HazRi TRAMM

Geomechanical properties and modelling of Ruedlingen landslide

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Laboratory Investigation

A laboratory investigation is presented for samples of a silty sand under saturated conditions and unsaturated conditions. The soil was sampled from test pits south of Rüdlingen in North–East Switzerland, where a landslide triggering experiment was carried out on a steep forest slope.

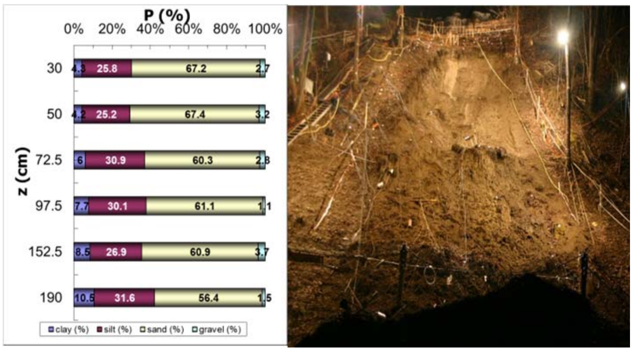

Fig. 1 a) Grain size distribution with depth; b) landslide test site

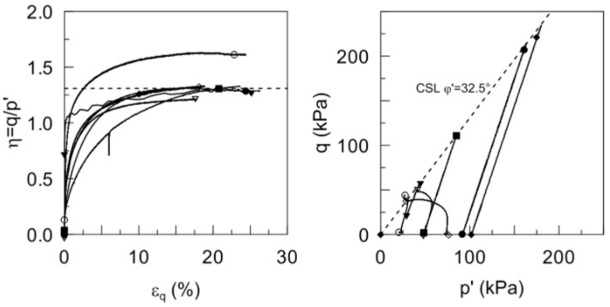

Fig. 2 Isotropic consolidation – standard drained (CIDC) and undrained compression (CIUC) $q = \sigma_a - \sigma_r$; $p' = (\sigma'_a + 2\sigma'_r)/3$; $\varepsilon_q = 2/3(\varepsilon_a - \varepsilon_r)$.

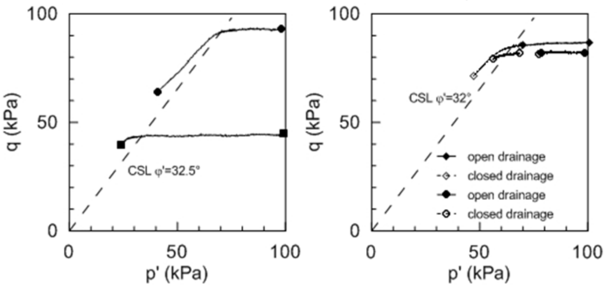

Fig. 3 a) Anisotropic consolidation constant axial load (CADCAL) results; b) CADCAL - undrained (U) results p'-q plane

The topsoil is classified as medium to low plasticity silty sand (ML) after USCS. The aim of the work on saturated undisturbed samples was to characterise the behaviour of the soil in triaxial tests, in the light of the possible failure mechanisms of the slope. A modified state parameter is explored as a potentially useful tool to determine conditions leading to eventual collapse (Casini et al. 2010a). An experimental programme, extending the study of the stress–strain behaviour of the soil to unsaturated conditions, is in progress.

In spite of the data variability, typical of natural samples, a value of $q/p' = \eta_{CS} = 1.30$, corresponding to a critical state friction angle of about $\varphi'_{CS} = 32.5°$, seems to represent the critical state conditions for this soil fairly well. The only exception is the test conducted under the lowest confining stress (Fig. 2).

The tests that simulate the in situ water pressure increase at constant axial load all cross the CSL following anisotropic consolidation (CADCAL & CADCAL/U), causing the specimens to reach a dilatant mode of failure with a $\eta_{max} = 1.5$ (Fig. 3).

Acknowledgements

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References

1. F. Casini, C. Jommi, S.M. Springman (2010). A laboratory investigation on an undisturbed silty sand from a slope prone to landsliding, Granular Matter, 12(3), 303-316.

Slope safety factor analysis

A simplified slope stability analysis is carried out, with shear strength determined under unsaturated conditions for homogeneous ground. Extending the infinite slope approach to a laterally limited slide, the factor of safety FoS becomes:

$$FoS = \frac{\dfrac{c^*}{\cos^2\alpha}\left(1 + 2K\dfrac{z}{d\cdot\cos(\alpha)}\right) + \gamma z\tan\varphi'\left(1 + K\dfrac{z}{d\cdot\cos^3(\alpha)}\right)}{\gamma z\tan\alpha}$$

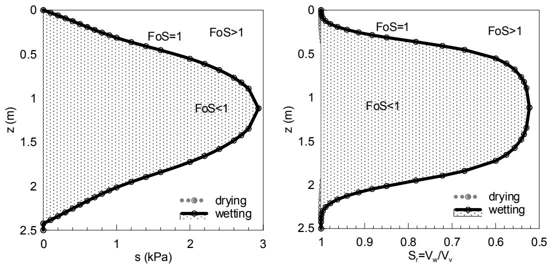

Fig. 4 Depth z for FoS = 1 for the drying and wetting branch of the Water Retention Curve: a) function of suction; b) function of saturation degree.

A critical depth, z = 1.12 m, is obtained for a suction of 2.9 kPa on the wetting path. All the other depths investigated needed less suction to reach a safety of factor FoS = 1.The approach used is quite simple, with all of the limitations valid for limit equilibrium analyses. Nonetheless, it can be applied to predict the zone of potential failure, which in the field experiment was located at a depth z ~ 1.25 m.

Hydromechanical modelling of slope behaviour

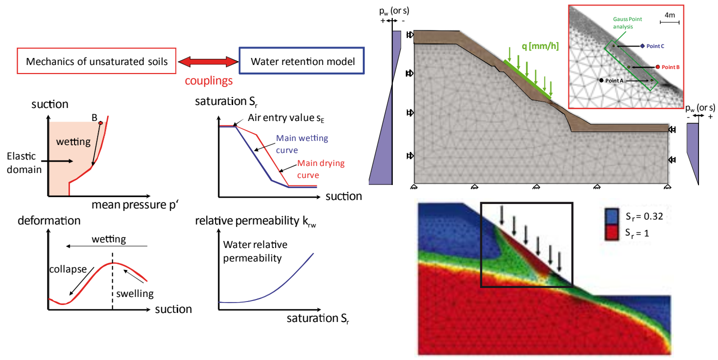

Fig. 5 Components of constitutive and finite element models to simulate slope behaviour under unsaturated conditions during rain infiltration

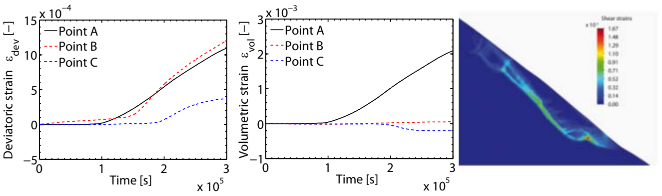

Fig. 6 Transient slope behaviour upon wetting in terms of volumetric and deviatoric strains

A hydromechanically coupled, transient finite element analysis of the partially saturated Ruedlingen slope subjected to rain infiltration revealed the onset of failure. The numerical model is capable of giving detailed information on the active physical mechanisms during rain infiltration. Deviatoric strains are first observed in the middle part of the slope (Fig. 6, left). Subsequently, volume contraction is predicted in the lower part of the slope together with mobilisation of deviatoric strains (Fig. 6, centre). Finally, a failure mechanism develops towards the slope surface in the upper part of the slope (Fig. 6, right) accompanied by slight dilation of the soil (Fig. 6, centre). The soil is close to saturation (S_r >0.95) At the time of failure. Matric suction is only marginal (Fig 5, below right).

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Precursor Events and Progressive Failure in Shallow Landslides and Snow Avalanches

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1. Introduction

- Snow cover and soil layers forming on steep slopes often exhibit lateral and vertical heterogeneity at various scales affecting their mechanical and hydrologic behavior
- During transient hydrologic conditions (precipitation) the system may be rapidly loaded and fail locally resulting in stress redistribution to neighboring units
- Such local event may cascade, causing other elements to fail and initiate a chain reaction that may culminate into material failure or mass release
- **Objective: To model cascading mechanical failures using concepts of Self-Organized Criticality (SOC) and Fiber Bundle Models (FBM)**

2. Progressive Failure and Scale Invariance: The Concept of Self-Organized Criticality

Fig. 1: *Landslides (left) and snow avalanches (right) triggered during intense precipitation. Size and frequency of 'events' can be characterized by a power-law without characteristic size of landslide or snow avalanche.*

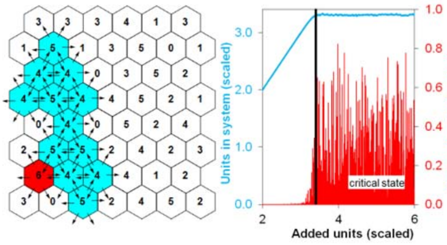

Fig. 2: *The concept of Self-Organized Criticality (SOC) explains scale-invariance by interactions of many elements. Left: By adding a 'load unit' at red cell (reaching threshold capacity 6), all 6 units will be distributed to neighboring cells, initiating redistributions in cells shown in blue. Right: The system evolves into critical state with avalanches (number of cells with redistribution) characterized by power-law. The axes-units are divided by the total number of cells.*

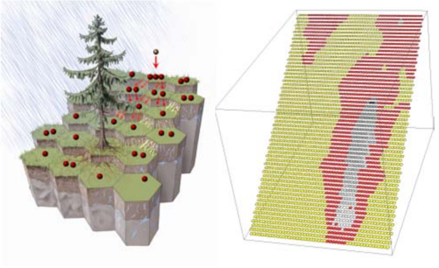

Fig. 3: *SOC-concept applied for landslide modeling. Left: A hillslope consists of soil columns with hexagonal cross-section. Columns are stabilized by fiber-bundles at base and between neighbored cells. Hydrologic loads added during rainfall (indicated by red balls) may initiate cascade of failure. For each time step, water content distribution, mechanical strength and progressive failures are computed. Right: After enduring rainfall the internal structure of the black cell is destroyed, initiating release of cells shown in gray (red cells with broken bundle at base).*

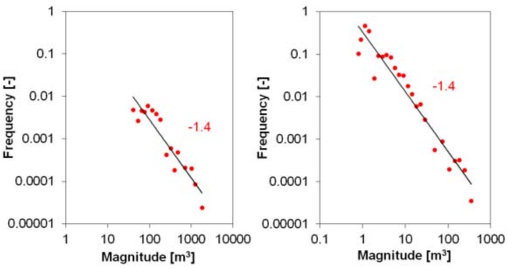

Fig. 4: *Power-law statistics of measured and modeled landslides. Left: Results of landslide inventory (Rickli; WSL) with mass release triggered in Prättigau 2005. Right: Modeled landslide statistics based on 100 realizations of hillslope with random soil depth distribution. Absolute value of power-law exponent equals 1.4.*

3. Progressive Failure and Precursor Events: The Fiber Bundle Model Applied for Snow, Soil and Roots

Fig. 5: *Within a snow or soil layer, elements at various scales exist that may fail before mass is released. Left: Weak layer (indicated by black lines) with ice crystals (hoar) overlaid by fresh snow. Right: Roots stretching across a tension track on a slope.*

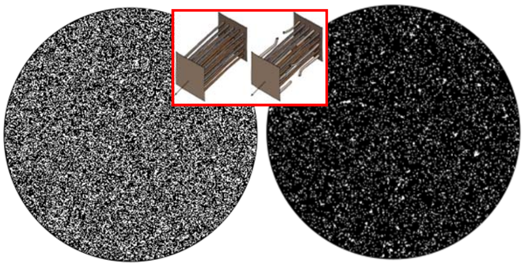

Fig. 6: *Progressive material failure is simulated with Fiber Bundle Model (FBM) consisting of many parallel fibers with random strength. When weakest fibers break, stress redistribution to intact fibers may initiate cascade of failure (see inset). Load can be redistributed to all (left) or the nearest (right) intact neighbors with broken fibers shown in white for two cross-sections with 70'000 fibers.*

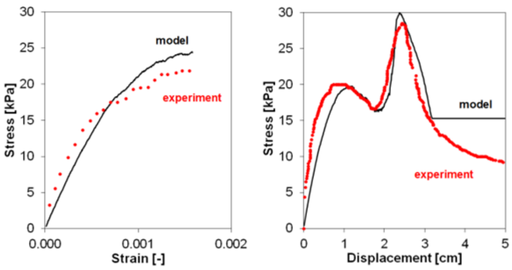

Fig. 7: *Various mechanical behavior can be reproduced with FBM. Left: Tensile stress of soil (Win, 2006) modeled with uniform strength distribution. Right: Soil and roots (Fannin, 2005) modeled with 2 uniform distributions with root-fibers loaded depending on fraction of intact soil-fibers.*

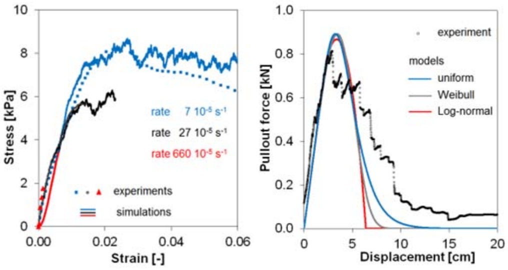

Fig. 8: *Simulation of snow and root mechanics with modified FBM. Left: Using fibers with different times for breaking and sintering, the strain-rate dependence of snow strength and the ductile-to-brittle transition can be reproduced. Right: Pullout experiment of tree roots modeled with different distributions of fiber strengths.*

4. Summary and Conclusions

- Landslides and snow avalanches are characterized by power-law relationship between volume and frequency; we could reproduce statistics by including concept of Self-Organized Criticality (SOC) into hillslope model
- Mechanical properties of roots, snow and soil material can be reproduced by Fiber Bundle Models (FBM)
- To implement SOC-approach in snow avalanche modeling, snow layering and snow metamorphism must be taken into account
- Field and laboratory measurements of precursor events by means of acoustic emission could be interpreted with FBM to draw conclusions regarding imminent mass release

Acoustic emissions for early detection of landslide and snow avalanche release

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Shallow landslides

Key features

- Appear in granular/cohesive earth material (slip surface depth < 2m);
- Multifactorial triggering causes apparently random occurrence and makes prediction hard;
- Progressive failure;
- Triggering is preceded by subsurface deformation and slip plane formation;
- Corresponding rearrangement of geo-material is associated with elastic waves.

Prediction: *Several shallow landslides were triggered in Alpnach (Switzerland) during a catastrophic rainstorm (Aug 2005). Although susceptibility of this area towards landslides is known, hazard assessment for infrastructure and buildings requires detailed knowledge of release locations.*

Progressive failure: *Tension cracks indicate the initiation of a slip plane during the rainfall in Aug. 2005. Although no landslide was triggered, further progress of the slip plane formation is likely during future rainstorm events.*

Relevance

- Heavy rainfall event Aug. 2005: more than 5000 shallow landslide in Switzerland
- Total damage caused by landslides during this event: approx. CHF 100 Mio.

Snow avalanches

Key features

- Take place in snow-covered, steep (>30°) terrain (fracture depth < 2 m) as either slab or point release;
- Multifactorial triggering causes apparently random occurrence and makes prediction hard;
- Progressive failure of weak layer below a cohesive slab;
- Triggering is preceded by concentration of deformation in weak layer (damage leads to catastrophic failure);
- Failure process is associated with release of elastic energy and the generation of transient elastic waves.

Avalanche formation: *Dry-snow slab avalanche (right) and loose snow avalanche (point release (left).*

Snow slab avalanches involve the release of a cohesive slab over an extended plane of weakness, analogous to the planar failure of rock slopes rather than to the rotational failure of soil. Loose snow avalanches start from a point, in a relatively cohesionless surface layer of either dry or wet snow. Initial failure is analogous to the rotational slip of cohesionless sands or soil.

Slab avalanche: *Fracture profile of a dry-snow slab avalanche.*
Failure in a weak layer of buried surface hoar (~1cm in thickness); slab thickness is ~50 cm. Tensile fracture through slab is approx. perpendicular to failure plane.

Relevance

- Heavy snowfall event in Feb. 1999: more than 1200 large destructive avalanche in the Swiss Alps;
- Total damage caused by avalanches during this event: approx. CHF 600 Mio.

Objectives

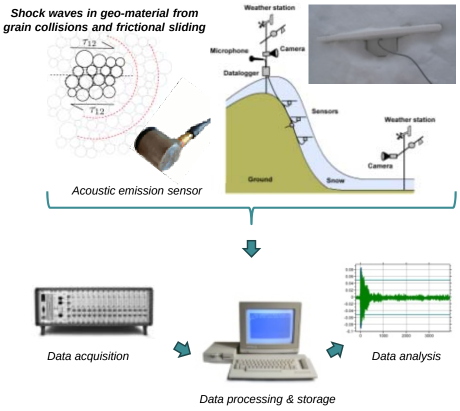
Development of methods to predict the imminence of failure from measurements of vibrations and shock waves in snow and earth material.

Conduction of lab and field experiments.

Find appropriate strategies to apply methods in the field for early warning of landslide occurrence / snow avalanche release in endangered areas.

Principle

- Failure in soil and snow is preceded by deformation and small scale structural damage;
- Such processes act as a source for elastic waves and vibrations;
- Characteristic wave frequencies amplitudes and dispersion features depend on source mechanism and host material;
- Measurement of waves with geophones (low frequencies, snow) and acoustic emission (AE) sensors (high frequencies soil);
- Advantages of AE/geophone measurements: fast (10^2–10^7 samples/sec), non-destructive, real time.



Shock waves in geo-material from grain collisions and frictional sliding

Acoustic emission sensor

Data acquisition

Data processing & storage

Data analysis

Key questions

- Is there a link between mechanical shear deformation and the occurrence of Acoustic Emissions in granular geo-material and snow?
- Can characteristic force jumps during displacement controlled shear tests be linked to AE bursts?
- How many AE events can be expected from different materials?
- Does the AE event frequency increase before failure?
- Is the increase exclusively related to catastrophic failure?
- Does damage localization and formation of cracks lead to low frequency signals?

Adapted shear test

To measure acoustic emissions during shear failure of soil.

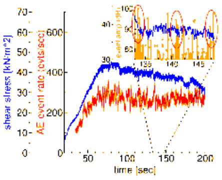
Shear frame key features:

- Conduction of displacement- and force-controlled shear tests;
- Shock wave measurements with 2 AE sensors inside sample;
- High resolution (100 samples/sec) force and displacement measurements in vertical & horizontal direction.

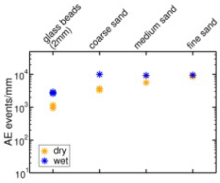
Specially designed ***shear frame*** *for simultaneous measurement of mechanical properties and AE (top). Sample material:* ***glass beads*** *(top left) and* ***coarse sand*** *(bottom right) under dry and wet conditions.*

Results show a clear link between acoustic emission rate (AE events/sec) and the shear resistance forces.

Different materials (dry/wet sand and glass beads) show different AE event rate.



Shear test results: *shear stress (blue) and AE rate (red); inset shows high amp. AE hits (orange) occurring together with force jumps (blue).*



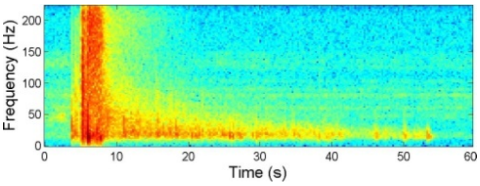
AE activity of different sample materials: *More events occur in dry, fine sand. Glass beads show significantly less AE activity.*

Wannengrat field site

We have developed a seismic sensor array to continuously monitor seismic signals in the snow cover in an avalanche start zone near Davos.

- String of 7 geophones (20 Hz), 6 in the snow, one in the ground;
- Amplification and digitalization of the sensor output at the sensor to minimize signal degradation;
- Continuous data collection with a data storage capacity of up to 30d;
- A microphone and two autonomous high resolution cameras to characterize background noise;
- Two automated weather stations (at the top and near the bottom of the slope).

Avalanche slope monitoring: *Slope where the sensor array was deployed: a steep NE facing slope on the lee side of a ridge at 2475 m. An automatic weather station is located at the top of the ridge and two additional automatic weather stations are within 200 m of the site. The location of the sensors on the slope is indicated with the red ellipse.*



Signal of avalanche release *Running spectrum of the signal associated with the release of a slab avalanche. Since the running spectrum is different from that associated with background noise it is possible to identify avalanches.*

Conclusions

- A clear link between the occurrence of vibrations/elastic waves and the failure behaviour was found.
- Granular geo-material emits high frequency (10-200 kHz) elastic waves (acoustic emissions) already at a very early stage of deformation.
- High AE rate during shear frame experiments even at slow shear rates. Strong differences of AE activity of different sample materials.
- Evidence that single high amplitude events occur as a consequence of shear force jumps → topic of ongoing research.
- Field application requires strategies to overcome strong attenuation of AE in earth material, in particular snow - waveguides may help.
- Reliable, robust and low power seismic system proved well suited to monitor AE in avalanche start zones.
- Due to considerable low frequency background noise an automatic detection and classification of events is required.
- Low frequency precursor events for snow avalanches not (yet) found.

Natural Hazards & Risks (HazRi)
Triggering of rapid mass movements in steep terrain (TRAMM)

Water flow and saturation of hillslopes prone to shallow landslides

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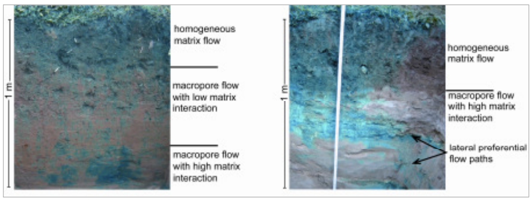
Hillslope failure and hillslope hydrology

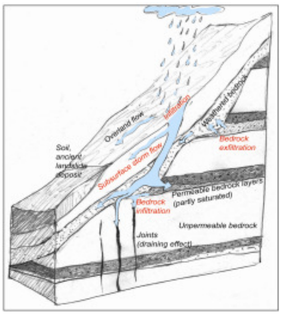
Saturation of the ground may trigger slope failure by
- increase of weight and
- decrease of shear strength (due to enhanced pore water pressure)

Therefore, the saturation and drainage characteristics of a hillslope – the "hillslope hydrology" - may exert a major control on the prevention or triggering as well as the shape of its failure. Thus, for the evaluation of a possible landslide triggering the following effects should be studied:

- **How do different soils saturate?**
- **Which precipitation intensities and amounts are necessary for soil saturation?**
- **What is the influence of the underlying bedrock on saturation?**

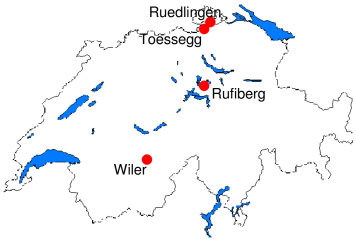


Saturation of the ground may vary widely at different sites. It is controlled:
- at the plot scale, by a complex, dynamic interaction of flow in the soil matrix and preferential flow, both in vertical and lateral directions.
- at the hillslope scale, by lateral subsurface flow and local groundwater infiltration and exfiltration.



Test slopes and methods

Water flow and saturation dynamics were monitored closely during sprinkling experiments and natural rainfall events across four different steep test slopes in Switzerland. The test slopes were identified according to their susceptibility to slope instability on the basis of geology, topography, accessibility, vegetation and ground profile. Temporally and spatially highly resolved measurements of soil moisture and suction, piezometric heads, electrical resistivity and surface and subsurface runoff were made. Instantaneous tracer injections during steady state conditions were used to estimate flow velocities. Combined sprinkling and dye tracer tests allowed infiltration processes and preferential flow paths to be visualised.



Site	Ruedlingen	Toessegg	Wiler	Rufiberg
Location	8°34'/ 47°34'	8°33'/47°33	7°47'/ 46°25'	8°33'/ 47°5'
Altitude [m_asl]	400	380	1800	1100
Exposition	NE	NW	SE	ENE
Slope [°]	37-40	27	40	30-35
Geologic parent rock	Molasse sandstone and marlstone		alpine crystalline Gneiss	Molasse: alternation of sandstone, conglomerate
Land use	forest	meadow	Forest	meadow

Ruedlingen
landslide triggering experiment

The purpose of this project was to trigger a rainfall induced landslide. In a first experiment in October 2008, a total of 1700 mm of rainfall, calculated as an average over the slope area, was supplied over 3.5 days. No water table could be sustained, most likely due to fractures in the Molasse sandstone. The degree of saturation of the ground was determined from TDR and Tensiometer data and some deformations in the range of millimeters were measured, but there was no failure event.

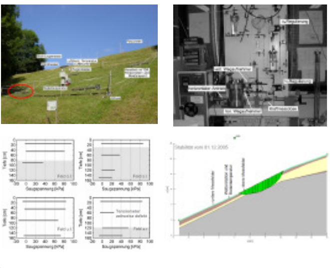
A follow-up experiment in March 2009, with an optimized sprinkling layout, resulted in slope failure that mobilized 130 m^3 of soil after 250 mm rainfall in 14 hours of sprinkling. The optimized sprinkling layout enabled higher pore pressures compared to the first experiment through the development of a perched water table. This is indicated by water level readings in piezometers as well as post-failure observations of subsurface water flow at the failure surface.

Toessegg
long term slope monitoring

A long-term monitoring system was installed for a period of 3 years (2005-07), recording meteorological data as well as water content and soil suction data, overland flow and water table.

The field measurements were completed by laboratory investigations of water retention curves, hydraulic permeability, as well as of shear strength. with the help of triaxial tests on saturated samples and suction-controlled direct shear tests on saturated and unsaturated samples. Results from field and laboratory tests were introduced in a two-dimensional numerical model of the water regime and in a stability analysis.

Soil saturation showed a seasonally two-phase slope behaviour with a typical summer and winter character. The stability analyses showed that the safety factor approaches the critical value under fully saturated conditions.

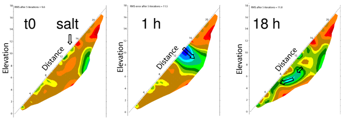


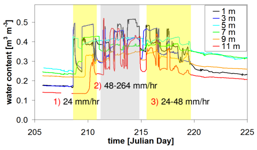
Wiler
failing to fail a slope

An area of 5 m x 10 m was instrumented with sensors in Wiler (Lötschental, VS) to measure water content and water pressure during 11 days of irrigation with rates ranging from 20 to 260 mm/h. In addition, water was applied to a trench above the investigated area.

The lack of overland flow, high subsurface flow velocities based on tracer travel time and quick fluctuations of water content and suction indicated very high drainage capacity. Despite the extreme hydrological pertubation, the test slope remained stable.

A combination of high internal friction mobilised in the ground, the high drainage capacity of the ground due to lateral flow paths, and high permeability of fractures within the underlying bedrock was responsible for the ongoing stability of the slope.



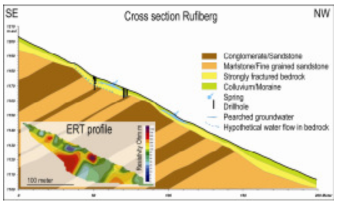


Rufiberg
local groundwater exfiltration

The "Rufiberg" slope near Arth-Goldau (SZ) is covered by 2-3 m of silty clay with very low permeability. Below, beds of conglomerate, several meters thick, alternate with beds of sandstone and marlstone.

Despite the low permeability of the colluvium, several temporal springs can be observed along the slope. Such local groundwater exfiltration might favour the regular occurrence of landslides in the region.

Electrical Resistivity Tomography (ERT) measurements, TDR measurements, groundwater level measurements in bore holes and hydrogeochemistry could be combined to explain the occurrence of local groundwater exfiltration in small springs.



Conclusions

The experiments allowed detailed insight into how the hydrological response influences the failure of a slope during extreme rainfall. Infiltration characteristics within the soil, the existence of preferential flow paths both in vertical as well as lateral directions and infiltration capacity at the transition to bedrock, are playing an important role in triggering or preventing shallow landslides. The high drainage capacity of the ground and its small-scale variability was surprising. On a larger scale, bedrock exfiltration processes seem to play an important role for the triggering of shallow landslides in the area of the Rufiberg test site.

Natural Hazards & Risks: TRAMM

Investigation of granular mass flows in the field and laboratory

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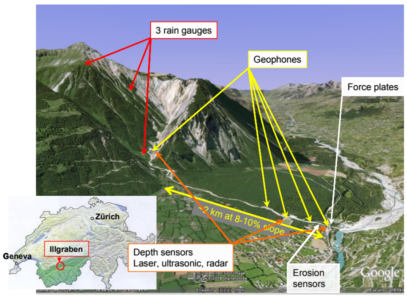
ABSTRACT: Within the TRAMM project, insight into the dynamics of rapid mass movements was gained through a combination of laboratory and field measurements. Observations within debris flows in the field are difficult due to the large inter-particle forces generated within the flow. Using a new bed entrainment sensor developed at the WSL, we were able to measure the timing and rate of erosion at the front of several debris flows in the field. Insight into the dynamics of highly concentrated granular flows was investigated at the EPFL in laboratory dam break experiments. Using innovative methods to create transparent particle-laden flows, it was possible to use particle-imagine techniques to non-invasively investigate the velocity and particle density profiles within the flows. The observations are consistent with recent theoretical work on the transition between flowing and intermittent stick-slip motion of landslide motion. Collectively, both observations indicate that the dynamics within the flows at the leading edge are important in controlling the properties of the flow, and that future work should focus on increasing our understanding of the dynamics within the front of the flows.

The transition from small to large rapid mass movements, e.g. snow avalanches and debris flows, requires a better understanding of the flow dynamics at the leading edge where entrainment of substrate material occurs.

Entrainment by debris flows in the field

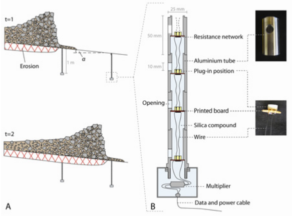
One goal of this project was to measure the timing and magnitude of sediment entrainment by debris flows in the field, thereby producing a unique data set which can be used to constrain theoretical models of debris flow entrainment. The WSL debris flow observation station at the Illgraben (VS), was selected as the study site because it is among the most active torrents in the world, with 35 debris flows observed over the last 10 years.

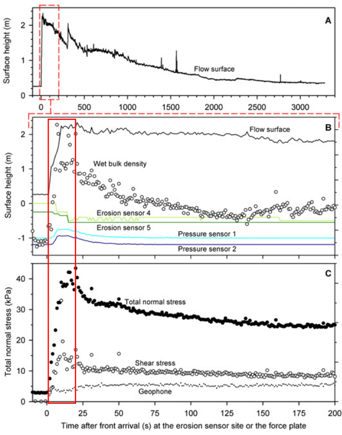


Instrumentation at the Illgraben catchment (left) and properties of the catchment (below).

Active (total) area	4.7 km^2 (9.5 km^2)
Rock, loose material	44 %
Forest	42%
Meadows	14 %
Highest point	2790 m ASL
Lowest point	610 m ASL

The erosion sensor (right) is a column of 5-cm tall elements, each containing an electrical resistor, allowing measurement of the change in total resistance as individual elements are eroded.

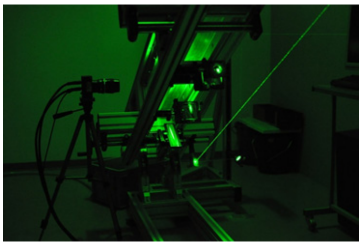




Observations of erosion were made for three debris flows, one is illustrated (left), and shows entrainment of debris within the first 20s at the leading edge of the flow where the fluctuating component of the internal collisional stresses within the flow is the largest (inside the red box).

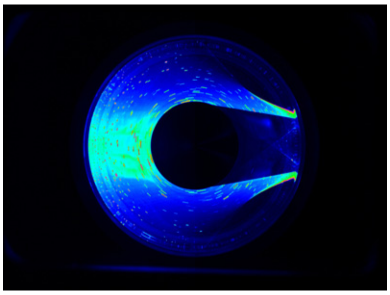
Flow front investigations in the laboratory

Insight into the dynamics of debris flows and avalanches is hampered by a lack of data on the deformation inside of the flow. To visualize the internal dynamics of the particles within the flow, innovative experiments using transparent particles and clear fluids was developed at the EPF Lausanne, allowing non-invasive visualization of the particles within the flow.



The chute used for the granular flow experiments at the EPF Lausanne laboratory (left), showing the camera and laser setup.

Visualization of particle motion in a fluid-solid mixture in a rheometer (right), which can be used to independently determine the properties of the flow.



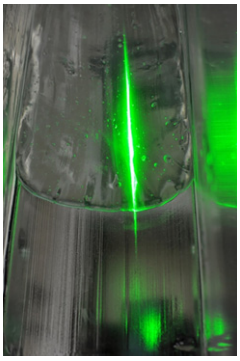


Illustration of the particles moving at the center of the chute in a dam-break experiment (left). The results are consistent with recent theoretical work on the transition between stick-slip and flowing motion in real landslides, and they illuminate the importance of the dynamics of the leading edge of the rapid granular flows.

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