Effect of Climate Change on Landslide Behaviour

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Landslides represent a major threat to human life, constructed facilities, and infrastructure in most mountainous regions of the world. Considering future climate scenarios and modified precipitation patterns, landslide activity will most probably change too. Shallow slips and debris flows will likely take place more frequently as a consequence of more extreme weather events.

In Switzerland, for example, although no trends are yet evident, annual rainfall totals for stormy events and their intensity, especially in fall, spring, and winter, appear to be increasing so that some precipitation will fall as rain rather than snow at higher altitudes. Consequently, the occurrence of shallow landslides in steep mountainous slopes will increase. At higher elevations, climate change will continue affecting glaciers and permafrost soils substantially. Glacial retreat and the melting of permafrost will cause more landslides, debris flows, and rock falls to occur.

Future Improvements in Predicting Unstable Slope Behaviour

While landslide researchers confront questions about the future impacts of climate change, they are particularly motivated by the observed and steady increase of the damaging effects which landslides exert. These effects are mainly due to increases in demographic density, infrastructure, and human activities in many landslide-prone areas around the world.

Within the landslide scientific community, geotechnical engineers strive to understand soil behaviour in its setting and propose solutions to minimise the economical and social impacts of slope movements (Figure 1). Increasing emphasis is being placed on developing reliable predictive tools capable of forecasting the behaviour of landslides, such as velocities and the time to failure of a slope, and on understanding and modelling failure initiation and landslide propagation. In the future, these predictive tools could be integrated into early warning systems to substantially improve the quantitative assessment of

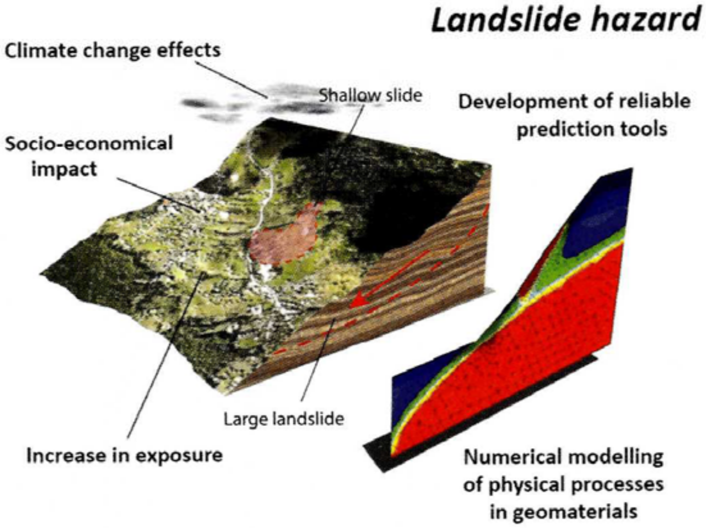


Figure 1. Climate change and increased human activities in landslide-prone areas will increase the risk of landslides in many regions around the world.

These issues, along with efforts to quantify the effects of global climate change scenarios on landslide hazard and risk in the future, are currently being addressed by 25 European research entities within the European Commission project "SafeLand: Living with landslide risk in Europe" (*www.safeland-fp7.eu*). Reliable landslide modelling and prediction tools are especially important for climate change problems because the anticipated stress, precipitation, and groundwater conditions may be outside of the observed range for a particular region.

Climate change may impact all of the hydro-mechanical processes acting to destabilize slopes.

Physically based models often try to reproduce the complex hydro-mechanical coupled processes in geomaterials. For landslide problems, these models, in many cases, allow a better understanding of the slope

Their accuracy, however, depends on using realistic boundary conditions and material parameters. Approaches available for improving the models and making them more flexible include using empirical relationships and selecting input parameters based on back-calculation.

Additional improvements can be achieved by incorporating input from continuous landslide monitoring to help improve and offer new possibilities for studying the time-dependent behaviour of potentially unstable slopes. And while not yet a part of standard design practice, application of statistical predictions using larger, higher quality datasets and tools, such as artificial neural networks or auto-regression techniques, should offer additional improvements. As such, mixed models with soft and hard computing components will certainly be a focus of attention in coming years.

Understanding Soil Behaviour in Variable Environmental Conditions

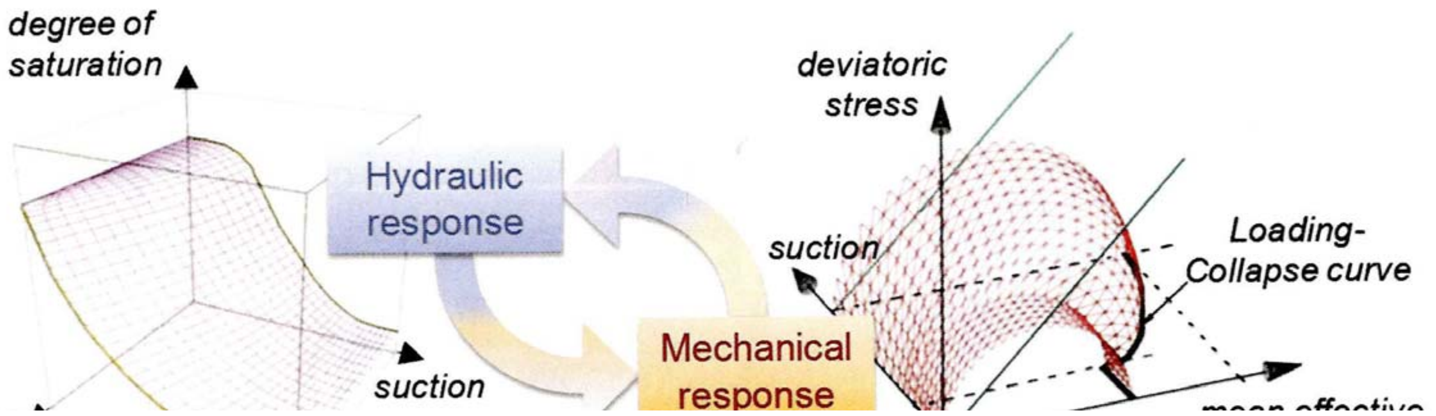
Commonly, two flow regimes are encountered in natural slopes: deep flows, most often parallel to the slope surface with possible complex bedrock interactions; and superficial flows with capillary pressures or positive, compressive pore water pressures controlled by rainfall. Rain infiltration and hydrologic conditions influence the occurrence and type of landslide triggering mechanisms. In general, slope behaviour depends mainly on the rainfall intensity and duration, on soil hydraulic and mechanical characteristics, on the thickness of the sliding mass and on antecedent weather conditions. Climate change may impact all of the hydro-mechanical processes acting to destabilize slopes. These processes include:

- *degree of saturation:* The degree of saturation of the upper soil layer increases, thereby reducing the capillary tension between the soil particles which weakens the slope;
- *flow within soil:* Due to the mobilized fluid flow inside the soil matrix, the fluid exerts a destabilizing, downhill frictional drag;
- *rainfall intensity:* If the rainfall intensity is higher than the capacity of the soil to dissipate the pore water, surface run-off occurs, risking slope erosion; and
- *infiltration:* Depending on soil permeability and on the intensity and duration of rainfall, infiltration could lead either to shallow slides or debris flows in the vadose zone, or time-delayed, deep-seated failures due to mounding of the water table.

Experience has shown that in many shallow landslides, unsaturated conditions must be explicitly considered to explain the landslide phenomena observed. Climate change may cause changes in temperature, precipitation, and overall ground water levels which all play an important role in unsaturated soil mechanics. Figure 2 illustrates the importance of unsaturated soil behaviour in a landslide. Increasing saturation during infiltration along with the suction reduction depends on the retention properties of the material. At the same time, the degree of saturation determines the permeability of the soil, affecting the flux into the partially saturated medium. Additionally, suction has an influence on the mechanical response of the material, both in terms of shear strength variation and volumetric response. Porosity variation can in turn change

FIGURE 2

Concept of a hydromechanically coupled constitutive framework.



the hydraulic properties of the soil, inducing changes in permeability and retention properties.

Consequently, the geotechnical framework needs two interconnected components – one component for the mechanical behaviour of the material and one for hydraulic behaviour of the material in generally saturated and unsaturated conditions. To efficiently include suction-induced mechanical and hydraulic phenomena (volumetric behaviour, strength, and retention capability), the generalised effective stress concept must be adopted:

$$\sigma' = \sigma + S_r s$$

σ' = effective stress
σ = external stresses
S_r = degree of saturation, varying from 0 to 1
s = capillary stress (suction)

Thus, the mechanical and hydraulic behaviours are intrinsically related through the suction and the degree of saturation. On the constitutive level, the stress-strain relationship is coupled to the retention curve by means of a suction-dependent preconsolidation pressure. This coupling enables suction-dependent soil compressibility and peak shear strength to be accounted for, and pore collapse via plastic compression upon wetting under a high mechanical load (Figure 2).

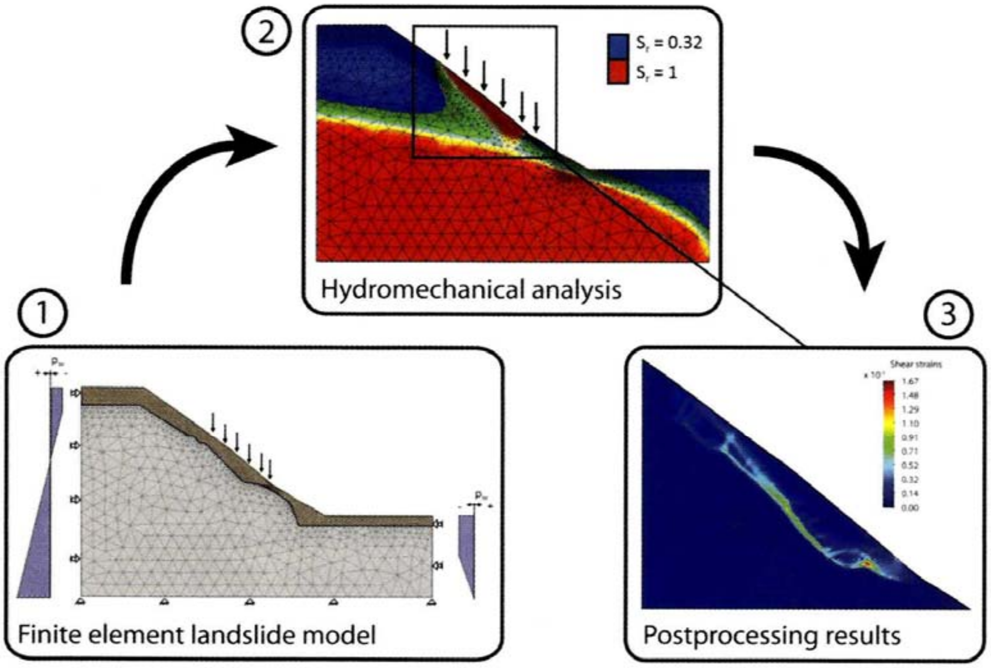


Figure 3. Modelling procedure: (1) Material properties, boundary and initial conditions are defined. (2) Evolution of state variables are observed. (3) Calculated shear strains delineate a mechanism at the onset of failure.

Modelling the Onset of Rainfall-Induced Landslides

For simulation purposes, hydro-mechanically coupled constitutive models are commonly integrated in finite element codes (Figure 3). Thus, the effect of rain infiltration on slope stability can be simulated in a time-dependent analysis to consider the effects of changes in precipitation and moisture regime due to the effects of climate change. Stresses and strains within the deformable solid matrix and pore pressures and water flow in the liquid phase are computed simultaneously. Unlike classical limit equilibrium methods, finite element analysis of landslide initiation show the progressive development of plastic strains within the whole soil mass as water infiltrates from the slope surface into deeper soil layers.

Advanced constitutive models within the critical state framework allow refinement of the deformation analysis. Volumetric deformations due to wetting (i.e., wetting collapse of the soil structure) can be spatially and temporally distinguished from shear deformations. Together, distinct conclusions can be drawn regarding the formation of failure mechanisms, possible types of instability and the effects of environmental change with time.

Obviously, the determination of material parameters in such coupled hydro-mechanical models when partial saturation is considered requires additional lab testing. The proper consideration of the unsaturated states of the soil implies that the material is tested under suction control (Figure 4). To this end, considerable efforts and improvements have been made within the past 20 years to develop experimental equipment and techniques to properly control suction during testing and to evaluate the volume variation of the materials tested.

Towards Computationally-Enhanced Prediction Tools

Many phenomenological or semi-physical based

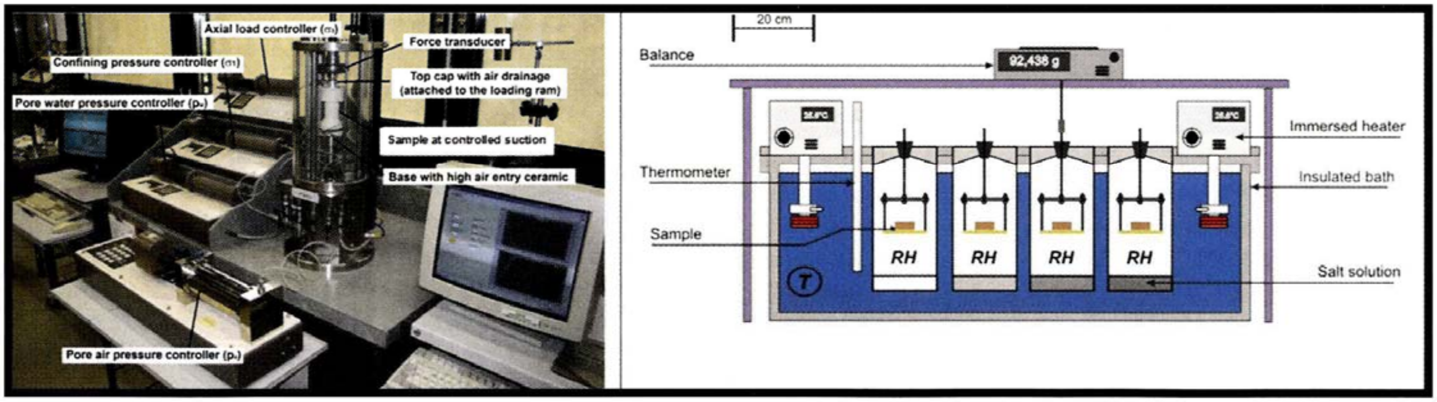


Figure 4. Examples of advanced testing facilities for the hydromechanical behaviour of soils in unsaturated conditions: (a) experimental layout for the application of the axis translation technique in triaxial cells; (b) sorption bench for the determination of the water retention curves in wide suction ranges.

models have been developed at regional and slope scales associating slope failure to local threshold values with respect to rainfall intensity and duration. Some methods interpret directly monitoring data to predict time to failure or velocity increase. A major drawback of these phenomenological models is their reliance on surface measurements of velocities, as well as on time-constant boundary conditions to predict failure. Other methods, such as back-propagation algorithms or neural network tools, are more useful in that case. Artificial neural network tools have proven to be efficient for forward calculations of slow-moving landslides.

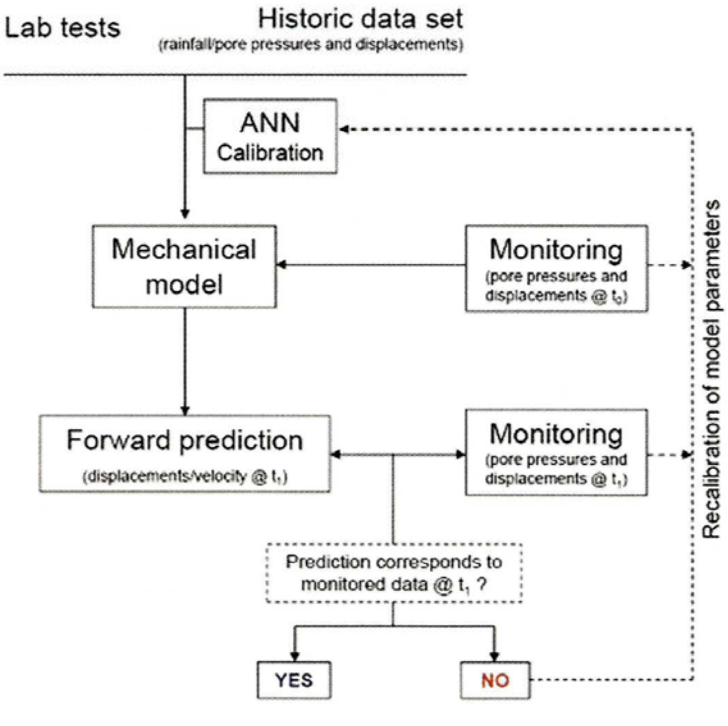


Figure 5. Coupled soft and hard computing tool for the prediction of landslide behaviour.

However, these networks, which are trained with test data sets from past measurements, are incapable of predicting sudden acceleration originating from changing physical soil properties. Thus, it would be very interesting to overcome this drawback by introducing a deterministic, mechanical-based model which takes into account the complex hydro-mechanical and time-dependent processes in landslides. Inversion is one approach for improving input parameters for these types of analyses whereby the model is run "in reverse" to find the set of input parameters that result in the prediction that most closely matches the behaviour measured in the field. In this way, computational tools can be calibrated using real-time soil parameters to improve the quantitative predictions of the models.

The use of models that can be updated as more observational data become available will help calibrate and interpret problems that, as a result of climate change, may have hydro-mechanical conditions outside of previously observed ranges. Ways of coupling the hard-computing geomechanical model with the soft-computing component are under development (Figure 5). Assuming that the hydro-mechanical model captures the key physical mechanisms, it needs appropriate initial conditions and carefully calibrated material parameters to make accurate predictions.

The geomechanical parameters could be calibrated by the use of a soft-computing tool which takes into account historic data sets as well as lab test results, depending on the parameter to calibrate. The calibrated parameters are inserted into the hydro-mechanical model which then performs a forward prediction based on the monitoring input data at time t_0. If the forward prediction corresponds to the monitoring data at time t_1, the model performs accurately and may continue with the predictive calculations. If this is not the case, the parameter calibration needs to be improved in an admissible range. A second calibration step is performed then which takes into account the recent monitoring data.

Looking Forward

With the advancements in constitutive modelling of soils and the predictive numerical capabilities at hand, it is possible today to evaluate the possible effects of climate change scenarios on slope behaviour. The advanced understanding of physical key mechanisms in landslide triggering and run-out combined with up-to-date real-time monitoring techniques will certainly help increase the reliability of predictive tools in the future. Still, big challenges remain in developing such integral predictive tools and increasing the quality of quantitative predictions.

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