Soil stability and natural hazards: from knowledge to action

a project of the National Research Programme NRP 68 "Sustainable use of soil as a resource"

Project partners:
- WSL Institute for Snow and Avalanche Research SLF
- Swiss Federal Institute for Forest, Snow and Landscape Research WSL
- Institute for Geotechnical Engineering IGT, ETH Zürich
- Office for Forest and Natural Hazards AWN, Grisons

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Swiss Federal Institute for Forest, Snow and Landscape Research WSL
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Introduction

In Switzerland, substantial damage on infrastructure of up to more than 100 million Swiss Francs related to one heavy rainstorm period and sporadically loss of lives have been caused by erosion and landslides in recent years. The frequency of such extreme events is expected to increase in future and, concomitant, the detrimental effects on ecosystem goods and services, particularly in steep terrain. The protection against as well as prevention and prediction of superficial soil failure are, however, still difficult.

To improve knowledge of and action against these hazards, we need to understand the processes at regional scale, define critical thresholds, and subsequently transfer knowledge into action at large scale. The most challenging questions we want to address are related to the interdependency of vegetation, mycorrhizal fungi and soil fabric. In this regard we want to quantify the effects of vegetation and land-use on soil resistance, in particular against superficial landslides but also against related surface erosion, triggerd by rainfall. In this context we want to consider the hitherto neglected fact that the majority of plants in mountain ecosystems live in symbiotic relationship with mycorrhizal fungi which contribute to soil aggregation and soil strength, too. This project aims, therefore, at (1) quantifying biological effects relevant to soil stability, (2) crystallising appropriate indicators for superficial soil failure, and (3) developing a concept of sustainable soil use.
We will take advantage of more than 700 documented landslides, restoration measures, and soil mechanical experiments, already available at WSL, SLF and IGT and analyse them in terms of thresholds for soil stability. These comprehensive and broadly conceived investigations include a wide range of areas prone to superficial soil movement and consequential conclusions will be of significance for Switzerland and other mountain regions. In order to bridge gaps of rhizosphere processes decisive for soil strength and facilitate the development of thresholds in respect of slope stability, we will specifically complement these existing data, with laboratory experiments (direct shear tests, soil aggregate stability analysis, rain-fall simulation) and additional field investigations on soil fabric (texture, hydrology), plant community aspects (diversity, growth forms, root types), land-use management and mycorrhiza. On this basis we will deduce appropriate indicators and, in close collaboration with projects of the NRP68 stream "land mapping/GIS", spatial models of the susceptibility to superficial soil failure.
Based upon these findings, we aim at providing thresholds for information and warning systems as well as input for land management planning. Furthermore, we will negotiate strategies to reconcile protection against natural hazards, land-use, and economic aspects of agriculture, forestry and tourism as well as nature protection in collaboration with other projects of the NRP 68 (Cluster "land mapping/GIS"). The results will be discussed in workshops, presented at meetings of practitioners and scientific conferences as well as published in scientific articles and summarised in recommendations for sustainable land management in areas susceptible to superficial soil movement. In this way, we are convinced to deliver substantial input to key issues related to soil stability in terms of using soil as a sustainable resource in a scientific perspective as well as for practical application.

Programme

Morning (10-12):

- Slope stability and natural hazards: from knowledge to action (introduction)
  Frank Graf (SLF)
- Soil strength and slope stability
  Sarah Marcella Springman (IGT, ETH Zürich)
- Effects of plants and mycorrhizal fungi on soil aggregate stability
  Frank Graf (SLF)
- Shallow landslides: field surveys and database
  Christian Rickli (WSL)
- Modelling of slope stability and plants effects: How roots reinforce soil and enhance slope stability
  Massimiliano Schwarz (HAFL, WSL)

Lunch Break (12:15-13:15)

Afternoon (13:30-15:30):

- Monitoring of landslide development in recent decades and causes for landslide susceptibility in three Alpine valleys
  Katrin Meusburger (University of Basel)
- Biodiversity and Erosion in Alpine Terrain
  Christian Rixen (SLF)
- Land-use, topography and other factors for shallow land-slides - what can we learn from GIS-based approaches?
  Peter Bebi (SLF)
- Soil bioengineering construction works: estimation of the proper function
  Martin Frei (AWN, GR)

Soil strength and slope stability

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Keywords: landslide triggering, slope instability, unsaturated soil mechanics, bio-engineering

Slope instability arises when a shear surface is formed along a continuous (or discontinuous) shear zone, as each 'soil element' reaches shear failure. This requires us to ask the question about how we determine strength in a soil element?

There is an interplay between:

Material specific

Solid fraction – friction, dilatancy, surface texture, fragmentation, ductility and brittleness.
Properties of the material (stiffness; strength; fracture toughness) and their surfaces (adhesion, interface friction) which together with the stress path applied (direct shear, compression, extension) cause different strengths to be mobilised accompanied by different characteristics of acoustic emissions (rate and total counts above a threshold level) approaching triggering of failure.
The positive effect of vegetation as reinforcement, creating tensile strength, raising the normal stress leading to raised frictional shear strength and/or cementing mycorrhiza.

Voids specific

Fluid/air: positive effect of partial saturation on the matric suction
Vegetation: positive effect of evapotranspiration on the matric suction

Layering specific

Hydro-mechanical interactions between different layers in the slope:
- Depth of the layer with sudden change in permeability
- Shape of the bedrock
- Draining fissures in the bedrock
- Exfiltration from the bedrock (springs)

Some examples will be presented from the Rüdlingen monitoring and landslide triggering experiment to illustrate these points. For example, why did the slope not fail during the monitoring experiment after application of 2.2 m of rainfall over 3.5 days in October 2008 when it failed after 15 hours and 0.35 m rainfall in March 2009?

Questions that must be answered in future include the level of complexity of the constitutive models necessary to expose, describe and quantify the behaviour.

Relevant to this project

- What is the effect of specimen preparation in a direct shear box (effect of microstructure on macro behaviour (loose cemented with macropores v. more uniform younger soils)?
- What is the effect of scale (and maximum particle size) on the results of the tests?
- What is the effect of vegetation on the shear strength of material?
- How can acoustic emissions help us to categorise the proximity of catastrophic failure?

Effects of plants and mycorrhizal fungi on soil aggregate stability

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Keywords: ectomycorrhiza, alder, root growth, soil mechanics

Eco-engineering aims at stabilising soil and slopes by applying technical and biological measures. Engineering structures are commonly well defined, immediately usable and operative, and their stability effects quantifiable. Differently, the use of plants requires more restrictive boundary conditions and the protection potential is rarely easily calculable and is developing as a function of growth time. Soil aggregation processes play a crucial role in re-establishing soil structure and function and, conclusively, for successful and sustainable re-colonisation. Mycorrhizal fungi are key-players that foster the development of a protective vegetation cover. They accelerate and increase plant growth and, additionally, contribute to soil aggregate stability which, on its part, was recently proposed as an appropriate indicator with regard to the quantification of biological effects on soil and slope stability.
The effects of mycorrhizal fungi on the host's root system and their joint contribution to soil aggregate stability were investigated. Furthermore, the biologically contribution to soil stability was compared to mechanical stabilisation due to soil compaction.
Aggregate stability tests were performed with differently treated moraine, including soil at low (~15.5 kN m^{-3}) and high (~19.0 kN m^{-3}) dry unit weight, soil planted with *Alnus incana* (White Alder) as well as the combination of planting with alder and inoculating with the mycorrhizal fungus *Melanogaster variegatus s.l*. After a 20 weeks growth period positive correlations were found between soil aggregate stability and the three variables dry unit weight, root length per soil volume, and degree of mycorrhization. In due consideration of all samples, dry unit weight and degree of mycorrhization were strongest correlated with soil aggregate stability. Additionally, a significant positive effect of root length per soil volume on soil aggregate stability was found. Mycorrhized alder produced significantly more roots and, consequently, higher soil aggregate stability compared to the non-inoculated plants. Furthermore, the combined biological effect of roots and mycorrhizal mycelia on aggregate stability in soil with low density was comparable to the compaction effect of the pure soil from 15.5 to ~19.0 kN m^{-3}.
Data on the effect of vegetation on the angle of internal friction Φ' of the same moraine showed similar correlations, i.e. that Φ' of low density soil (~15.5 kN m^{-3}) increased by the same amount whether by planting with White Alder or by compaction to ~19.0 kN m^{-3}. Based on this coincidence and from a soil mechanical perspective, soil aggregate stability is suitable to estimate the joint effect of plants and mycorrhizal fungi with respect to their contribution to soil and slope stability in the near-surface soil layers of the analysed moraine.
Results from three catchments with eco-engineering measures investigated after the heavy rainfall event in 2005 are in line with the presented laboratory analyses.

Shallow landslides: field surveys and database

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Keywords: shallow landslides, landslide inventory, field survey, hazard events, database

Shallow landslides triggered off by heavy rainfall are recurrent phenomena on steep slopes. The danger due to these slope instabilities is considerable, as they often evolve into debris flows, which may damage cultivated land, buildings, and infrastructure, and even cause fatalities. In recent years, WSL investigated several study areas in Switzerland after hazard events aiming at identifying the decisive triggering factors. Within the boundary of six study areas, all shallow landslides that occurred during the specific rainfall events were mapped and related to the site characteristics of the source area, such as its geomorphology and vegetation. The landslide inventories were carried out in the Pre-Alps and Alps of central and eastern Switzerland and range from 1.6 to 10.2 km^2 in size, with between 16 and 50 % covered by forest. Following a standardised protocol, a set of parameters was recorded for each landslide, including their dimension, the soil properties, and various site characteristics such as vegetation, geomorphology, and topography. Information on more than 700 landslides was collected, thereof 522 were recorded completely (240 in forest and 282 in open land) and about 200 with a reduced parameter set. First and foremost, the evaluation of the collected data show a considerable effect of the vegetation on both the occurrence of rainfall-triggered shallow landslides and the slope inclination of the release zones. Objectives of future work and, particularly, within the framework of our NRP 68 project (SOSTA-NAH) include the extension of the present database with further available data of rainfall-triggered shallow landslides and a more sophisticated evaluation of the compiled information with respect to vegetation effects on slope stability.

Modeling of slope stability and plants effects: How roots reinforce soil and enhance slope stability

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Keywords: root reinforcement, shallow landslides, root bundle model, SOSlope, upscaling, protection forests, bioengineering.

The quantification of root reinforcement represents a key issue in different area of engineering (slope stability, soil protection, silviculture/tree stability, hydraulic). Between all the effects of plants (direct and indirect) on the physical and chemical soil processes, the mechanical effect of roots is considered particularly important for slope stability. The study of root reinforcement is faced with the high complexity of interactions of processes and factors at different spatio-temporal scales. In particular, the hierarchical spatial heterogeneity of vegetation and its effects on soil processes represent a big challenge for quantitative up-scaling methods. The objective of this contribution is to contextualize the complexity of the root-soil interactions in view of slope stability problems, to review the recent scientific contributions in the quantification of root reinforcement, and to discuss the practical meaning of recent research results.

In the presentation of an up-scaling framework for the implementation of root reinforcement in slope stability analysis, the following arguments will be discussed: tensile force and pullout force of single roots, apparent elasticity of single roots, strain loading approach for the characterization of root bundle mechanics, meaning of root diameter distribution on root reinforcement, spatial heterogeneity of root distribution, mechanical and rheological properties of rooted soil under tension and compression, and triggering mechanism of shallow landslides.

The above-mentioned factors and processes build up the modules implemented in a numerical model for slope stability calculations, the SOSlope model. The SOSlope model is characterized by the use of a spring-block framework (with 1x1 m cell grid), a strain step loading approach for the redistribution of forces, and the implementation of a spatial distribution of root at the hill slope scale. The results of simulations performed with the SOSlope model serve as background for the discussion on the role of root reinforcement for protection forests management and bioengineering applications.

Monitoring of landslide development in recent decades and causes for landslide susceptibility in three Alpine valleys

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Keywords: Alps, shallow landslide susceptibility, landslide causal factors

The alpine valleys of Switzerland have always been subject to landslides. The occurrence of landslides depends strongly on catchment characteristics like geology and topography, etc. However, also causal factors that are variable in time such as climate and land use may have an impact on the recent and future pattern of landslide occurrence. In this study we aim to indentify the relative importance of land use and climate as landslide causal factors by comparing landslide inventory patterns and trends for three Alpine valleys that differ in land use and climatic conditions: Obergoms (65 km^2), Urseren (30 km^2) and Bedretto/Piora (90 km^2). For these valleys the development of shallow landslide susceptibly over the last five decades was mapped by aerial photograph interpretation. Based on the inventory maps shallow landslide susceptibility maps were constructed with a multivariate logistic regression model using various potential causal factors (e.g. geology, slope, etc.). Climate data was available from MeteoSwiss and tested for trend with the Mann-Kendall trend test. Land use data was obtained from alp reports, subsidy bills and the farmers directly. All three sites showed an increasing trend of shallow landslide incidence since the last 40 to 50 years. The spatial pattern of the increase is, however, very different between the sites. The Bedretto/Piora valleys show the weakest increasing trend, which might be attributed to a very constant and extensive land use management over the last centuries. In the Urseren valley the landslides strongly increased on a very susceptible geological formation located at the intensively pastured areas close to the valley bottom. In the neighbouring valley Obergoms these highly susceptible geological formations are hardly affected by landslides, because in contrast to the Urseren valley these formations are forested and not pastured. Another land use effect was observed for the Obergoms: the landslide increase and the change in pasture stocking (Nst/ha) were significantly ($p<0.001$) related. However, most of the landslides in the Obergoms occurred in elevated grasslands that never have been managed. This increase in elevated unmanaged areas was also observed in the Bedretto/Piora valleys, indicating altered and higher landslide susceptibility potentially caused by changing snow and permafrost conditions.

Biodiversity and Erosion in Alpine Terrain

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Keywords: Alpine plants, Diversity, Interrill erosion, Rainfall simulations, Soil aggregate stability

Restoring an intact plant cover and maintaining high biodiversity is crucial to prevent soil erosion in steep alpine terrain after natural or unnatural disturbances. In this talk, I will report on how disturbances can influence vegetation, plant biodiversity and soil. We tested in several experiments the effects of alpine plants on the soil aggregate stability and on surface erosion at disturbed Swiss alpine sites with the following key results:

1. The number of plant species was positively correlated with soil aggregate stability, and species number was a better explanatory variable than any other variable related to soil or vegetation. Higher plant diversity was associated with a higher number of different root types.
2. Rainfall simulation experiments demonstrated that surface erosion was strongly driven by the percent of vegetation cover. At a vegetation cover of approx. 60%, an increase in plant diversity significantly reduced surface erosion.
3. Belowground traits of alpine plant species showed large differences e.g. in root length, horizontal and vertical spread and root tensile strength, illustrating that below-ground diversity of functional root types is crucial for slope stability.

Our experiments demonstrate a positive relationship between species diversity / functional type diversity and soil physical properties. Not only percent vegetation cover is crucial to prevent soil erosion but also the diversity of plant growth forms. A high diversity of belowground growth forms is the most likely mechanism for the positive effect of plant diversity on soil properties.

Finally, scientific results need to be conveyed into practical applications. In the Swiss work group for high altitude restoration, we elaborate ways of knowledge transfer by means of guidelines, courses and conferences in order to improve restoration in alpine terrain.

Land-use, topography and other factors for shallow land-slides – what can we learn from GIS-based approaches?

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Keywords: GIS-modelling land-use change, landslide susceptibility, forest succession

In recent years, the availability of high resolution digital elevation models, landslide inventories and other spatial data have increased the potential of GIS-based approaches for spatial landslide models and susceptibility maps. Predictive statistical models exploit thereby the correlation between landslide occurrence and explanatory variables such as topography or bedrock properties. Key-factors in such models include slope steepness (higher susceptibility for steeper slopes), geology and soil properties (higher susceptibility for greater soil depth and lower permeability of the soils), vegetation and forest cover (lower susceptibility where roots stabilize the soil in different soil horizons) and stream flow density and regional precipitation regime (higher susceptibility with increasing water inflow). Land-use changes in the vegetation pattern came out as important factors in several GIS-based analysis (e.g. higher susceptibility in the time period between land abandonment and forest succession or higher susceptibility after natural or anthropogenic disturbances in forests). However, temporal changes in land-use and their effects on soil properties and root systems make it often challenging to include land-use related variables in predictive models (cf also contribution of Meusburger and Alewell).
Within module 2 of our NRP 68- project, we take advantage of large landslide datasets (cf. contribution of C. Rickli) and of new insights about superficial soil failure in order to evaluate and, hopefully, improve the potential of GIS-based approaches for landslide susceptibility maps. This would also provide a link to other projects within NRP 68, where systems of pedotransfer functions and for the valuation of ecosystem services should be improved. We will complement existing studies on shallow landslide datasets with new multivariate statistical analysis and models, which will be validated in different other regions. A particular focus will be on areas with a high degree of forest cover (e.g. St. Antönien, Sachseln), where we intend also to analyse and disentangle the effect of different forest structural characteristics on landslide susceptibility.
This contribution gives a short overview on the potential and limits of GIS-based approaches for land-use susceptibility maps and an outline of intended activities in the related module of our NRP 68 project.

Soil bioengineering construction works: estimation of the proper function

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Keywords: construction works, soil bioengineering, proper function

The protection of settlement areas, roads and railroad lines against natural hazards is an important task in mountainous regions. Therefore, numerous protective systems as wooden check dams, rock fall barriers and snow bridges were built over several decades. Using the example of the canton of Grison, there are more than 1‘400 areas with such systems, whereas more than one third of them belong to the class of soil bioengineering systems.
In the past, the main activities of the stakeholders were focussed on engineering and construction of protective systems. However, to keep such constructions in good a condition becomes nowadays more and more an important task in daily business. From a point of view of the owners and the administration, a long durability of these construction works is to be expected. But this requires preservations and maintenance works to delay the aging process of the constructions. Thereby, information about the conditions and the reliability of the construction works is needed to initiate the necessary maintenance timely.
In Grison, a monitoring of the protective systems takes place since several years, performed as systematically on-side inspections. However, a careful general inspection containing a check of the damage potential, the risk of natural hazard and particularly a structural engineered check of the protective systems would be very wishful. Such an inspection, for instance performed after $^{2}/_{3}$ of the anticipated technical live, would be a good basis for principle decisions with regard to regular maintenance, but also extensively reconditioning works.
There are already well established standards concerning quality check of concreted components and devices made of steel. However, there is a lack of comparable methods for soil bioengineering systems. To this day, the quantification of plant effects with regard to slope stability is partly possibly, only. Therefore, the estimation of the proper function of soil bioengineering systems is difficult and is associated with several difficulties, not only for today’s requirements, but also for the future development. Accordingly, basic principles are to develop, which allow determining medium term strategies of activities for such systems. This will be an important requirement that the plant effects take rapid and with lasting effect the function of the engineering construction works on.

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