Hydromechanical modelling of slope stability at Dollendorfer Hardt, Germany, using the Local-Factor-of-Safety concept

S. Moradi[1], J.A. Huisman[1], H. Class[2], T. Heinze[3], A. Kemna[3], H. Vereecken[1]

1Agrosphere Institute (IBG 3), Forschungszentrum Jülich GmbH, Germany, 2 Institute for Modeling Hydraulic and Environmental Systems (IWS), University of Stuttgart, Germany, 3 Department of Geophysics, Steinmann Institute, University of Bonn, Germany.

University of Stuttgart
Germany

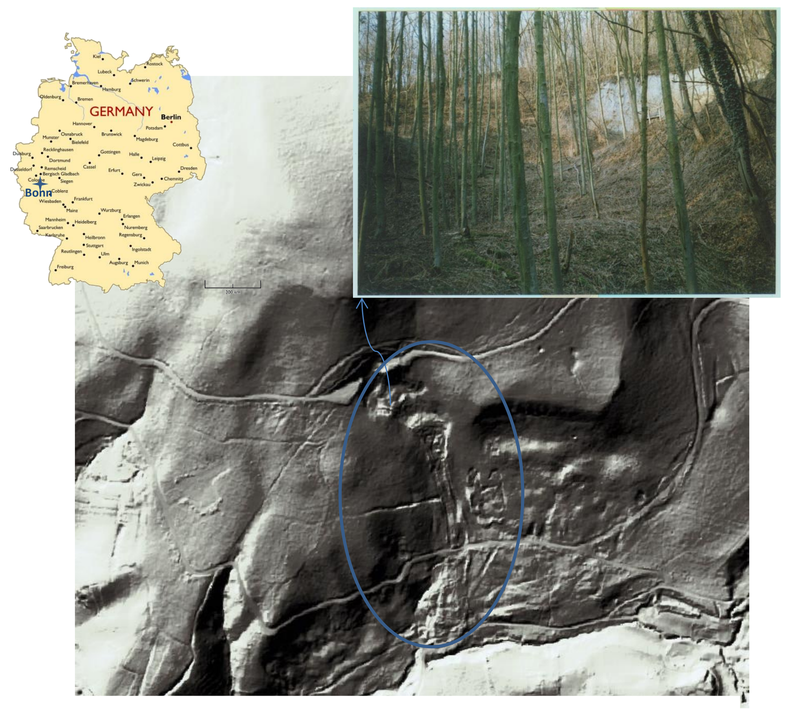
JÜLICH Forschungszentrum

Bundesministerium für Bildung und Forschung

Motivation and aim

Rainfall-induced landslides are one of the most important natural hazards. One state-of-the-art modelling approach for coupled hydromechanical slope stability analysis is based on the Mohr-Coulomb concept that allows evaluating the stability at each point within a hillslope using the so-called Local-Factor-of-Safety (LFS) approach. The LFS approach has so far mainly been used to analyze in silico experiments with relatively simple slope geometry. This study aims to apply the LFS concept to a slope with complex morphology and spatially distributed material properties that are expected to have a strong influence on flow orientation, water content, stress distribution, and slope stability. Our study site is located at Dollendorfer Hardt, Germany, and has been investigated in a range of previous studies. The slope geometry was obtained from a high-resolution digital elevation model (DEM), and the subsurface layering was derived from geophysical site characterization. The results of the hydromechanical simulations will be compared to available soil water content monitoring data obtained using a wireless sensor network and time-lapse electrical resistivity tomography. In a final step, slope stability will be evaluated for several hypothetical rainfall scenarios to determine conditions for potential slope movement.

Set-up of the model



Location of the study area
(Dollendorfer Hardt land slide area)

Soil properties in the landslide scar area based on the measurements and derived from pedotransfer functions (Rosetta Lite)

Symbol	Parameter name	Units	Layer 1	Layer 2	Layer 3
θ_s	Saturated water content*	-	0.29	0.25	0.29
θ_r	Residual water content *	-	0.06	0.07	0.065
K_s	Saturated hydraulic conductivity	$m\ s^{-1}$	5.0e-7	6.0e-8	5.5e-9
α	van Genuchten fitting parameter *	m^{-1}	1.9	2.0	1.1
n	van Genuchten fitting parameter *	-	1.22	1.18	1.31
ρ_b	Bulk density	$kg\ m^{-3}$	1900	2000	1900
E	Young's modulus *	MPa	15	15	30
v	Poisson's ratio *	-	0.35	0.35	0.35
Φ'	Friction angle	°	34	25	20
c'	Effective cohesion	kPa	20	10	30
-	Sand content	%	26	11	3
-	Silt content	%	40	41	64
-	Clay content	%	34	48	33

* Derived from Rosetta Lite

A coupled hydro-mechanical framework for slope stability analysis

Time = t

↓

Transient water flow for fields of pressure head and water content

$$\nabla . k(h) \nabla H + W = \frac{\partial \theta(h)}{\partial t}$$

↓

Momentum balance for field of total stress

$$\nabla . (\boldsymbol{\sigma}) + \gamma \mathbf{b} = 0$$

↓

Consideration of suction stress provides field of effective stress

$$\sigma^s = -\frac{\theta(h) - \theta_r}{\theta_s - \theta_r} h$$

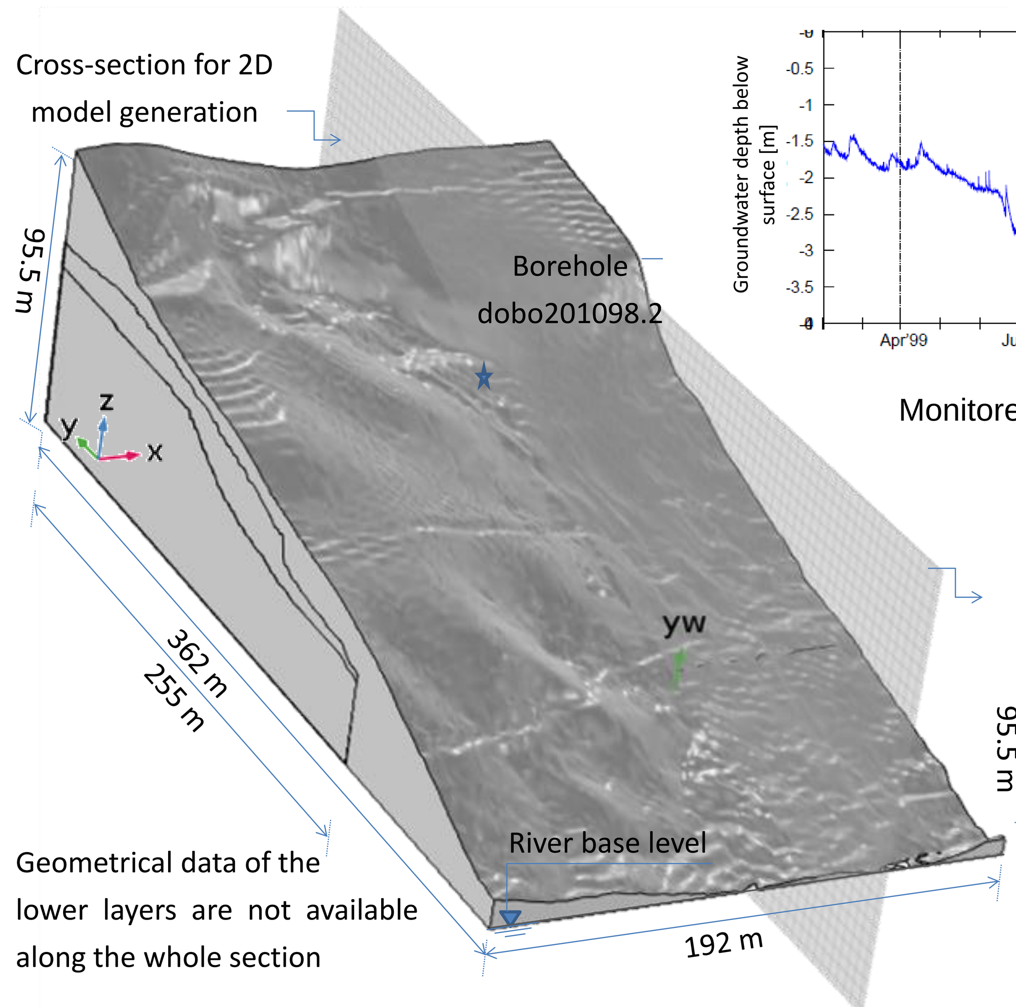
↓

Local factor of safety

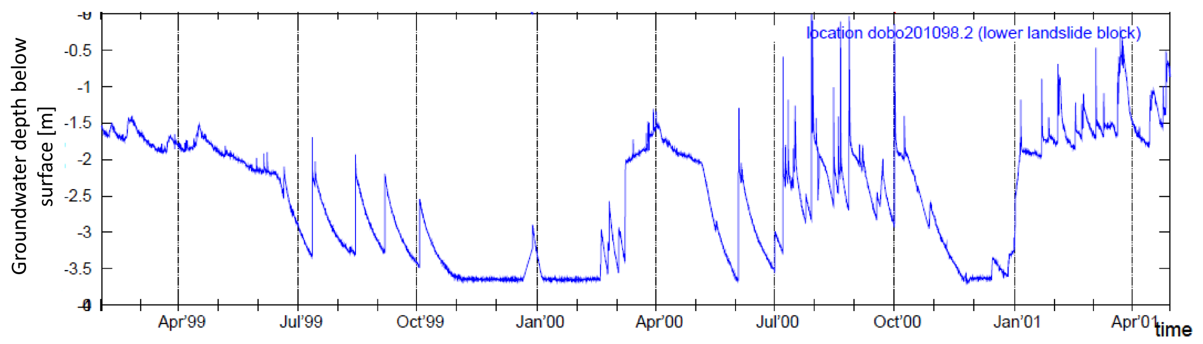
$$LFS = \frac{c' + \left(\frac{\sigma_1' + \sigma_3'}{2} - \sigma^s\right) \tan\phi}{\frac{\sigma_1' - \sigma_3'}{2} \cos\phi}$$

↓

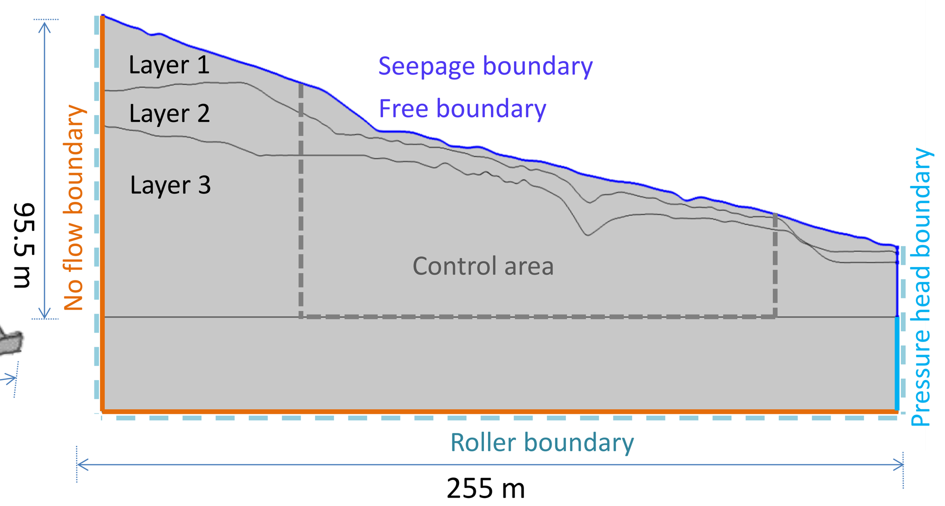
Time = t + Δt



COMSOL Multiphysics generated 3D geometry and soil layering model of the landslide scar area of Dollendorfer Hardt based on the geophysical measurement data.



Monitored groundwater levels at borehole dobo201098.2 (Schmidt, 2001)



Geometry and boundary conditions of the 2D hydromechanical model

$$\text{Infiltration} = P - PET - EX$$

Thornthwaite equation (1948):

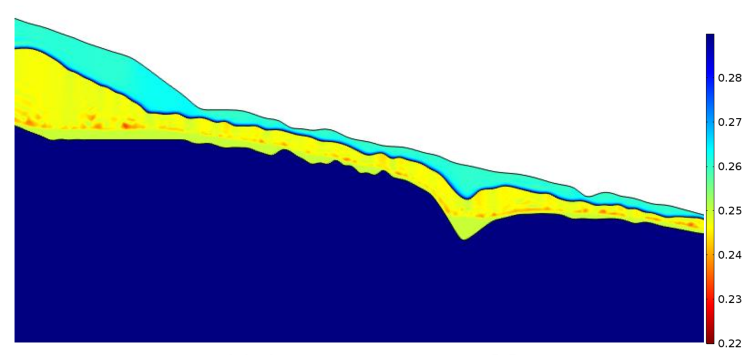
$$PET = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(10\frac{T_a}{I}\right)^a$$

$$a = 6.75e^{-7} * I^3 - 7.71e^{-5} * I^2 + 1.792 * 1e^{-4} * I + 0.49239$$

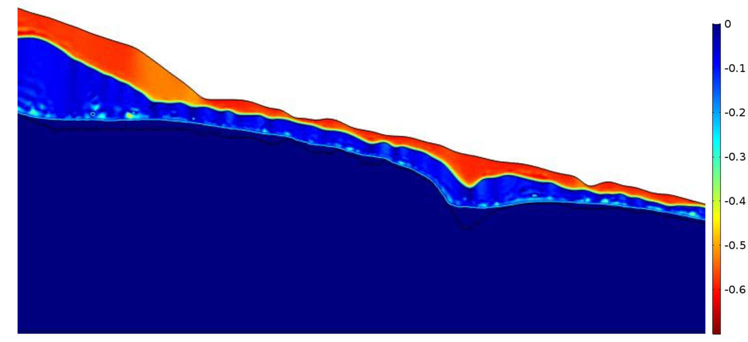
$$I = \sum_{i=1}^{12} \left(\frac{T_{a_i}}{5}\right)^{1.514}$$

Slope stability evaluation

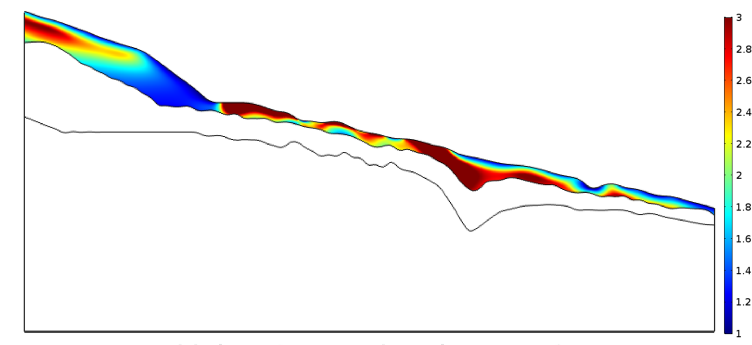
Initial condition is obtained from running the model with an average infiltration of 165 (mm/year) for 30 years.



Initial water content [-]



Initial water head [m]

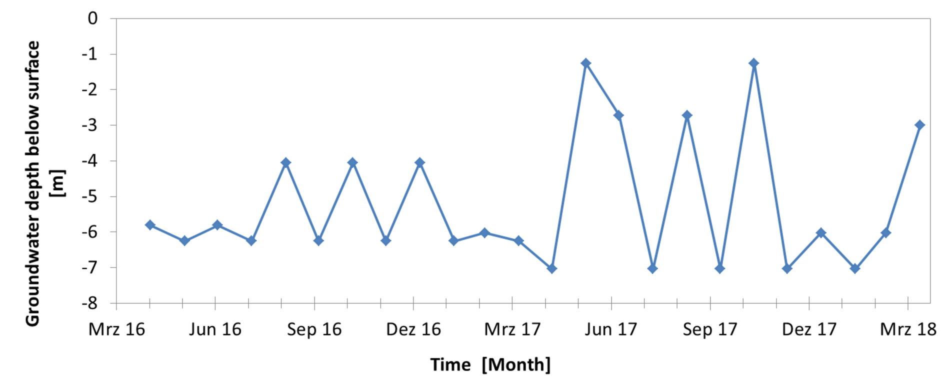


Initial LFS near the slope surface

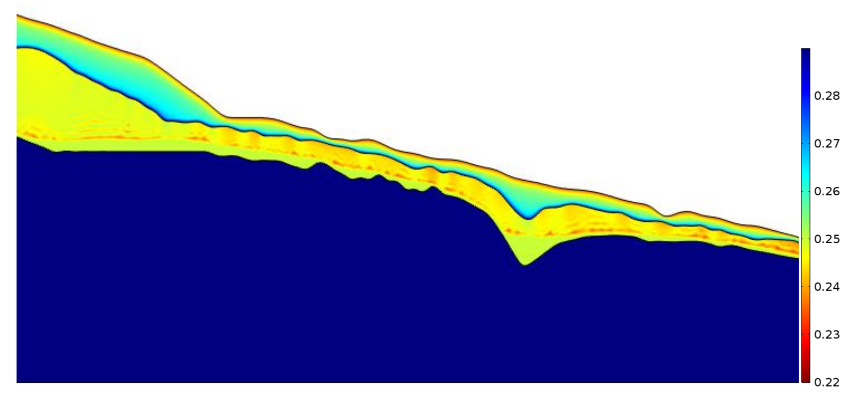
Two years of monthly infiltration is used to obtain initial conditions for the event rainfall

Characteristics of the implemented rainfall and infiltration

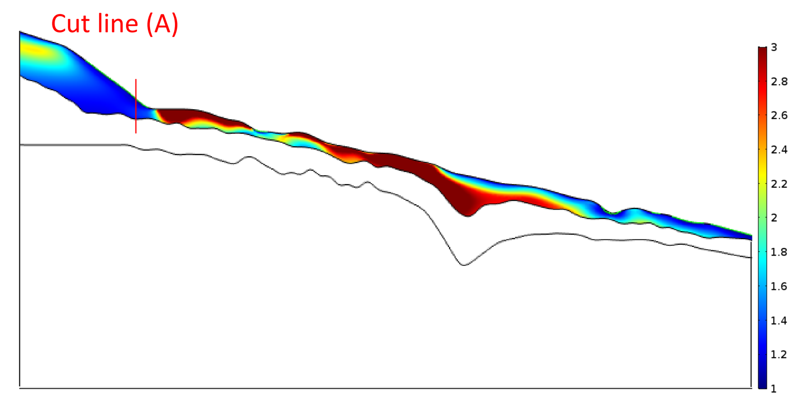
Rainfall	Units	Value
Annual rainfall	$mm\ y^{-1}$	650
Annual infiltration	$mm\ y^{-1}$	165
Event rainfall	$mm\ h^{-1}$	20



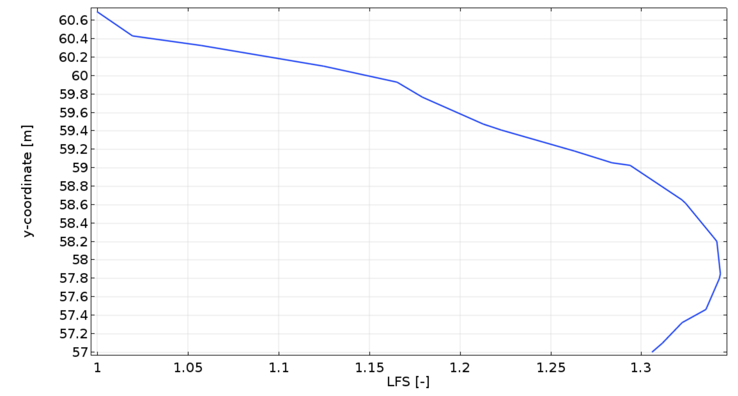
Modeled groundwater levels at the location of borehole dobo201098.2



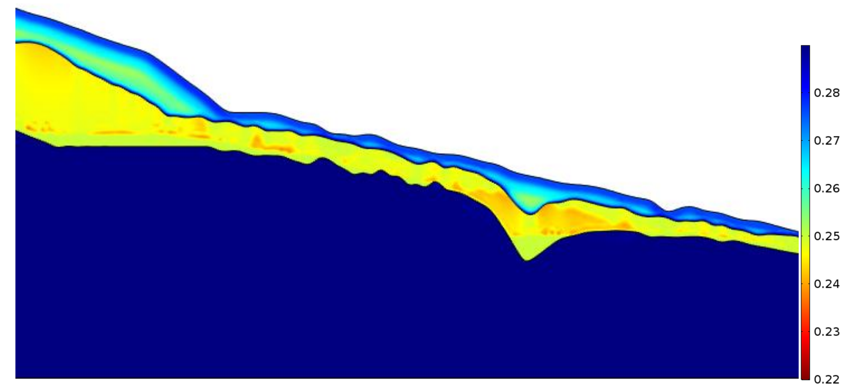
Initial water content for event rainfall in March 16



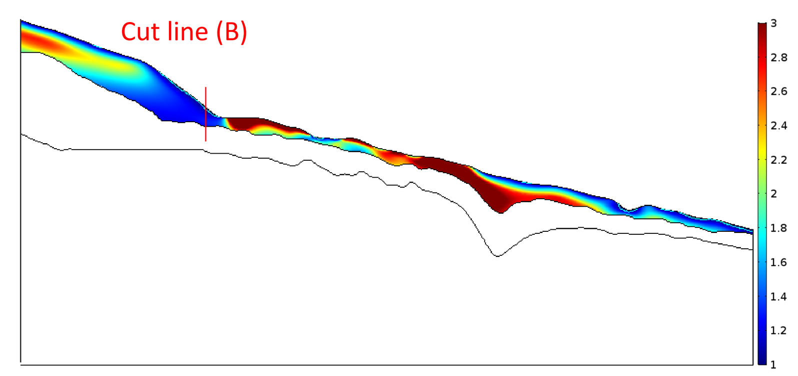
LFS after 10 hours event rainfall in March 16



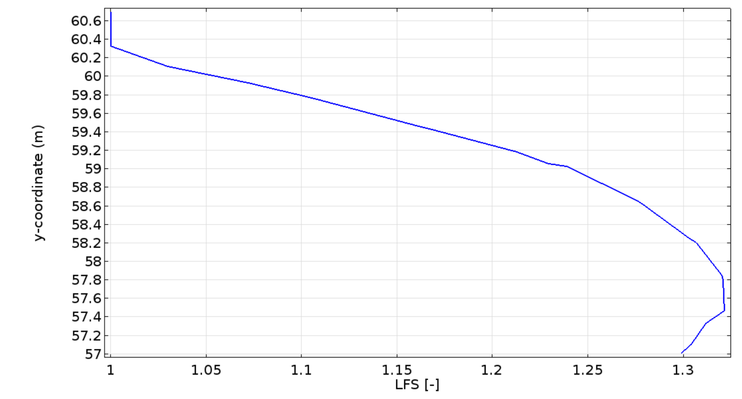
LFS along the cut line (A)



Initial water content for event rainfall in December 16



LFS after 10 hours event rainfall in December 16



LFS along the cut line (B)

Conclusions

- We have used the LFS approach for slope stability assessment of a real slope in Dollendorfer Hardt with a relatively complex geometry and heterogeneity in material properties.
- The results of the hydrological simulations are consistent with the available soil water content monitoring data obtained using a wireless sensor network and time-lapse electrical resistivity tomography, as well as the measured groundwater table at the site.
- The hydrological initial condition plays an important role in timing of slope failure and determines the amount of rainfall that is required for potential slope instability.
- We are thankful for funding within the Geotechnologien program of BMBF (Grant number 03G0849A)