone with high-saturated hydraulic conductivity has been used as an equivalent for a soil pipe (Uchida et al. 2001).

Shao et al. (2014 and 2015) and Krzeminska et al. (2012) used the dual-permeability approach to estimate the influence of macropore flow on hillslope stability. Krzeminska et al. (2012), using the dual-permeability approach, showed that preferential flow routes increase the vertical infiltration rate and affect the storage capacity of the soil. Further, the modeling done by Krzeminska et al. (2012) shows that the presence of preferential flow in the landslide body increases its overall stability, however intensive convergence of the preferential flow downslope fostered by well-connected macropore networks causes intensive accumulation of the water in the toe of the landslide which can decrease the stability in the lower part (Krzeminska et al. 2012). The dual-permeability approach assumes a specific proportion of dual-permeability media (macropores and fractures) in a volume of soil matrix (Stadler et al. 2012; Beven and Germann 2013). This approach is often used if preferential flow paths cannot be simulated individually. However, to understand the influence of preferential flow in separated pipes on hillslopes, a modeling approach using discrete groundwater conduits would be useful.

To understand hillslope stability in the context of the hydrological processes and forcing functions, different conceptualization approaches of preferential flow (i.e. through dual permeability or through discrete fractures) can be applied. However, the hydrogeological response to precipitation in a borehole does not directly allow one to establish whether preferential flow occurred in a dual-permeability or a discrete-fracture like manner. It is therefore not entirely obvious as to how to conceptualize preferential flow in a hydrogeological model used for hillslope stability simulations. Therefore a systematic analysis in needed on how the different approaches to conceptualize preferential flow paths affect the subsequent hillslope stability analysis.

In the first modeling step, synthetic 3D hydrogeological models of hillslopes using preferential flow were elaborated for dry initial conditions. This demonstrated the importance of preferential flow in the hillslope hydrogeology. In the subsequent modeling steps, 3D hydrogeological models are combined with slope stability models, which allows for systematic investigation of the influence of different types of preferential flow conceptualization and their climatic responses on the slope stability. Two fundamentally different preferential flow conceptualization approaches using dual permeability and discrete fractures were introduced and compared with the base case without preferential flow. The base case represents the conventional single permeability without preferential flow paths as most slope stability simulations do.

Integrated hydrogeological and slope stability simulation allows researchers to investigate the effect of preferential flow on slope stability depending on the conceptualization approach applied. The possible application of each of the approaches in different geological settings will be discussed.

Methodology

Coupling hydrogeological and slope stability models allow assessment of the different conceptualizations of preferential flow in hillslope stability analysis. Synthetic hydrogeological models serve as the basis for this analysis. Factors such as stratigraphy or topography were deliberately kept simple to focus on the influence of preferential flow conceptualization in relation to hillslope stability. Two preferential flow conceptualizations (discrete fractures and dual permeability) are investigated and compared to a base case composed of porous media without preferential flow. For all these simulations, two different initial conditions (antecedent conditions) are employed—in a first antecedent scenario, dry initial conditions are assumed, to investigate the development of the saturated zone and the flow dynamics of the different preferential flow conceptualizations, and no slope stability simulations are carried out in this stage; in the second antecedent scenario, partially saturated ("wet") initial conditions are tested and subsequently used in slope stability models. The models with wet antecedent conditions were compiled using three different slope angles; this results in nine synthetic models which allowed for estimation of the effect of each preferential flow conceptualization approach on hillslope stability depending on the slope angle (see Fig. 1).

For the subsequent stability simulations (based on the saturated antecedent conditions), the conditions when the pressure heads are highest are relevant. For identifying these critical groundwater conditions at which the landslide is triggered, the dynamics of pressure heads were analyzed spatially and temporally. A global factor of safety representing the likelihood for a landslide was calculated considering the critical pressure heads.

Numerical simulators

Hydrogeological simulator

Groundwater simulation was conducted using the HydroGeoSphere software. HydroGeoSphere (HGS) is a 3D fully integrated surface and subsurface flow simulator capable of modeling surface flow and subsurface flow in porous, fractured and dual-permeability media for both saturated and unsaturated conditions (Brunner and Simmons 2012; Aquanty Inc. 2013). This model has been widely employed to understand the basic physics, interactions and feedback mechanisms between complex hydrological processes (Banks et al. 2011; Xie et al. 2014).

HGS uses a modified version of the Richards' equation (Eq. 1) to simulate 3D transient subsurface flow in a variably saturated porous and dual-permeability media. The coefficient ω_{m} (the volumetric fraction of the total porosity occupied by the porous media) in Eq. (1) can represent a second porous continuum (dual-permeability media), for instance, pipes or macropores. The volumetric fraction is 1 if no dual-permeability media is applied.

$$-\nabla \cdot (\omega_{\mathrm{m}} q) \pm Q_{\mathrm{s}} + \sum \Gamma_{\mathrm{ex}} = \omega_{\mathrm{m}} \frac{\partial}{\partial t} (\theta_{\mathrm{s}} S_{\mathrm{w}}) \quad (1)$$

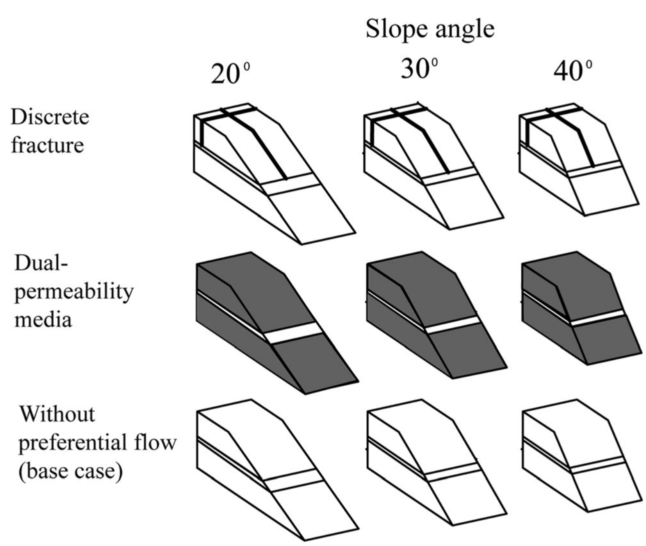


Fig. 1 Scenarios of synthetic models for wet antecedent conditions applied in the hydrogeological and subsequent slope stability simulations

where

ω_m is the volumetric fraction of the total porosity occupied by the porous media [dimensionless]; $\nabla = \partial/\partial x, \partial/\partial y, \partial/\partial z$

Q_s characterizes fluid inflow or outflow from an exterior of the simulation domain [$L^3\ T^{-1}$]

$\sum\Gamma_{ex}$ is the volumetric fluid exchange rate between the subsurface domain and all other simulation domains of HGS (e.g. surface, fractures etc.) [T^{-1}]

θ_s is the porosity [dimensionless]

S_w is the water saturation [dimensionless]

In Eq. (1), q is the Darcy flux of water [LT^{-1}] given as:

$$q = K \cdot k_r \nabla(\psi + z) \quad (2)$$

where

K is the hydraulic conductivity [LT^{-1}]

ψ is the pressure head of water [L]

z is the elevation head [L]

k_r is the relative hydraulic conductivity which varies between 1 (when the media is saturated) and near zero (when the media is totally unsaturated) [dimensionless]

Using the dual-permeability preferential flow conceptualization approach, preferential flow paths (dual-permeability media) are considered as planes with a defined spacing that subdivide the soil or rock matrix (primary media). Transient flow in a coupled porous–dual-permeability media system is modeled (Aquanty 2013).

HGS allows for simulation of variably saturated flow in a discrete fracture with aperture ω_f [L].

The governing 2D flow equation in a fracture is:

$$-\overline{\overline{\nabla}} \cdot (\omega_f \cdot q_f) - \omega_f \cdot \Gamma_f = \omega_f \cdot \frac{\partial S_{\omega f}}{\partial t} \quad (3)$$

where fluid flux [LT^{-1}] equals:

$$q_f = -K_f \cdot k_{rf} \overline{\overline{\nabla}} (\psi_f + z_f) \quad (4)$$

and where:

ω_f is a fracture aperture [L]

$\overline{\overline{\nabla}}$ is the 2D gradient operator defined in the fracture plane

Γ_f is the fluid exchange rate between dual-permeability media and fracture [T^{-1}]

k_{rf} is the relative permeability of the fracture [dimensionless]

ψ is the pressure head in the fracture [L]

z_f is the elevation head of the fracture [L]

$S_{\omega f}$ is the water saturation for the fracture [dimensionless]

The saturated hydraulic conductivity of the fracture is K_f with uniform aperture w_f and is calculated as follows:

$$K_f = \frac{\rho g \omega \frac{2}{f}}{12\mu} \quad (5)$$

where

ω_f is a fracture aperture [L]

μ is the viscosity of water [$ML^{-1}\ T^{-1}$]

ρ is the density of water [ML^{-3}]

g is the gravitational acceleration [LT^{-2}]

For the surface flow simulation, the diffusion-wave approximation of the Saint Venant equation was applied:

$$\frac{\partial \phi_o h_o}{\partial t} - \frac{\partial}{\partial x}\left(d_o K_{ox} \frac{\partial h_o}{\partial x}\right) - \frac{\partial}{\partial y}\left(d_o K_{oy} \frac{\partial h_o}{\partial y}\right) + d_o \Gamma_o \pm Q_o = 0 \quad (6)$$

where

ϕ_o is the surface porosity varying between zero at the ground surface and unity at the top of a rill or obstruction [dimensionless]

h_o is the elevation of the water surface [L]

d_o is the depth of surface water [L]

Q_o is a volumetric flow rate representing external sources and sinks [LT^{-1}]

K_{ox} and K_{oy} are surface conductance [LT^{-1}] given in the following

$$K_{ox,y} = \frac{d_o^{2/3}}{n_{x,y}} \frac{1}{(\partial h_o/\partial s)^{1/2}} \quad (7)$$

where

$n_{x,y}$ are the Manning roughness coefficients in the x and y directions [$L^{-1/3}\ T$]

s is the coordinate along the direction of the maximum ground surface slope [L]

Γ_o represents fluid exchanges with other domains [T^{-1}] (Aquanty 2013)

A wide range of boundary conditions can be imposed in the model. Precipitation is conceptualized through a surface boundary condition. A so-called critical depth boundary condition can be applied to the surface domain, which allows surface runoff to exit the model domain without affecting the upstream hydraulic heads or surface-water depths. Constant-hydraulic-head boundary conditions allow a prescribed hydraulic head to be maintained during the simulation.

Slope stability simulator

For the slope stability estimates, the limit-equilibrium analysis method was used. The slope safety factor in the limit-equilibrium analysis can be expressed as a relation between the average shear strength of the soil and the average shear stress developed along the potential failure surface (Das 1998). If the average shear stress developed along the potential rupture plane is higher than the average shear strength of the soil, the safety factor is less than one and a slope rupture can be expected. A common approach for calculating the safety factor of a nonhomogeneous slope (regarding lithology and pore-water pressure) is segmentation of the landslide body into vertical slices (Das 1998). Further, through an iterative procedure, the failure surface with the minimum factor of safety is determined (Lu and Godt 2013). Depending on the limit-equilibrium method applied and the equations of the statics calculated, the relationships between the interslice shear and normal forces vary (Das 1998).

In this study, the Morgenstern-Price method was applied to the SLOPE/W module in the GeoStudio2012 environment. The Morgenstern-Price method satisfies moment and force equilibrium principles and considers inter-slice normal and shear forces (Morgenstern and Price 1965). Furthermore, two equations of safety factors were calculated: the first for moment equilibrium (F_m) and the second for horizontal force equilibrium (F_f). F_m [M LT^{-1}] and F_f [MLT^{-2}] are equal if both moment and force equilibrium are satisfied. Therefore, after the simulation, one global factor of safety for the whole slope was determined (Morgenstern and Price 1965). Recently, the local factor of safety (LFS) approach has been more frequently used allowing researchers to determine the factor of safety at every point in the hillslope (Lu and Godt 2013; Shao et al. 2015). Shao et al. (2015) determined the local factor of safety to evaluate the influence of preferential flow simulated by the dual-permeability approach on hillslope stability. Contrary to the limit-equilibrium approach, no initial assumptions are needed for the critical failure surface (e.g. entry and exit range of the failure surface; Griffiths and Lane 1999). However, in the current study, the limit-equilibrium method using GeoStudio 2012 was preferred, because the limit-equilibrium method has been widely used during the last few decades and it has been adapted for considering the various effects of groundwater on hillslope stability such as increased weight due to soil saturation, buoyancy, negative pore-water pressures and seepage forces (GEO SLOPE Int. 2015). For each hydrogeological model during the entire simulation period, the critical groundwater heads causing the highest pore-water pressures in hillslope were determined and imported in the slope stability simulation.

Model setup

Hydrogeological models

The synthetic models were designed as 3D slope-sections composed of three sediment layers (see Fig. 2) the hydrogeological modeling parameters are summarized in Table 1. High hydraulic conductivity values were applied to the upper and lower layers, and the middle layer consists of lower-permeable soil (e.g., clay) that allows a perched water table to develop under high intensity rainfall. This arrangement was chosen because it is associated with frequent slope failures (Lourenço et al. 2006; Fox and Wilson 2010); therefore the modeling approach estimates a wide range of both

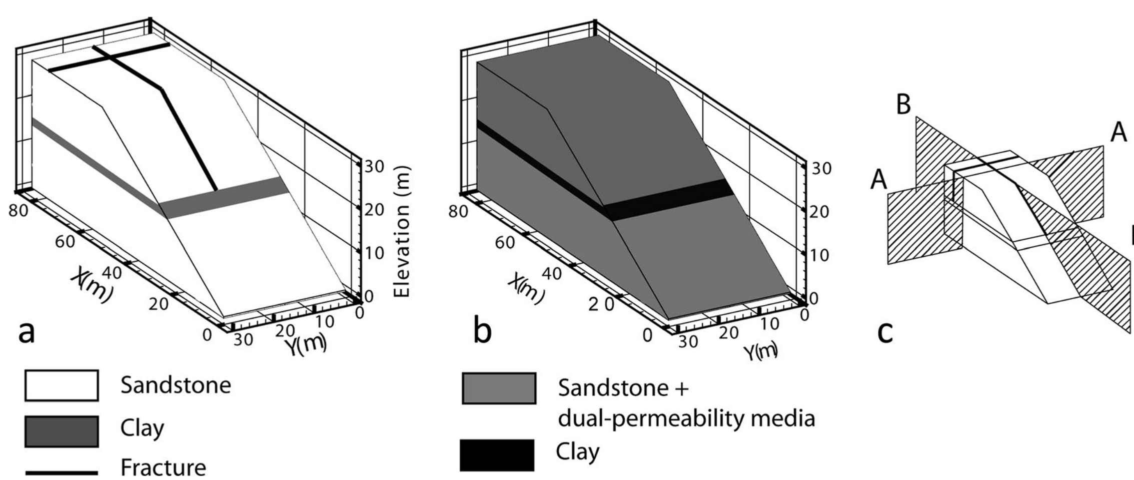


Fig. 2 Two synthetic hydrogeological models containing **a** one discrete fracture and **b** dual-permeability media. **c** represents the section lines of the model domain described in the text

Table 1 Hydrogeological modeling parameters

Domain	Parameter	Sandstone	Clay	Dual-permeability media
Subsurface	Hydraulic conductivity, K (m/s)	0.00005	7×10^{-11}	0.002
	Van Genuchten α (m^{-1})	6	1	-
	Van Genuchten β	3	2	-
	Volume fraction	-	-	0.15
	Porosity	0.25	0.35	0.5
	Specific storage (m^{-1})	1.5×10^{-4}	2×10^{-3}	-
Surface	Manning's roughness coefficients, n_x and n_y ($m^{-1/3}$ s)	0.6/0.6	0.6/0.6	0.6/0.6
	Rill storage height, D_t (m)	0.05	0.05	0.05
	Obstruction height, O_t (m)	0.005	0.005	0.005
Fractures	Aperture (m)	0.005	-	-

natural and artificial hillslopes where perched aquifers can be formed. The dimensions of the whole model domain comprise 82 × 30 m. Total simulation time was set to 672 days to attain flow conditions close to steady state and to observe hydrogeological responses to severe precipitation events. A fracture aperture of 5 mm was used because it has been shown that preferential flow paths with an aperture larger than 3 mm have a significant impact on hillslope hydrogeology (Mosely 1979).

Boundary conditions for the surface and subsurface flow system were applied in the hydrogeological simulation. In the subsurface, the first-type (Dirichlet) boundary condition of prescribed hydraulic head was used to represent the groundwater afflux from adjacent areas into the hillslope section. Two first-type boundaries of the surface flow were used as well. A rainfall rate boundary condition was applied to the model's surface to maintain water infiltration into the model's domain. A critical depth boundary condition was set at the foot of the slope, which allows water to leave the domain. A rill storage height of 0.05 m was applied to the surface of the model's domain. If the depth of surface water is smaller than the rill height, all water is stored in the rills and no surface runoff can occur. Surface runoff is crucial to simulate the surface–subsurface water interactions of the hillslopes. During the simulation, water was able to leave the modeling domain above the first clay layer, turn to surface flow and infiltrate again into the lowest sandstone layer. The parametrization of the synthetic models is based on the existing field sites in the Gauja River Valley in central Latvia, where landslides have occurred in the recent past (Kukemilks and Saks 2013). The hydraulic conductivity, porosity and van Genuchten parameters α, β were determined from clay and sandstone samples taken in the Turaida Castle mound (see Table 1).

Additional modeling parameters were taken from a literature review such as hydraulic conductivity of the dual-permeability media (Uchida et al. 2001) and specific storage (Domenico and Mifflin 1965). For dual-permeability media instead of van Genuchten α and β parameters, pseudo-soil relations were used (Coats et al. 1971) which are implemented in the HGS code.

In the first hydrogeological scenario (Fig. 2a), a discrete fracture is encompassed by highly conductive porous media at the sides and sealed by a low-conductivity layer in the bottom part (see Fig. 2a). In the second scenario (Fig. 2b), preferential flow routes are conceptualized by dual-permeability media in the sandstone deposits. The first scenario would correspond with discrete bedrock fractures. The second scenario would be applicable if the characteristics of individual macropores cannot be determined (e.g. an exact location of macropores is not known). In the case of dual-permeability, two different sets of hydrogeological characteristics were applied to one geological unit. The primary media characteristics are attributed to the matrix (in this case sandstone), while dual-permeability media represents preferential flow paths. In addition, there was a base case scenario without any preferential flow. This allows evaluation of the effect of discrete fractures and dual-permeability media compared to the base case where no preferential flow is considered.

The hydrogeological scenarios were simulated and used as pressure-head boundary conditions for the slope stability model. A time series of precipitation ranging from 1.4 to 2.2 mm/day was applied until flow conditions close to steady state were reached. The time series of precipitation corresponds to the average monthly precipitation in Latvia, which has a temperate, humid semi-continental climate (Latvian Environment, Geology and Meteorology Centre 2016).

Subsequent intensive precipitation events (up to 80 mm/day) for a period of 8 days were introduced. During the first modeling phase (first antecedent condition), dry initial conditions were chosen. This allowed investigation of the development of the saturated zone considering different preferential flow parametrization approaches and precipitation amounts. In the second hydrogeological modeling phase used for slope stability analysis, two initial heads, one at 2.5 and the other at 19 m, were set in each permeable sandstone layer. These initial heads create saturated conditions for the first 2.5 m at the bottom of the model, as well as the perched aquifer above the clay layer (see Fig. 2). The initial heads represent groundwater flux entering the modeling domain from the adjacent areas, as, due to the small surface area of the model, no realistic groundwater heads can be maintained with the precipitation water infiltration.

From the hydrogeological simulation, only extreme groundwater conditions regarding slope stability were used. Namely, when the maximal level of water table was reached. There are three morphological variations (20, 30 and 40° slope angles) for each of the three hydrogeological scenarios, resulting in a total of nine synthetic model scenarios.

Slope stability models

The soil mechanical characteristics were applied as shown in Table 2, in which φ is the internal friction angle [°]; c is cohesion [$ML^{-1}T^{-2}$]; and Υ is bulk density [$ML^{-2}T^{-2}$]. The soil samples were taken from the Turaida Castle mound in the Gauja River Valley and their soil mechanical parameters determined in the soil mechanical laboratory of the University of Trier, Germany. Consolidated direct shear box tests were applied to determine the internal friction angle and cohesion of clay and sandstone samples.

During the slope stability simulation, various effects of groundwater on hillslope stability were estimated: buoyant and hydraulic gradient force, increased soil weight due to water saturation, and influence of negative pore-water pressures (GEO-SLOPE Int. 2015). The buoyant and hydraulic gradient forces are among the forces that decrease slope stability the most (Fox and Wilson 2010). The effect of the increased soil weight due to water infiltration varies depending on the location of additional surcharge in the slope profile. An increase of weight in the foot of the slope improves slope stability; however, additional surcharge in the uppermost part reduces the hillslope stability. Negative pore-water pressure or suction may improve slope stability and explain the initiation of shallow landslides after a heavy rainfall when the negative pore-water pressure is reduced (Lu and Godt 2013). For the limit-equilibrium slope stability analysis, the same entry and exit range of slip surface was chosen for all synthetic models. The exit range was located in a single point at the foot of the slope, and the entry range was set along the entire overland surface of the model's domain. This allows the formation of various slip surfaces in the slope profile.

Table 2 Soil mechanical characteristics for slope stability modeling

Sediment	Υ (kN/m^3)	c (kPa)	φ (°)
Sandstone (sand)	20	5	30
Clay	22	48	17

Results

Dry antecedent conditions (no subsequent stability simulations)

Three models using different preferential flow conceptualization approaches (discrete fractures, dual-permeability media and no preferential flow) were compared in equal time steps and with changing precipitation amounts (see Fig. 3). Unsaturated initial conditions were set for the simulation.

Figure 3 shows the cross-section of the model depicted in Fig. 2 in four time steps. In the initial stage (1.1, 1.2 and 1.3 in Fig. 3), the infiltration process in all three domains can be observed. As is to be expected, the infiltration velocity is higher in the scenario with dual-permeability than in the model without any preferential flow paths; however, in the scenario with fractures, the zone of discrete fractures remains unsaturated. In the second time step (see case 2.1, 2.2 and 2.3 in Fig. 3), saturation can be seen after 264 days with low precipitation amounts. The center image shows that, in the dual-permeability model, water has already reached the less-permeable layer, but in the case without preferential flow infiltration, velocities are slower. Figure 3 also illustrates that the models without preferential flow paths and containing dual-permeability media are saturated faster, while the fracture zone remains unsaturated. In the 3rd time step, after 321 days, all images show the water table to be above the less permeable layer; however, the discrete fracture is still not saturated. Finally after 663 days (cases 4.1, 4.2 and 4.3 in Fig. 3), when the high intensity of rainfall has started, the fracture is saturated and can also transport groundwater. In the upper part of the section (cases 4.1, 4.2 and 4.3 in Fig. 3), the intensively saturated area represents saturation by severe precipitation followed by a dry phase.

As previously observed, the discrete fracture was not saturated until high overall saturation amounts of the porous media were reached. Figure 4 explains fracture flow dynamics under changing precipitation conditions (see also Fig. 3, first column, for model with discrete fractures). Figure 4 shows that after a relatively long phase of low fracture flow, a phase of increased fracture flow occurs (note the intense fracture flow after 400 days in Fig. 4). This point in time corresponds with the entry of water into the discrete fracture network, after the saturation threshold is reached. Afterwards, the water balance of the fracture stabilizes at around 80 L/day. A rapid increase of fracture flow happens shortly after the intense 8-day precipitation event. The abrupt increase in fracture flow is followed by a decrease, indicating that the water leaves the fracture network. The rapid decrease is critical for hillslope stability because it causes an intensive saturation downslope of the fracture outlet.

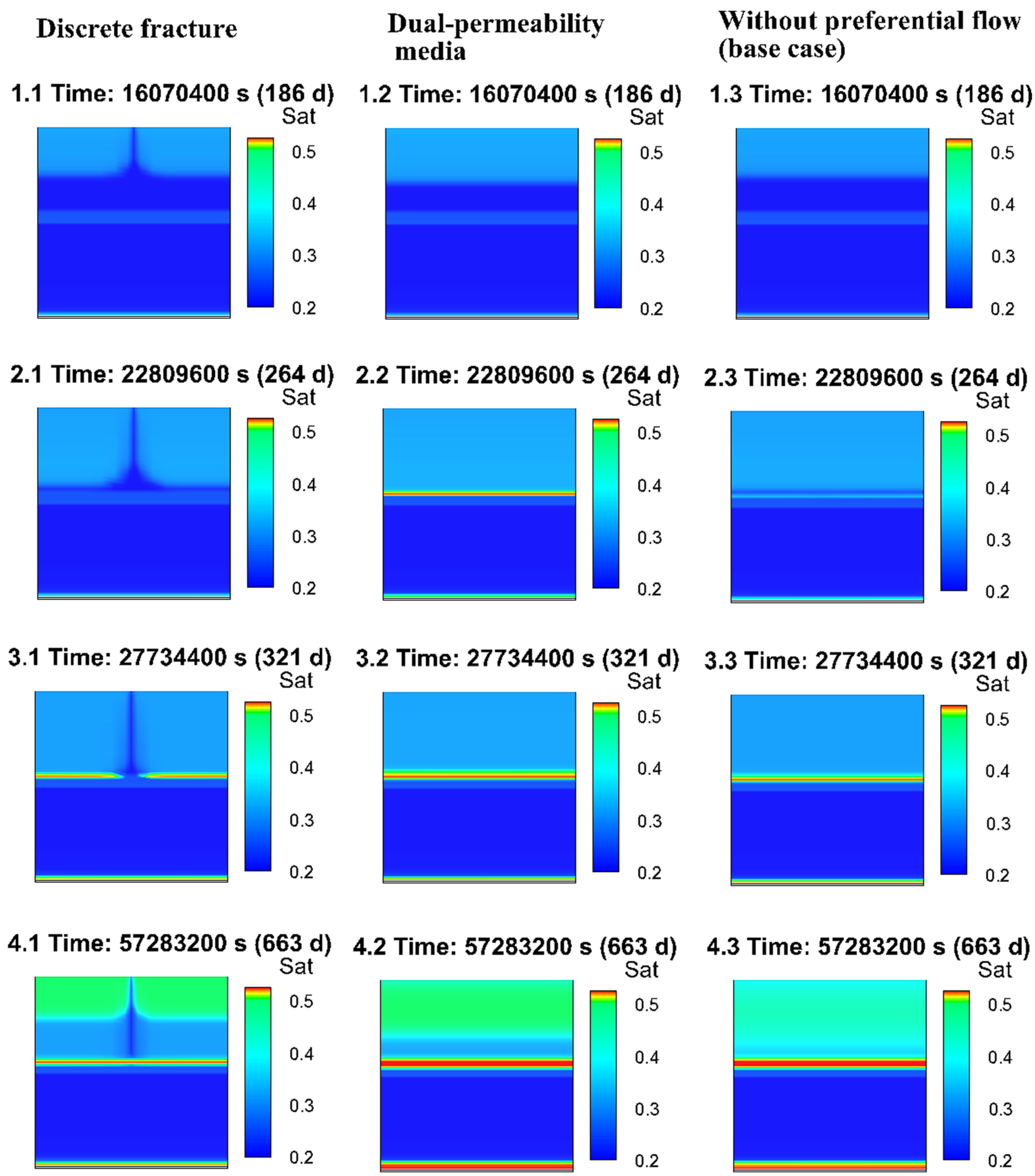


Fig. 3 Saturation of the section A–A (see Fig. 2c) showing a model with discrete fractures, dual-permeability media, and the base case without preferential flow

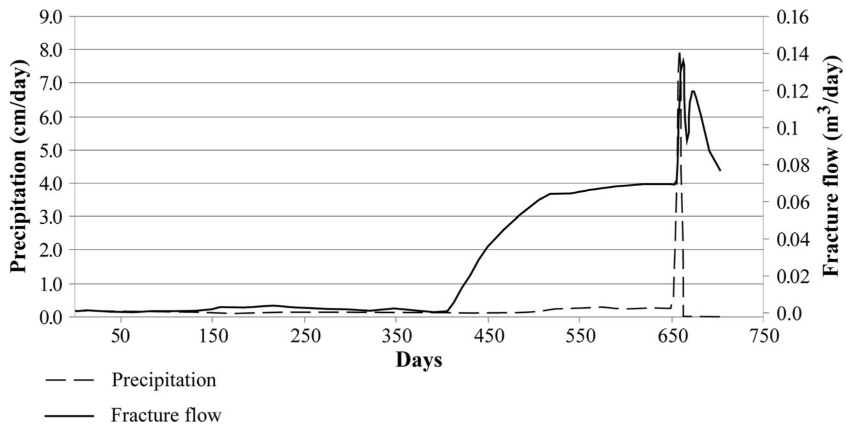
Saturated antecedent conditions and subsequent stability modeling

To analyze the influence of two different preferential flow models on slope stability, longitudinal sections of the synthetic model were made. The section was located along the fracture plane (see Fig. 5). All conditions were kept the same as in the previous analysis, including changing precipitation. The two initial heads were set at 2.5 and 19 m in the conductive layers here; therefore, groundwater afflux from adjacent areas is considered in addition to precipitation in the saturated antecedent condition. This allows for simulation of slope stability with regard to preferential flow.

The other parameters such as soil mechanical properties or lithology, were kept constant for all three scenarios, allowing for comparison of the hydrogeological scenarios using the slope safety factor. The single global safety factor was preferred, because it allows for determination of the effect of each hydrogeological scenario on the stability of the whole slope.

Figure 5 illustrates that after the fracture has started to conduct water, a rapid saturation of the model's lower part occurs (see Fig. 5, case 2.1). Groundwater discharges from the discrete

Fig. 4 Fracture flow and precipitation



fracture above the less permeable clay layer and intensively saturates the zone downslope. After an intense precipitation event, discharge from the fracture increases and saturates the foot of the slope. Only slight differences can be observed between the scenarios with dual-permeability media and the base case with no preferential flow. Consequently, the critical pressure heads occurred shortly after the intense precipitation event and they were located downslope of the discrete fracture outlet. The same hydrogeological modeling approach was applied for the synthetic models with slope angles of 20 and 40°. Finally, the profiles with the critical heads responsible for the highest pore-water pressures in the slope profile were chosen for subsequent slope stability analysis.

Figure 6 illustrates hillslope stability depending on groundwater conditions, type of preferential flow conceptualization and slope angle. The safety factor characterizes the stability of the slope. If it is less than 1, slope rupture is to be expected. Figure 6 shows that the most critical hillslope stability is reached at high slope angles. Also, the influence of the slope angle in absolute numbers, when comparing 20 and 40° steep slopes, can reach up to 0.89 units in dry conditions. Figure 6 also shows that the preferential flow conceptualization using discrete fractures has the least stable slopes. The safety factor for this scenario varies from 1.25 (20° slope angle) to 0.72 (40° slope angle), which is the most critical value attained during the modeling. In comparison with the scenario without

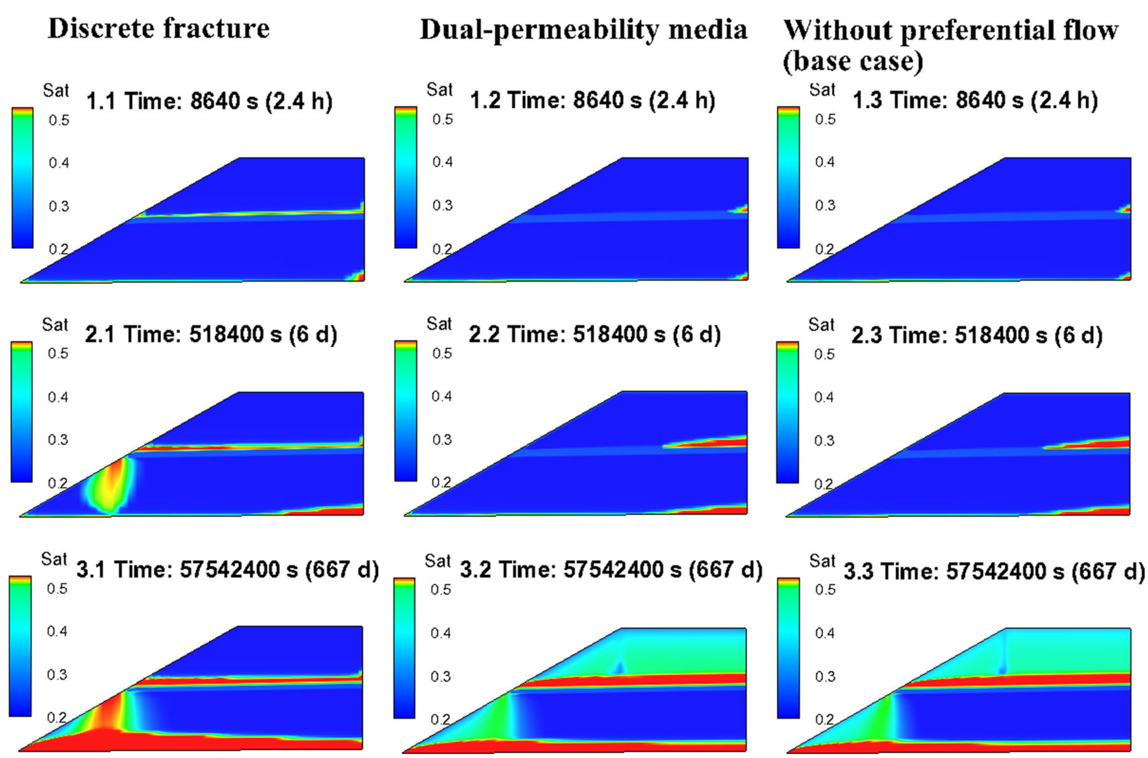


Fig. 5 Longitudinal sections B–B (see Fig. 2c) showng saturation of the synthetic model (slope angle 30°) along the discrete fracture plane, model with dual-permeability media, and base case without preferential flow

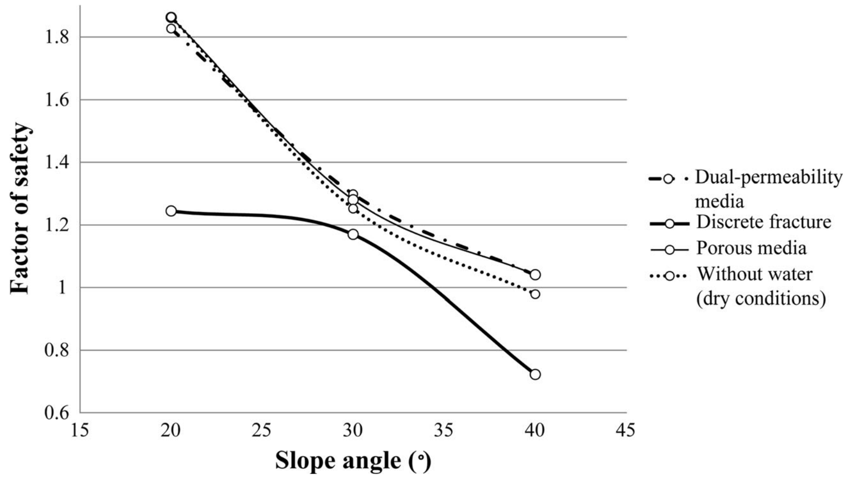


Fig. 6 The safety factor in relation to slope angle, and preferential flow models. The factor of safety was calculated at three different slope angles (20°, 30°, 40°)

water, in the case of the discrete fracture, the difference can reach up to 0.62, which illustrates how high the influence of groundwater on hillslope stability can be. It should be noted that all hydrogeological and morphological scenarios, except discrete fracture, have a safety factor over one, which means that the slope is relatively stable; however, only the scenario with the discrete fracture predicts the slope rupture at 40° slope angle. This means that the scenarios without a discrete fracture can underestimate potential landslide risks significantly. It should be noticed that the scenario without water is less stable than the scenarios with dual-permeability and without preferential flow at a 40° slope angle. This may be explained by the fact that there is no negative pore-water pressure considered in the scenario without water. Obviously, negative pore-water pressures can increase the stability of the hillslopes. At a 20° slope angle, the scenario without water tends to be the most stable, which means that in this case the stabilizing effect of negative pore-water pressures is not as emphasized as in the scenario with a 45° slope angle, probably due to the relatively small proportion of the unsaturated zone. This can be explained by the geometry of the slope because, according to the results of the modeling, flatter slopes are more intensively saturated by infiltrating surface water and water discharging from discrete fractures, compared with steeper slopes.

Discussion

A fully coupled, physically based hydrogeological model was used in combination with a slope stability model to demonstrate the importance of the inclusion of preferential flow on slope stability analysis. Two different preferential flow conceptualizations, namely, discrete fractures and dual permeability, were simulated with a state-of-the-art hydrogeological model. A third base-case scenario without preferential flow was developed using the same simulation software. The model's parameters were based on a real-world study area in the Gauja River Valley, central Latvia, where recent landslide events have been observed.

The hydraulic response to precipitation in the case of discrete fractures (Fig. 3) shows that, at average precipitation amounts, groundwater flow occurs primarily not through the fracture but through the surrounding porous media. Fractures, on the other hand, remain unsaturated until high levels of overall saturation are reached. Once this happens, fractures, compared to porous media without preferential flow paths, are able to transport significant quantities of groundwater in short periods of time. In the scenario using the dual-permeability conceptualization approach, faster infiltration after a precipitation event compared to the scenario without preferential flow can be observed. This also leads to a more rapid discharge in the lowest part of the model and does not cause pore-water pressures to be as high as with discrete fractures.

These simulations underscore the differences between different preferential pathways, and therefore the critical importance of an appropriate consideration of groundwater hydraulics for slope stability assessment. Nevertheless, the appropriate conceptualization of preferential flow paths seems to receive little attention in the current or past literature. The decision about which conceptualization should be applied strongly depends on the character of discontinuities in the field site. The conceptualization approach with discrete fractures can be used if there are separated well-distinguishable preferential pathways, which can be parametrized to be introduced in a hydrogeological simulation. The scenario with dual permeability can be applied if the location and apertures of individual discontinuities are not known and only statistical data of parameters such as spacing and apertures can be determined. This approach can be relevant in areas where bedrock is intensively fissured and it is not possible to parametrize individual preferential flow paths.

Subsequent slope stability analysis indicated that for the selected model's setup, the scenario with the discrete fracture conceptualization approach is the most critical for hillslope stability. This scenario (Fig. 5, case 3.1) can be considered the most dangerous for hillslope stability, because it leads to high pore-water pressures in the lower part of the slope. The scenario with dual permeability and the base case without preferential flow, proved not as critical as the scenario with discrete fractures because it does not lead to such high groundwater heads. It is noteworthy that the different conceptualizations of preferential flow had an important influence on the slope stability simulations, while the differences in hydraulic responses in terms of groundwater heads were more of local scale. These local effects can be easily overlooked using standard slope stability monitoring measures such as observation wells. As a result, the conceptualizations of preferential flow paths can be wrong, and the subsequent landslide risk estimation biased.

Conclusions

Slope stability is intrinsically linked to the hydrogeological conditions and dynamics at a given site. Preferential flows have a major impact on groundwater dynamics in response to precipitation events. While some earlier studies have analyzed the effect of preferential flow on slope stability using dual-permeability approaches, the importance of preferential flow in slope stability modeling does not seem to have received the required attention. The latest generation of fully coupled, physically based hydrogeological models opens new possibilities to simulate the physics and dynamics of preferential flow in hillslopes. Owing to their capacity to explicitly simulate discrete fractures, these models are able to consider additional impacts of preferential flow on hillslope stability without previously employed approaches of simulating preferential flow using dual-permeability media. Coupled hydrogeological and slope stability simulations have shown that the different conceptualizations of the preferential flow paths can significantly affect slope stability. Importantly, the synthetic models suggest that the most critical scenario with the discrete fracture leads to local increases of pore-water pressures and subsequent slope instability. There is thus an urgent need to more explicitly consider this type of preferential flow in slope stability simulations.

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