Special Section: Landslides

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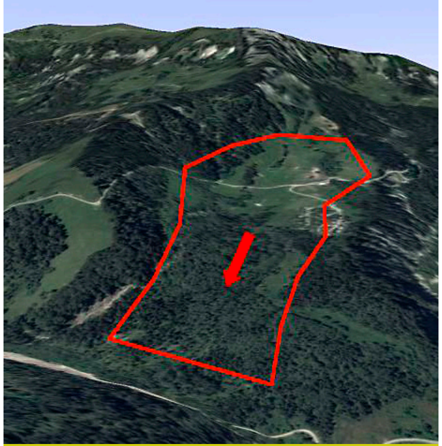

The guest editors introduce the special section on landslides, including each of the contributions and implications for future research. Advances in our understanding will involve multidisciplinary research and applications with the goal of preventing damage to infrastructure and the environment.

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Special Section on Landslides: Setting the Scene and Outline of Contributing Studies

Landslides generally impose a considerable threat to human life, infrastructure, and the environment, especially in alpine areas. Landslides belong to the phenomena of mass movements, such as rock falls, avalanches, and debris flows. Although landslides and debris flows have much in common at first sight, they differ strongly with respect to underlying physical processes, as elaborated in Armanini and Michiue (1997) and Wang et al. (2004, 2007).

Landslides are categorized as shallow or deep seated. Shallow landslides have a vertical extent up to a few meters and horizontal extent up to a few hundred square meters. Formation of shallow landslides mostly occurs in response to extreme rainfall events (Terlien, 1998; Delmonaco and Margottini, 2004) and depends on near surface structures and processes. Understanding and predicting shallow landslides is a more straight forward exercise, when compared to deep seated landslides, although it is by no means simple. Deep seated landslides have a vertical extent up to several tens of meters and spread horizontally from a hundred to a few thousand square meters. They are distinguished into fast moving and creeping landslides. Fast moving, or active, landslides, such as the "Super-Sauze" in the French Alps (Malet et al., 2003), exhibit movement rates of up to tens of meters per year. Creeping landsides move several centimeters or decimeters per year; a prominent example is Sibratsgfäll/Rindberg in Vorarberg Austria (Jaritz et al., 2008). Understanding the cause-and-effect relationships of deep seated landslides is much less straight forward than those of shallow landslides because: (i) they are controlled by multiple structures that in turn affect multiscale interactions and feedbacks between hydrologic, geohydraulic, and soil mechanical processes, and (ii) both short- and long-term triggers affect soil deformation, shear band formation, and thus movement of the creeping hillslope body. Short-term triggers are heavy rainfall events, vadose zone and groundwater flows, and pressure dynamics, but they can also include river bank or hillfoot erosion during flood events, depending on site conditions. Long-term triggers include seasonal changes of the self-load, due to seasonal soil moisture variations and snow cover, and the contribution of trees and infrastructure to the self-load.

Although creeping, deep seated landslides appear less spectacular than the active landslides, they cause steadily increasing damage to buildings and infrastructure in the long term. Creeping landslides can furthermore be regarded as the ideal and "safe" environment to learn:

- Whether and how do most recent measurement technology and experimental design allow assessment of information on dominating structures, processes, and their feedbacks that is sufficient for understanding how flow and creeping deformation processes within large and heterogeneous systems respond to the abovementioned short-term and long-term triggers?
- Whether and how can we develop and implement a coupled model to simulate these process interactions at creeping hillslopes at a level of appropriate complexity?

This special section presents a set of studies conducted at the Heusmöser (characterized below) that have jointly addressed these questions within a joint research project ("Coupling of Flow and Deformation Processes for Modeling the Movement of Natural Slopes") in three main areas:

1. By performing benchmark experiments to explore flow and deformation processes under controlled conditions to parameterize and verify reductionist, physical models for subsurface, multiphase flows and continuum mechanics.
2. By setting up an observatory to (i) identify dominating surface and subsurface structures and key material properties, (ii) monitor the short- and long-term triggers and geohydrological states, and (iii) quantify "hillslope responses" in terms of surface discharge, surface displacement rates, shear zone development, and nanoseismic events.
3. By combining top-down and bottom-up approaches to assess a model of appropriate complexity by (i) stepwise simplification of reductionist, physically based models, and (ii) adding more complexity to simplified models that rely on macroscopic observables.

The study site is the "Heumöser," which has been creeping for more than 15 yr. It is located in a remote side valley (50 km^2) of the Vorarlberg Alps that forms the catchment of the Dornbirner Ach. The catchment is characterized by a broad upper valley, cut into soft marlstone rocks, and a very steep middle valley formed in carbonaceous rocks. Bedrocks date from the Upper Cretaceous to the Lower Tertiary. The Heumöser extends 1800 m in the east–west direction and about 500 m in the north–south direction and ranges in elevation from 940 to 1360 m. The slope is partly forested with secondary spruce and alder and is used as pastures or meadows in summer and for skiing in winter. Additional characteristics of the study area are provided in the manuscripts of this special section, as well as in Lindenmaier et al. (2005) and Wienhöfer et al. (2009). For additional information on geophysical methods and model approaches in landslide research, the reader is referred to Jongmans and Garambois (2007), van Asch et al. (2007), and Stadler et al. (2009).

In the following, a brief introduction of the four papers is given. The studies of Germer and Braun (2011) and Ehlers et al. (2011) are mainly related to areas 1 and, partly, 3. Germer and Braun (2011) investigated the effect of different saturations and external loads on slope stability during controlled field experiments. Ehlers et al. (2011) used these same experiments to verify their multiphase soil mechanical model and studied the development of rainfall-induced shear bands for parts of the Heumöser. The studies of Walter et al. (2011) and Wienhöfer et al. (2011) are mainly related to areas 2 and, partly, 3. Walter et al. (2011) mapped rainfall-induced fracture processes using nanoseismic methods and determined the Heumöser's landslide volume and bedrock topography using seismic methods. Wienhöfer et al. (2011) used the infinite slope model as a diagnostic instrument to point out related difficulties in assessing the right data to parameterize such a simple model at this scale.

Overview of Contributions

Experimental Work in the Laboratory

In this section, the contribution of Germer and Braun (2011) is discussed. Shear failure is one of the key processes initiating a landslide and is assumed to be responsible for creeping processes observed in parts of the Heumöser. The hypothesis of the joint research project is that slope instabilities are triggered by a rapid change in pore water pressure in the lower reaches of the slope and that these rapid changes are due to infiltration into macropores in the upper reaches of the slope. The aim of the experimental work in the VEGAS laboratory was to better understand shear failure mechanisms under the influence of changing boundary conditions. In laboratory experiments under controlled conditions, idealized soil and water pressure conditions of the Heumöser were set up in close collaboration with the numerical modelers. The experimental results provided physical insight into the processes and, additionally, data and parameters needed for model calibration and validation.

Germer and Braun (2011) designed and performed numerous experiments in which they investigated the effects on slope stability of variable groundwater tables and corresponding water saturations in the vadose zone, varying groundwater flow conditions, and variable pore water pressures. To transfer the experimental results into numerical models, experiments were built using fine sand with known characteristics (e.g., capillary–pressure–saturation relations, grain size distribution). Initial conditions were varied to simulate different water distributions or changing geometry (upper reaches of the slope were simulated by an external load). Boundary conditions depicted varying flow, and hence, water pressure situations and varying external excitations (load) in the slope. Their results show that lower water saturations and the corresponding high capillary tensions in the reaches of the expected shear band stabilize the slope. High water saturations or, in an extreme case, positive water pressures destabilize the slope. Rapidly increasing (pore) water pressures due to rapid infiltration in the vicinity of the slope foot led to additional destabilizing effects, even while the shear zone itself was still under negative water pressure.

The experiments prove the hypothesis: rapidly changing water pressures due to upslope infiltration in macropores might greatly contribute to slope destabilization. Furthermore, Germer and Braun (2011) observed that development of shear bands and slope failure were preceded by an abrupt decrease in pore water pressure in the vicinity of the shear band. Monitoring such pressure fluctuations could be an indicator for slope failure in the field; however, this aspect needs additional and more detailed investigation.

Structure and Process Identification in the Field

This section first introduces the paper of Walter et al. (2011) followed by the one of Wienhöfer et al. (2011). Geophysical investigation methods are important to better characterize subsurface structures, which contribute to a good numerical modeling basis. They enable a better understanding of processes, and their analyses enable detection of cause-and-effect relationships. Using such methods, Walter et al. (2011) estimated the moving landslide volume of the creeping Heumöser, and they mapped rainfall-induced fracture processes.

Determination of the moving landslide volume is based on active seismic measurements. The study by Walter et al. (2011) represents the first time this has been performed at the Heumöser. The authors are aware that their results are rough estimates, which must be improved in the future, possibly by combining refraction and reflection seismic investigations.

The authors applied nanoseismic monitoring during several campaigns to analyze fracture processes after heavy rainfalls. The advantage of this method is that it can detect fracture processes one to two orders of magnitude lower than other seismic methods. The recorded data were processed with spectral analyses methods and then interpreted further. Fracture processes have been observed in areas with variable water saturations and high deformation rates at the surface. However, no fracture processes have been registered in permanently water saturated areas, where the highest surface deformation rates have been measured. These results show a dependency of water saturation and surface deformation. From the measurements, the authors deduced that local earthquakes probably influence the fracture processes. To gain further insight, a permanent monitoring network has been installed, and data analysis is underway.

In the contribution of Wienhöfer et al. (2011) hydrological processes are dealt with, including rainfall, runoff, infiltration, and subsurface flow dynamics, and how they control the water (or pore) pressure and buoyancy in the subsurface. Thus, these processes have a strong influence on the mobility of creeping landslides such as the Heumöser. Wienhöfer et al. (2011) improve the understanding of these hydrologic controls by linking subsurface exploration, field monitoring, data analyses, and a simple stability modeling approach, also known as the infinite slope model.

A hydrometeorological monitoring network that collects rainfall, wind, global radiation, air humidity, and temperature data was set up, and additional data were obtained about soil moisture contents at different depths, water levels in creeks, snow depths, groundwater levels (including pore pressure in several boreholes at different depths), and one inclinometer (relative movements). Data analyses include regression and correlation methods. Modeling is based on the infinite slope method, where a single soil body is sliding along a planar failure, and shear strength is taken into account with the Mohr–Coulomb criterion.

The measured movement rates indicated seasonal dependency, associated with increased pore pressures. From the pore pressure measurements, Wienhöfer et al. (2011) concluded that the multilayered aquifer of the Heumöser consists of confined and separated layers with different pressure dynamics. From a multiple regression model, they found that effective pore pressures at the slip surface partially differed from borehole measurements, probably caused by macropore infiltration and subsurface dynamics in neighboring subsurface domains. The simulated pore pressures agreed well with measured values. A comparison of simulation results with and without snow cover also demonstrated that the snow increased the slope stability; however, the conclusions from the infinite slope model must be considered carefully given the high sensitivity to parameter variations.

Model Concepts and Simulation Methods

In addition to the simple, infinite slope model of Wienhöfer et al. (2011) discussed in the previous section, a more "sophisticated" approach was chosen by Ehlers et al. (2011), applied to the Heumöser and introduced in this section. This approach uses a thermodynamic analysis of a thriphasic porous medium consisting of a deformable solid phase (soil) and two fluid phases (water, air). Mass and momentum balance equations are formulated for all three phases. Elastic and viscoplastic deformations are taken into account. Ehlers et al. (2011) obtained a fully coupled flow and deformation model for the vadose zone and for groundwater that is embedded in the framework of the Finite-Element solver, known as PANDAS.

The model requires numerous parameters that were determined for the same fine sand as being used by Germer and Braun (2011) in laboratory experiments. The mechanical (elastic and viscoplastic) parameters were derived from triaxial experiments while the hydraulic parameters were obtained from Germer and Braun (2011). The experimental results reported by Germer and Braun (2011) also serve for model validation. An overall good agreement between simulated and measured results were obtained, indicating that PANDAS can simulate the strongly coupled flow and deformation processes in multiphasic materials (e.g., sandy soil in the vadose and groundwater zones) and that it can predict the development of shear bands triggered by hydraulic conditions. The importance of the pore pressure on the slope stability was also emphasized.

Finally, the PANDAS model was applied to simulate the impacts of an extreme rainfall event in two representative cross-sections at the Heumöser. Again, shear bands were initiated, highlighting the strong interaction between hydrologic and mechanical processes. These studies have a qualitative character, as many parameters are currently unmeasured and therefore had to be assumed, and because the real Heumöser needs to be considered as a three-dimensional problem.

Perspectives on Future Research

Future research should focus on understanding and predicting landslide processes. Laboratory experiments can be designed to be more representative of actual initial and boundary conditions (e.g., spatial scales of 10 m or more). More geophysical methods should be included to better identify the structure and geometry (e.g., airborne photography and seismic, borehole, and direct push methods), and to monitor processes in the field (soil moisture dynamics with geoelectric methods). Characterization and monitoring should be performed hierarchically, combined with geostatistical methods as scales increase. Additionally, tracer experiments in the field and hydrochemical analyses can be valuable.

A good conceptual understanding of site structure and geometry is a necessary prerequisite for effective modeling. Likewise, measuring process values in the laboratory and field is necessary for model calibration and validation, allowing models to be checked for application ranges, limitations, predictability, and reliability. We envision further conceptual model developments that account for macroporous media at different scales (e.g., double-domain approaches) with potentially large deformations (e.g., discrete element methods). Linking (heavy) rainfall, surface runoff, in- and exfiltration, subsurface flow dynamics, and soil deformation models, which are strongly physically based, poses challenges to coupling strategies, from the conceptual to the software technical points of view. Multiscale approaches should be further developed as processes, structures, spatial resolutions, and heterogeneities are different at different scales.

Landslide research is multidisciplinary. It includes laboratory and field experiments, field monitoring, and different modeling approaches. It also requires efficient information processing and management. Combined, these new elements detect triggering mechanisms and cause-and-effect relationships, opening new possibilities for optimal model complexity that should be sufficiently accurate—conceptually—to account for relevant processes, yet resolve the structural and geometrical heterogeneities only as far as necessary.

If development of reliable models is to be successful, they need to be applied to different engineering realms to prevent damage to human and natural infrastructure (e.g., drainage and soil stabilization measures) and to reduce vulnerability and risk. Finally, the results should be generalized and tested at other landslide sites, so that transferability of results can be assessed.

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