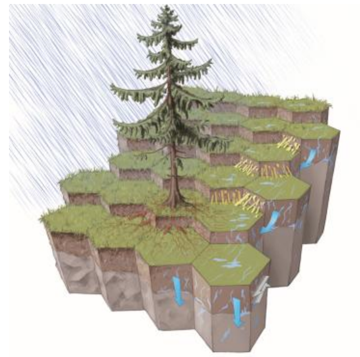
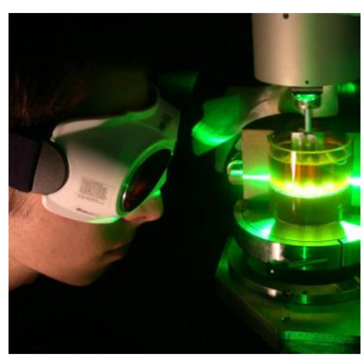
  

Synthesis report of research project TRAMM

Triggering of RApid Mass Movements in Steep Terrain

In short…

The sudden failure and mass movement on steep slopes (landslides, avalanches and debris flows) represent a ubiquitous and significant natural hazard in Switzerland, claiming lives and causing millions of CHF in property damage every year.

In 2006 eight research groups of the ETH domain joined forces to shed new light on processes controlling onset of rapid mass movements. In the frame of the project TRAMM - funded by the ETH Competence Centre for Environment and Sustainability (CCES) - they developed model approaches and sensors applicable to monitoring and quantifying various forms of hazardous mass movements.

A notable achievement of TRAMM was the performance of unique large scale field experiments for inducing landslides that were possible only through close collaboration among the different groups.

The results and conclusions of the TRAMM project have been presented in international scientific conferences, and published in several international scientific journals, as well as in a national brochure for natural hazard experts (FAN-Agenda). The following synthesis report summarizes the main activities and achievements of TRAMM for natural hazard experts and decision makers.

In Kürze …

Spontane Massenbewegungen (flachgründige Hangrutschungen, Lawinen und Murgänge) gehören zu den bedeutendsten Naturgefahren in der Schweiz. Jedes Jahr verursachen sie Schäden in Millionenhöhe und fordern Todesopfer.

Im Jahr 2006 schlossen sich acht Forschungsgruppen des ETH Bereichs zusammen, um im Hinblick auf die Vorhersage von spontanen Massenbewegungen einen Schritt weiter zu kommen. Im Rahmen des Projekts TRAMM – finanziert durch das ETH Kompetenzzentrum für Umwelt und Nachhaltigkeit (CCES) - wurden neue Modellansätze, Sensoren und Methoden entwickelt, welche für verschiedene spontane Massenbewegungen anwendbar sind.

Wichtige Meilensteine des Projekts waren gross-skalige Feldexperimente, die in enger Zusammenarbeit zwischen den Instituten realisiert wurden.

Die Ergebnisse des Projektes TRAMM sind sowohl in verschiedenen internationalen wissenschaftlichen Zeitschriften, als auch im Organ der Fachleute Naturgefahren Schweiz (FAN-Agenda) publiziert worden. Der folgende Synthesebericht fasst die wichtigsten Aktivitäten und Ergebnisse für Behörden und Naturgefahrenexperten zusammen.

En bref …

Les mouvements de masse spontanés (glissements de terrain superficiels, avalanches et laves torrentielles) sont parmi les dangers naturels les plus importants de Suisse. Chaque année, ils coûtent des vies et causent des dégâts matériels chiffrés en millions de CHF.

En 2006, huit groupes de recherche du domaine des EPF se sont associés afin d'améliorer la compréhension du déclenchement et de l'écoulement des mouvements de masse rapides. Dans le cadre du projet TRAMM - financé par le centre de compétence Environnement et durabilité (CCES) du domaine des EPF - de nouvelles approches de modélisation et des senseurs applicables à diverses formes de mouvements de masse spontanés ont été développés.

Un des faits majeurs de TRAMM a été la réalisation d'expériences de terrain à grande échelle, rendues possible grâce à la collaboration étroite entre les différents instituts partenaires.

Les résultats et conclusions du projet TRAMM ont été publiés dans diverses revues scientifiques internationales, ainsi que dans le bulletin national suisse pour les experts en dangers naturels (Agenda FAN). Le rapport de synthèse ci-dessous résume les principales activités et résultats du projet pour les experts en dangers naturels et les décideurs.



Motivation of the TRAMM project

Large areas of Switzerland are exposed to the risk of rapid mass movements with enormous damages caused on annual basis. Federal and cantonal agencies are responsible for an optimized protection of humans and infrastructure against natural hazards. Following the approach of an integral risk management, such an optimized protection includes maintenance of existing measures, land use planning as well as, technical, biological and organizational measures.

For the case of rapid mass movements (i.e. snow avalanches, debris flows and shallow landslides) the following measures are predominant:

Hazard maps - indicating areas that are prone to the rapid mass release as a base for land use planning and subsequent measures.

Warning systems – announcing the imminent occurrence of rapid mass movements.

Temporary and permanent protective structures – retaining or deviating rapid mass movements.

Maintenance of protection forest – being the most important natural protection of alpine residences.

For the design of these measures, engineers and planners need to know A) where and under what conditions rapid mass movements can release, and B) how far and at what speed/pressure they extend.

While for the practitioners there are already tools available predicting the run-out of rapid mass movements, there is still a striking lack of tools that adequately can predict their spatial and temporal occurrence.

This gap is caused by the still very limited basic understanding of triggering processes, that are not only governed by weather (rain amount and intensity) and topography, but are controlled as well by the internal structure of soil and snow coverage defining spatial distribution of weak mechanical elements.

Exploring the inner structure of a snow cover or a soil layer before or during the formation of a rapid mass movement is a great challenge and (normally) cannot be executed as part of establishing a hazard map or planning and constructing protective measures.

Therefore, for the elaboration of hazard maps and protective structures, practitioners need a firm and spatially exact estimation of the impact of rapid mass movements. These have to adequately reflect the specific mass properties of the anticipated hazard.

The project TRAMM has strongly oriented itself at these needs of the practice and intends to provide new solutions and tools to cope with the above-mentioned challenges.

Summary – Main Achievements of the project TRAMM

(1) TRAMM AS MODEL FOR COLLABORATION

TRAMM facilitated the collaboration across the ETH domain. The project connected eight research groups of ETH domain with different expertise related to snow and soil properties, hydrology and fluid dynamics. The consortium planned and executed large field experiments that one institute alone would not be able to carry out.

Training of students. In semi-annual meetings the PhD students funded by the research project presented their work and discussed the findings with principal investigators. They learned approaches and strategies from other groups enabling them to handle problems that must be solved with multidisciplinary approaches.

(2) GENERAL SCIENTIFIC ACHIEVEMENTS

The triggering of rapid mass movements is due to a combination of various factors. Not single factors, such as precipitation rate or height of snow and soil coverage are determining the occurrence of mass release, but a combination of high load and weak mechanical strength causing incidence and propagation of local failures. A key for understanding triggering mechanisms is the analysis of mechanical strength as a function of water content and information on spatial distribution of weak hillslope elements ('sweet spots').

Unifying concepts were found that are applicable to different types of rapid mass movements. As an alternative to classical hydromechanical models, TRAMM applied also other physical concepts (fiber bundle models, Self-Organized Criticality) simulating material failure and mass release as progressive failure culminating into hazardous mass movement.

(3) SPECIFIC SCIENTIFIC ACHIEVEMENTS

Spatial statistical models are useful for assessing the disposition of a slope to trigger shallow landslides. Analysis of landslide inventories confirmed that models based on geomorphic information alone are able to identify slopes prone to mass release. Future work will clarify to what degree prediction of landslide susceptibility can be improved by adding soil hydrological information.

Bedrock permeability is a key-property of slopes prone to shallow landslides. In our three major hillslope experiments (Wiler, Rüdlingen and Rufiberg) we experienced that the permeability of the underlying bedrock was of key-importance for the occurrence or non-occurrence of a shallow landslide. So far the relevance of exfiltrating deep ground-water is not yet confirmed by field experiments and this process must be further analyzed in the ongoing Rufiberg experiment.

An inside view of rapid mass movements is necessary to improve run-out predictions. Both the field measurements at Illgraben and the small-scale lab experiment at EPF Lausanne provided insights into the internal structure of moving masses and debris flows. The Illgraben experiment depicted the erosion and deposition of mass along the channel, and the lab experiment illuminated the critical role of the solid concentration for the stability of flow motion. Based on these findings it should be possible to improve existing runout prediction models.

(4) SENSOR DEVELOPMENT

Sensors were developed to measure entrainment and precursor events. To quantify entrainment in course of debris flow a new erosion sensor was developed and installed in field site. For monitoring precursor events and local failures, acoustic sensors were developed and tested. Difficulties related to limited wave propagation and noise filtering must be solved, and further development is needed to make warning systems operational.

(5) *DISSEMINATION*

Findings of the TRAMM project have been recognized by the international research community. To discuss findings of research project TRAMM we organized a workshop at Monte Verità (Centro Stefano Franscini) and invited leading experts and young scientists to explore differences and analogies of the three different types of mass release. Swiss national experts on natural hazards joined the conference for one day to explore relevance of project achievements.

Zusammenfassung – die wichtigsten Erkenntnisse

(1) ZUSAMMENARBEIT INNERHALB DES PROJEKTS

TRAMM verstärkte die Zusammenarbeit innerhalb des ETH Bereichs. Das Projekt brachte acht Forschungsgruppen des ETH-Bereichs mit unterschiedlichem Spezialwissen in Schnee- und Bodenphysik/-mechanik, Hydrologie und Fluiddynamik zusammen. Das Konsortium plante und führte aufwändige Feldexperimente durch, die für ein einzelnes Institut alleine nicht realisierbar gewesen wären.

Doktorierenden-Ausbildung. In halbjährlichen Treffen stellten die Doktorierenden ihre Arbeit zur Diskussion. Sie machten sich mit Ansätzen und Strategien aus den anderen Gruppen vertraut und lernten so, ihre Probleme auf multidiziplinäre Art und Weise zu lösen.

(2) GENERELLE WISSENSCHAFTLICHE ERKENNTNISSE

Spontane Massenbewegungen werden durch eine Kombination von Faktoren ausgelöst. Nicht einzelne Faktoren, sondern eine Kombination von hoher Belastung und schwacher mechanischer Festigkeit ist verantwortlich für das Auftreten und die Ausbreitung von lokalem Versagen. Die mechanische Festigkeit als Funktion des Wassergehalts ist eine Schlüsselgrösse. Ebenso wichtig ist die räumliche Verteilung von schwachen Hangelementen ('sweet spots').

Allgemeingültige Konzepte wurden erarbeitet, welche für verschiedene Arten von Massenbewegungen anwendbar sind. Als Alternative zu klassischen hydromechanischen Modellen wurden im TRAMM-Projekt auch andere physikalisch-basierte Konzepte erarbeitet, wie z.B. Faserbündelmodelle oder Self-Organized Criticality-Modelle. Diese simulieren die Auslösung der Masse als progressives Versagen, welches in eine Massenbewegung mündet.

(3) SPEZIFISCHE WISSENSCHAFTLICHE ERGEBNISSE

Räumliche statistische Modelle können die Disposition eines Hangs bezüglich dem Auftreten von Hangrutschungen abschätzen. Es wurde gezeigt, dass Modelle mit geomorphologischen Informationen in der Lage sind, Rutsch-anfällige Hänge zu identifizieren. Zukünftige Arbeiten werden zeigen, wie weit die Vorhersage von Hangrutsch-Prädisposition mit Hilfe von bodenhydrologischer Information verbessert werden kann.

Die Felsdurchlässigkeit ist eine Schlüsselgrösse im Hinblick auf das Auftreten von flachgründigen Hangrutschungen. In unseren drei Hangexperimenten (Wiler, Rüdlingen und Rufiberg) haben wir festgestellt, dass die Durchlässigkeit des unterliegenden Fels eine entscheidende Rolle spielte, ob ein flachgründiger Hangrutsch entstehen kann oder nicht. Anderseits konnte bis jetzt mit unseren Experimenten noch nicht festgestellt werden, wie wichtig aus dem Untergrund exfiltrierendes Grundwasser ist. Das laufende Rufiberg-Experiment soll diesbezüglich neue Erkenntnisse liefern.

Prozesse im Innern einer Massenbewegung müssen berücksichtigt werden, um die Auslaufdistanz besser abschätzen zu können. Sowohl die Messungen im Illgraben, wie auch die Laborstudie an der EPF Lausanne haben neuen Einblick in die inneren Strukturen einer dynamischen Masse gewährt. Das Illgraben-Experiment hat aufgezeigt, wo im Gerinne sich Erosions- und Depositionszonen des Murgangs befinden. Das Laborexperiment machte die kritische Rolle der Feststoffkonzentration hinsichtlich der Stabilität der Fliessbewegung sichtbar. Mit diesen neuen Erkenntnissen dürfte es möglich sein, bestehende Auslauf-Simulationsmodelle zu verbessern.

(4) SENSOR-ENTWICKLUNGEN

Neue Sensoren wurden entwickelt. Zur Quantifizierung der Erosion und der damit verbundenen Massenzunahme von Murgängen wurden neue Sensoren entwickelt und im Illgraben erfolgreich getestet. Akustische Sensoren wurden zur Erfassung von Vorboten auf Lawinen und Hangrutschungen neu entwickelt und getestet. Noch müssen Schwierigkeiten hinsichtlich Wellenfortpflanzung und Hintergrundgeräuschen überwunden werden, damit diese Technik operationell werden kann.

(5) *KOMMUNIKATION DER ERGEBNISSE*

Die Erkenntnisse aus dem TRAMM-Projekt wurden von der internationalen Forschungsgemeinschaft zur Kenntnis genommen. Im Rahmen eines internationalen Workshops auf Monte Verità wurden die Ergebnisse des TRAMM-Projekts diskutiert. Führende Experten sowie Nachwuchs-ForscherInnen wurden eingeladen, ihre Erfahrungen bezüglich der Auslösung von spontanen Massenbewegungen mit uns zu teilen. Bei dieser Gelegenheit waren auch nationale Naturgefahren-Fachleute während einem Tag anwesend und machten sich mit dem Projekt vertraut.

Résumé – Faits majeurs du projet TRAMM

(1) TRAMM: UN MODELE DE COLLABORATION

TRAMM a facilité la collaboration dans le domaine des EPF. Le projet a réuni huit groupes de recherche du domaine des EPF avec des compétences variées en lien avec la neige, les propriétés du sol, l'hydrologie et la dynamique des fluides. Le consortium a planifié et exécuté des expériences de terrain à grande échelle qu'un institut seul n'aurait pas pu réaliser.

Formation des étudiants. Lors de colloques semestriels, les doctorants financés par le projet de recherche ont présenté leurs travaux et discuté des résultats avec les principaux examinateurs. Les contacts avec les autres groupes leur ont permis de développer des approches et des stratégies multidisciplinaires.

(2) RESULTATS SCIENTIFIQUES GENERAUX

Le déclenchement de mouvements de masse rapides est dû à une combinaison de plusieurs facteurs. Ce ne sont pas des facteurs isolés, tel que le taux de précipitation, la hauteur de neige ou la couverture du sol qui déterminent l'occurrence d'un mouvement de masse, mais la combinaison d'une forte charge et d'une faible résistance mécanique causant l'apparition et la propagation de ruptures locales. Pour comprendre les mécanismes de déclenchement, une analyse de la résistance mécanique en fonction de la teneur en eau et d'informations relatives à la distribution spatiale de zones fragiles s'avère utile ('sweet spots').

Des concepts unificateurs applicables à différents types de mouvements de masse rapides ont été trouvés. Comme alternative aux modèles hydromécaniques classiques, TRAMM a également appliqué d'autres concepts physiques (fiber bundle models, Self-Organized Criticality) simulant la rupture et le mouvement en tant que rupture progressive aboutissant en un mouvement de masse dangereux.

(3) RESULTATS SCIENTIFIQUES SPECIFIQUES

Des modèles spatiaux statistiques sont utiles pour évaluer la prédisposition d'une pente au déclenchement de glissements de terrain superficiels. L'analyse d'inventaires de glissements de terrain a confirmé que des modèles basés uniquement sur des informations geomorphiques sont capables d'identifier les pentes prédisposées aux mouvements de masse. Des études futures permettront de déterminer dans quelle mesure la prédiction de la potentialité au glissement de terrain peut être améliorée en intégrant des informations sur l'hydrologie des sols.

La perméabilité de la roche en place est une propriété clé des pentes prédisposées aux glissements de terrain superficiels. Nos trois sites pentus de recherche (Wiler, Rüdlingen et Rufiberg) nous ont appris que la perméabilité de la roche en place était déterminante pour l'occurrence ou la non-occurrence de glissements de terrain superficiels. Jusqu'ici, la pertinence de l'exfiltration des aquifères n'a pas été confirmée par les expériences de terrain. Ce procédé sera analysé plus en détail dans l'expérience en cours au Rufiberg.

Une connaissance des processus internes des mouvements de masse rapide est nécessaire afin d'améliorer les prédictions de longueur de zone de dépôt. Les mesures de terrain de l'Illgraben ainsi que les expériences de laboratoire à échelle réduite de l'EPF Lausanne ont fourni un aperçu sur la structure interne des laves torrentielles et des masses en mouvement. L'expérience de l'Illgraben a décrit l'érosion et la déposition de masses le long du chenal. L'expérience en laboratoire a démontré le rôle critique de la concentration de solide pour la stabilité de l'écoulement. A l'aide de ces résultats, il devrait être possible d'améliorer les modèles actuels de prédiction de longueur de zone de dépôt.

(4) DEVELOPPEMENT DE CAPTEURS

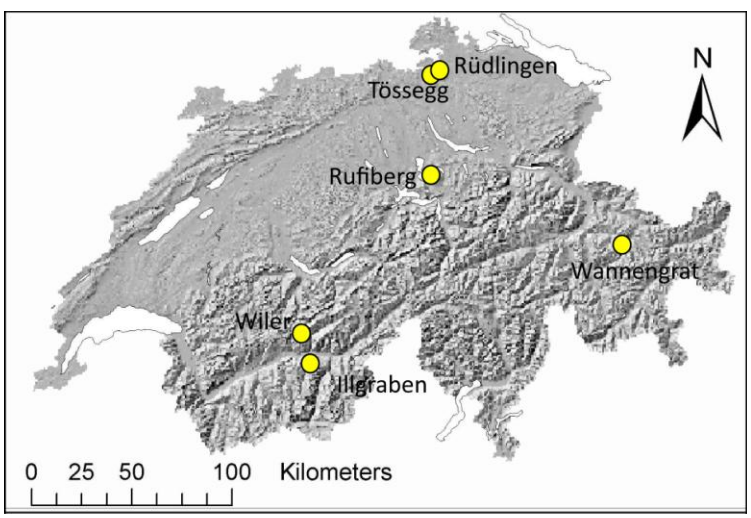
Des capteurs mesurant les événements précurseurs et les mouvements de masse ont été développés. Pour quantifier les mouvements de masse durant une lave torrentielle, un nouveau capteur d'érosion a été développé et installé sur site. Pour le monitoring des événements précurseurs et des ruptures locales, des capteurs acoustiques ont été développés et testés. Des difficultés liées à la propagation limitée des ondes et au filtrage du bruit doivent être résolues. Des développements complémentaires sont nécessaires afin de rendre les systèmes d'alarme opérationnels.

(5) *COMMUNICATION*

Les résultats du projet TRAMM ont été reconnus par la communauté scientifique internationale. Les résultats du projet de recherche TRAMM ont été discutés lors d'un séminaire au Monte Verità (Centro Stefano Franscini). Des experts reconnus et de jeunes scientifiques ont été invités à étudier les différences et les analogies des trois types de mouvement de masse. Des experts suisses en dangers naturels ont rejoint la conférence afin d'évaluer la pertinence des résultats du projet.

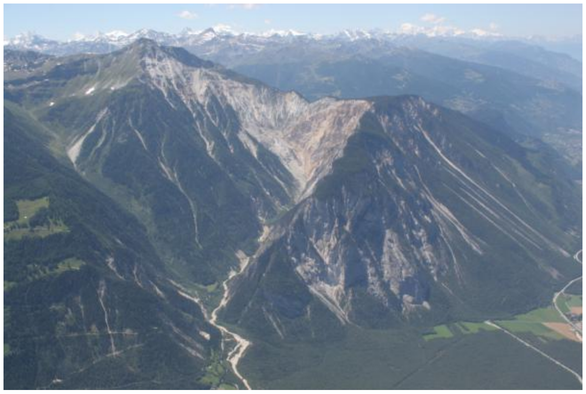
Field experiments

Six comprehensive field experiments provided a unique data basis for developing and testing model approaches. They were organized in collaboration between several groups. The data from these experiments are freely available on request. On the following pages, a short description of the field experiments can be found.



Location of the TRAMM field experiments in Switzerland.

Illgraben (Leuk, VS) - Debris flow erosion



The Illgraben (Photo: P. Wicki, 14.7.2007)

The Illgraben, located in western Switzerland, experiences several debris flows every year. The Illgraben catchment (10.4 km^2, North exposition) extends from the summit of the Illhorn (2716 m a.s.l.) to its outlet into the River Rhone (610 m a.s.l.). The climate is temperate-humid and influenced by the rain shadow effect within an interalpine valley which generates relatively low annual precipitation, ranging from 700 mm in the lower part to 1700 mm in the summit region. The Illgraben catchment is underlain by Triassic meta-sedimentary rocks, mainly quartzite, calcite and dolomite. Bedrock and debris deposits cover 44% of the Illgraben catchment, 42% are covered by forest, and 14% by grassland. The debris fan is unusually large for the Alps and has a radius of about 2 km. After a large rock avalanche in 1961, the Illgraben channel was protected by a large sediment retention basin and additional 28 check dams further downstream.

Site instrumentation

A novel erosion sensor was developed and installed on the lower third of the fan to study the timing and amount of entrainment during a debris flow. Together with data from the observation station (operated by the WSL) located 70 m downstream and from a camera installation, the timing and amount of erosion was related to flow parameters. Pore water pressure was measured at the erosion sensor site; flow depth, normal and shear force, and geophone inpulse frequency were measured at the observation station.

Sediment transfer observations and allocation of sediment sources within the upper catchment were based on analysis of four aerial image series. An analog air-survey camera (Leica RC30) was used and 35 images were taken during each survey. The images were analyzed with photogrammetry and the geomorphic changes were compared with debris flow occurrence and magnitude.

Arrival of the 1 July 2008 debris flow at the erosion sensor site (red ellipse; WSL, 1.7.2008)

Measurements

Erosion during debris flows and floods was determined at the erosion sensor site from May to November 2008 for three debris flows and four floods.

Aerial image surveys were performed on 2 October 2007, 15 July and 29 September 2008, and 23 September 2009.

Data availability

The data are available on request (see contact information).

Contact

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Rüdlingen (SH) - Landslide triggering by artificial rainfall

Instrumented slope in Rüdlingen, SH.

Field site

The experimental slope is 7.5 m wide by 35 m long, located in the Swiss lowlands on an east facing slope over-looking the river Rhine, at an altitude of ~ 350 masl. Originally there were forestry covertures of circa 80%, heights of 5-20 m. Shrubs up to 1-5 m high and a free herb layer covered ~ 50% of the surface. The average gradient was determined to be from 38° to 43° with a slightly concave surface. The underlying rock consists mainly of Molasse, which is formed by alternate layers of sea deposits under the Tethys Sea (Seawater Molasse) and land deposits (Freshwater Molasse). Several augured samples, as well as an outcrop of the bedrock about 20 m above the selected field, revealed horizontal layering of fine grained sand- and marlstone at the test site. The sandstone was later proven to be highly permeable and fissured. Grain-size distributions were determined and the soil was classified as medium-low plasticity silty sand.

Site instrumentation

Measurements of soil suction, groundwater level, soil volumetric water content, rain intensity and soil temperature were taken and combined with geophysical monitoring using Electrical Resistance Tomography (ERT) and investigations into subsurface flow by means of tracer experiments. Deformations were monitored during the experiment, both on the surface via photogrammetrical methods and within the soil mass, using a flexible probe equipped with strain gauges at different points and two axis inclinometers on the top and acoustic sensors. Instruments were installed mainly in three clusters at depths of 15, 30, 60, 90, 120, and 150 cm below the ground surface over the slope, including jet-fill tensiometers, TDRs, Decagon TDRs, piezometers, soil temperature sensors, deformation probes, earth pressure cells, acoustic sensors and rain gauges. A ring-net barrier (provided by Geobrugg AG) was set up at the foot of the slope to protect the road.

Location of instrumentation clusters (Cl. 1 – 3), the sprinklers and the photogrammetry cameras.

Experiments

A sprinkling experiment was carried out in autumn 2008 to investigate the hydrological and mechanical response of the slope, followed by a second one to trigger a landslide in spring 2009.

Data availability

All measured data concerning soil suction, water level, soil volumetric water content, rain intensity, and soil temperature are available on the TRAMM ftp for members.

Contact

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Wannengrat (Davos, GR) – Snow avalanche test area

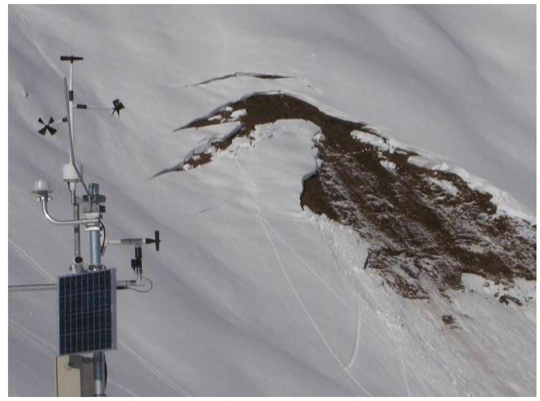
Overview of the Wannengrat field site above Davos. The site is instrumented with seven automatic weather stations. One avalanche start zone is instrumented with an array of seismic sensors.

Field site

The experimental site Wannengrat is located in the eastern Swiss Alps near Davos and covers an area of about 4 km^2. The area is mainly located above treeline with an average elevation of 2300 m. The terrain is characterized by various ridges and bowls as well as some steep cliff faces. The site has a variety of slopes of different size and aspect, very well suited for avalanche research, and is easily accessible from the village of Davos. The Wannengrat site is employed for diverse areas of research. Current experiments investigate snow cover distribution, avalanche formation, hydrology and meteorological forcing using terrestrial laser scanning, acoustic emission monitoring, a runoff station, meteorological stations and manual snow cover observations.

Site instrumentation

Seven automatic weather stations (AWS) are located within the experimental site. These seven stations include three so-called meteorological stations and four so-called wind stations. Meteorological stations measure air temperature (with a ventilated sensor), relative humidity, short-wave and long-wave radiation (incoming as well as outgoing), surface temperature, snow height, wind speed and wind direction. The data are available at 10 minute intervals. Wind stations measure air temperature, relative humidity, snow height, wind speed, wind direction and, with a separate anemometer, speed of the three wind components u, v, w. Within the framework of TRAMM, an avalanche start zone was instrumented with an array of seismic sensors in order to monitor acoustic emissions. This array consists of seven geophones (natural frequency of 14 Hz) which are continuously sampled at 500 Hz. Additional observations methods consisting of a microphone and several cameras were also installed to provide metadata for the acoustic measurements.



Automatic weather stations at the Wannengrat field site record meteorological parameters at 10 minute intervals. These data are used for a variety of research purposes, including avalanche formation.

Experiments

During the winters of 2006 to 2009 slopes of different aspect were investigated in order to investigate the spatial variability of the snow cover. These investigations included spatial distributed high resolution penetrometer (SnowMicroPen) measurements as well as manual snow cover observations (snow profile and stability tests). Furthermore, regular observations were made to provide information on the snow cover stratigraphy.

Data availability

Snow-meterological data are available through the SwissEx data portal.

Contact

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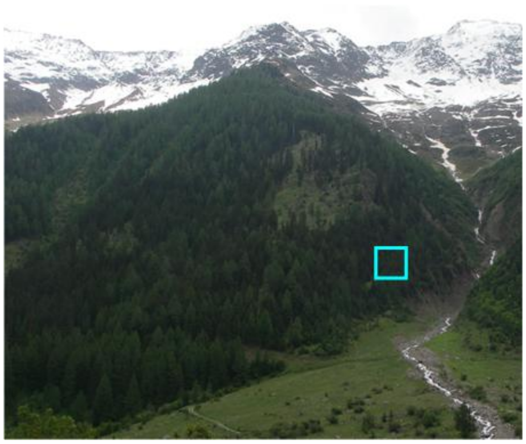
Wiler (VS) - Hydrologic perturbation of a steep slope



Study area in Wiler (Lötschental) with the blue rectangle indicating the position of field site.

Field site with sprinklers and trench at the top, to 'load' the slope with water.

Field site

The Wiler field site is located in the canton of Valais (Lötschental) at an elevation of 1800 m a.s.l. It is a steep (40°) forested slope with soil depths between 0.4 to 1.0 m overlying fractured bedrock. In the east, a steep ravine with a creek ('Wilerbach') is a natural boundary of the field site. The soil is a 'sandy loam' with more than 50% sand fraction. The site is located in the Aar massive which is composed of crystalline rocks. The experimental site is based upon chlorite-gneisses dipping 60° to 80°. The tree canopy is dominated from spruce (pice abies) and in more open places the larch (larix decidua) and the rowan can be found.

Site instrumentation

At eleven locations of the slope section water content and water pressure were measured in depth up to 1 m by means of water capacitors and tensiometers, respectively. In addition, electrodes were installed to determine travel paths of a salt pulse using electrical resistivity tomography (ERT). Water was supplied form the nearby Wilerbach. To measure water balance rain gauges were installed and water in- and outflow were measured by flow meters.

Experiments

In a first experiment 2007 with water supply of 40 Liters per minute, water flow velocities of about 30 meters per hour were measured indicating presence of fast water flow along decaying tree roots. After onset of water supply, soil water content increased and converged to a constant value after a few hours corresponding to flow equilibrium. Hence, due to high drainage capacity it was not possible to 'load' the slope to values prone to landslide triggering.

To reach higher water contents, we repeated the experiment 2008 with maximum water supply of 220 liters per minute at a different site with higher soil depths (up to 1 m) and less reinforcing tree roots.

During five days with high water supply we added the cumulative rainfall of 8 years. While sensors indicated presence of free water in higher soil depth, it was not possible to maintain high water content and to saturate the slope completely. According to ERT measurements, a large fraction of added water percolated into the bedrock and the slope remained partially unsaturated.

The extreme values of irrigated water exceeded by considerable amount the threshold values reported in various studies on landslide triggering – yet the test slope remained stable. Three factors are responsible for the high drainage capacity and slope stability: i) underlying fractured bedrock with high permeability, ii) incorporated dead wood acting as stabilizers or fast water pathways, and iii) a stone skeleton connected with root system.

Data availability

The data can be downloaded from www.swiss-experiment.ch

Contact

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Rufiberg (Arth, SZ) – A hydrological study of a slope prone to shallow landslides

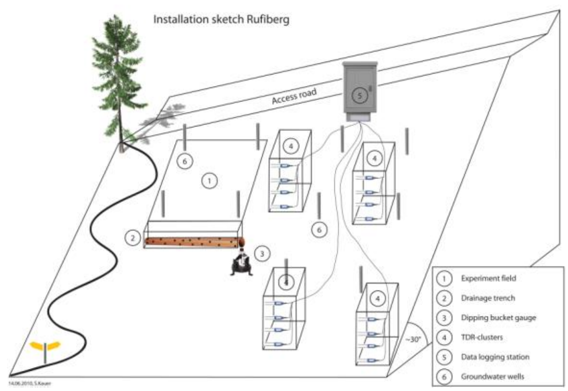
Resent scar of a shallow landslide in the 30 – 35 ° steep slope of the Rufiberg, SZ.

Field site

The Rufiberg is located at the NW side of Mount Gnipen north of the village Arth-Goldau in the Canton of Schwyz. In the summer months the site is used for pasturing. Usually, from December to March a snow cover is present at Rufiberg. The site is at an altitude between 1080 – 1180 m a.s.l., is ENE oriented, and has an average slope of 30°. The Subalpine Molasse in the region is inclined with 30 - 35° to SE. In the area of the field site, beds of conglomerate with several m of thickness alter with beds of sandstone and marlstone. A ca. 2 – 5 m thick eluvium/colluvium layer, composed of silty and sandy clay covers the bedrock.
This site has been chosen because of numerous landslides which occur during heavy rainfall events, (e.g. autumn 2005) in the region of the Gnipen and the Rufiberg.
The goal of the investigation is to understand the water flow and saturation of the slope during critical situations potentially triggering shallow landslides.

Site instrumentation

On the 40 m x 60 m large experiment field, four measurement clusters instrumented with TDR probes and tensiometers at four different depths (0.25m, 0.7m, 1.1m and 1.5m) were installed to continuously monitor the changes in volumetric water content and the soil saturation.
To monitor the subsurface flow rate within the soil, two drainage tubes have been installed at a depth of 1m and 0.25m, respectively, from which discharge is measured using tipping bucket gauges.
Groundwater level changes are recorded in 10 min intervals in 10 groundwater wells spread over the field and reaching a depth of 1.5m.
To obtain information of the subsurface, Electric Resistivity Tomography (ERT) is carried out along the slope. Based on ERT profiles in different scales we estimated the soil thickness and saturation as well as deeper geological structures and units. Several drill holes are planned to monitor the groundwater level in the soil and the bedrock, to study the hydrogeochemistry and to correlate it with precipitation records and spring flux. The reaction time to precipitation and the chemistry of the water can shed light on the origin of the water.
To gather information about the soil properties, undisturbed soil samples have been retrieved to make permeability and plasticity tests, analyze the grain size distribution and characterize the present clay minerals.



Sketch of the measurement set-up at Rufiberg.

Experiments

ERT profiles are made during different hydrological conditions (before snowmelt, after snowmelt, after heavy rainfall) in order to record hydrological patterns like local saturation and preferential water flow path.

Data availability

The data will be available at ftp.wsl.ch/pub/TRAMM

Contact

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Manfred Stähli, WSL, manfred.staehli@wsl.ch

Tössegg (ZH) - Hydromechanical monitoring experiment

Test site Tössegg.

Dye tracer experiment to investigate water flow paths in the soil.

Field site

A series of 42 landslides occurred in May 2002 in North Switzerland near the river Rhine after an extreme rainfall event. An area, close to Toessegg (ZH), was severely affected and an experimental test site was installed in order to study the interrelationship between the many factors influencing the triggering of landslides. The regional geology is characterised by sedimentary rocks formed from erosion of the Alps. The Rhine has eroded a steep valley into Tertiary sandstones, in particular Saltwater Molasse from the Lower Oligocene overlain by Freshwater Molasse; a sandstone deposited in freshwater in the Upper Oligocene. The sandstone bedrock is typically covered by well-drained cambisol soils above loose weathered or residual sands and silty sands of glacial and fluviatile origin. A grass-covered site with an area roughly 50×20 m, located approximately 25 m above the Rhine, was selected for a detailed study of the response of soil to heavy rainfall. The slope angle varied between 26° and 28°.

Site instrumentation

A monitoring system was installed for a period of 3 years (2005-07), recording meteorological data as well as soil water content and soil suction at different depths down to 1.5 m, overland flow and ground water table.

Experiments

The field measurements were completed by combined sprinkling and tracer tests to evaluate the infiltration behavior of the soil over a local (1 m^3) area. Laboratory investigations were conducted 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.
The water flow along the slope and the saturation of critical slope areas were simulated with the 3-D model HillVi for selected rainfall events.

Data availability

The data is presented in detail in the doctoral dissertation of Thielen (2007) and the Master thesis of Gilgen (2008).

Contacts

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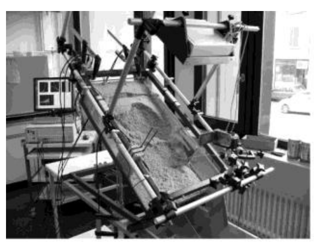
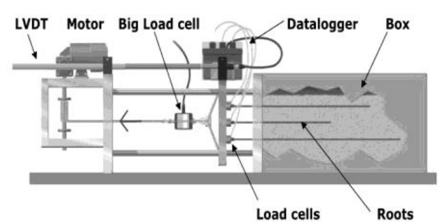
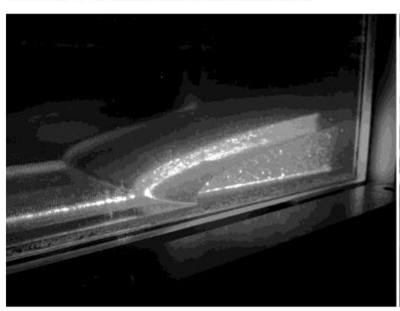
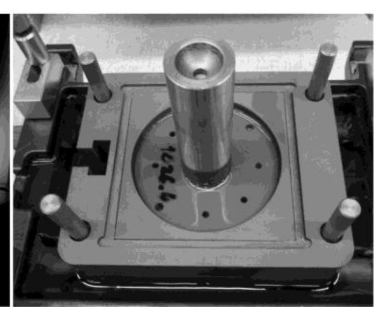
Lab experiments

Lab experiments provided a more detailed insight into the triggering and flow mechanisms of rapid mass movements. Also, they were carried out to determine specific properties of soil and roots. On the following pages, a short description of the lab experiments can be found.

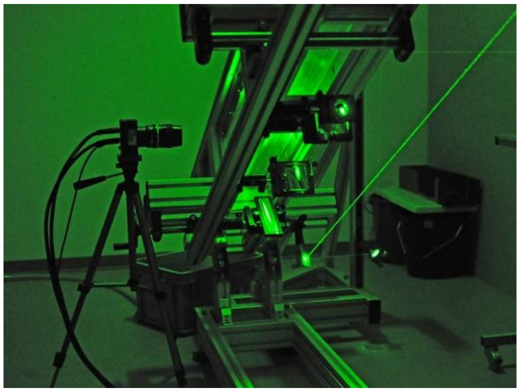








Simulating debris flows in the laboratory



Detail of the flume enlightened by a laser beam, with a high-speed camera filming from the side.

Objective of the experiment

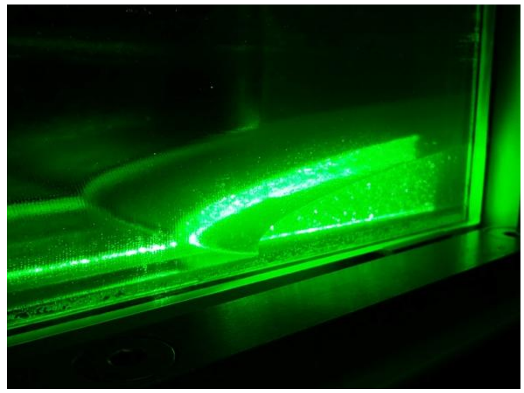
The experiment aims at better understanding the physics of gravity-driven flows of concentrated suspensions of non-colloidal particles. The problem is an idealization of the transition from a landsliding mass of poorly sorted coarse materials into a debris flow under the effect of water seepage.

The solid concentration of our suspensions is close to the maximum packing fraction (maximum fraction of solid material that a suspension can contain). Minute changes in the solid concentration (e.g., under the effect of dilatancy) can cause a resting suspension to flow or, conversely, a flowing suspension to come to a halt. Using image-processing techniques and pressure transducers, we are tracking the various regimes (rest and flow) experienced by a suspension placed in an inclined flume. The experimental data can then be compared with theoretical predictions (in particular, Iverson’s work on the role of excess pore pressure as a driving mechanism for debris flows).

Set-up

The experimental facility is made up of an inclined flume (2-m long, 10-cm wide) Using image processing techniques, we can visualize what occurs inside the flow. Indeed, the suspensions are composed of PMMA (Polymethyl methacrylate) particles (mean diameter of 0.2 mm) and a mix of oils with the same index of refractions than the PMMA, which makes it possible to obtain transparent suspensions. Some particles are tagged with a fluorescent dye. These tagged particles behave as markers and can be tracked by high-speed cameras. We are currently able to measure velocity profiles inside the flow in this way and in the coming months, we might be able to obtain concentration profiles. Pressure transducers are placed along the flume centerline and record bottom pore pressure. Four cameras film the flow from above and provide the flow depth as a function of the time.

Flow visualization makes this experimental setup unique since both bulk features and internal structure can be documented.



Front of an avalanching mass of a highly concentrated suspension of particles. The tip region is enlightened by a vertical laser sheet.

Experiments

The typical experiment conducted in this flume is the so-called dam-break experiment, where a fixed volume of suspension is instantaneously released down the flume and flows under the action of gravitational acceleration. A wide range of flume slopes (in the 10-30° range) has been explored. Various iso-density iso-index particle suspensions have been tested; the mean solid concentration ranges from 0.58 to 0.61. Although this range is narrow, minutes changes in this parameter causes substantial changes in flow behavior.

Data availability

Data will be published in Journal of Fluid Mechanics.

Contact

Christophe Ancey and Nicolas Andreini, Laboratoire d'hydraulique environnementale, EPF Lausanne, 1015 Lausanne, christophe.ancey@epfl.ch

Lab-Experiment: Mechanics of unsaturated soils

The shear box (10 cm x 10 cm x 2 cm) of IGT-ETHZ used for mechanical testing of the Rüdlingen soil.

Introduction

A landslide triggering experiment was carried out in autumn 2008 and spring 2009 near Ruedlingen in North East Switzerland. A failure mechanism was triggered in March 2009, incorporating about 150 m^3 of debris. A series of direct shear box tests and the relation between the pore water pressure and the amount of water in the soil (Water Retention Curve) were investigated in laboratory.

Objective of the experiment

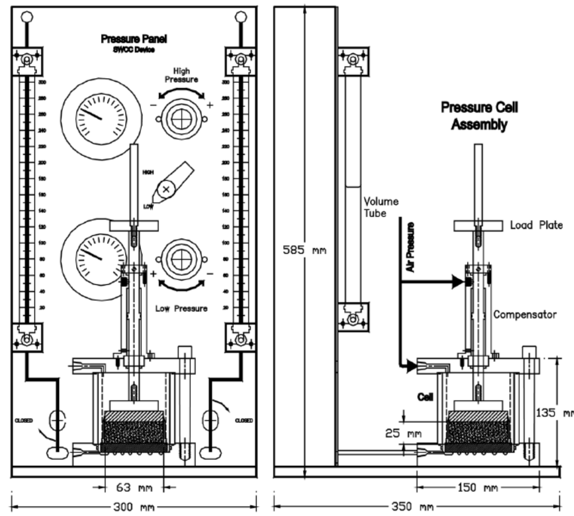
The aim was mainly to establish a correlation between the degree of saturation and slope stability. It is essential to establish a suitable model for the shear resistance of the soil in order to conduct stability analysis. Shear tests on reconstituted samples and the WRC obtained in laboratory with a Fredlund oedometer (Figure 2) are used. The shear tests are interpreted based on a Water Retention Curve (WRC) by considering the influence of vertical load and water content. A simple slope stability analysis is also performed that takes the hysteresis of the WRC into account in respect to the suction acting on the shear plane.

Set-up

The Ruedlingen soil was classified as a medium to low plasticity silty sand (ML). The activity, I_A, derived from a chloritic-smectitic clay fraction, is higher than 1.25 in the upper part of the soil profile, decreasing to I_A = 0.75 with depth. Specimens were compacted statically at water contents of w ≈ 15%, 20% and 25%, at a target void ratio e = 0.9.

Experiments

The WRC was obtained using a Fredlund Oedometer under suction controlled conditions for a reconstituted specimen with an initial void ratio e_0 = 0.83 and w_0 = 17%.



Oedometer-type pressure plate apparatus (after Perez Garcia et al., 2008).

Direct shear test series were performed on reconstituted specimens of a standardised Ruedlingen soil, with dimensions of 10 cm x 10 cm x 2 cm using an ordinary shear apparatus (Strassentest Typ 963). Tests were conducted under undrained conditions for the water phase, on specimens prepared at different gravimetric water contents. The soil was saturated after shearing to analyse the effect of wetting on shear strength. The shear tests were performed at a rate of 0.333 mm/min to an absolute displacement of 10 mm (and back to the initial position) under three vertical stresses σ_v = 20, 40, 80 kPa, respectively. Three of the samples were saturated after 6 mm horizontal displacement, in order to analyse the effect of the wetting on the mobilised shear strength.
The WRC was obtained under suction controlled conditions applying a net vertical stress σ_v - u_a = 5 kPa, changing the air pressure u_a from 70 kPa to 0 kPa and back to 50 kPa in steps in order to perform a wetting-drying cycle.

Data availability

The following data are available for further interpretation and analyses:

- WRC data: air pressure and water in/out of the samples for the different steps;
- Shear tests data: shear stress-displacements for three water content and in saturated conditions for three vertical stresses.

Contact

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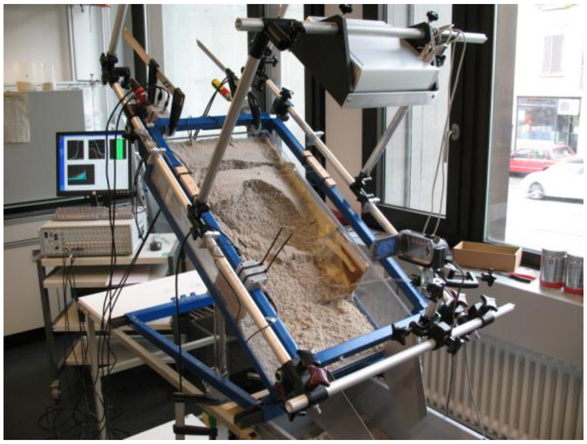
Laboratory Tilt-box Experiments



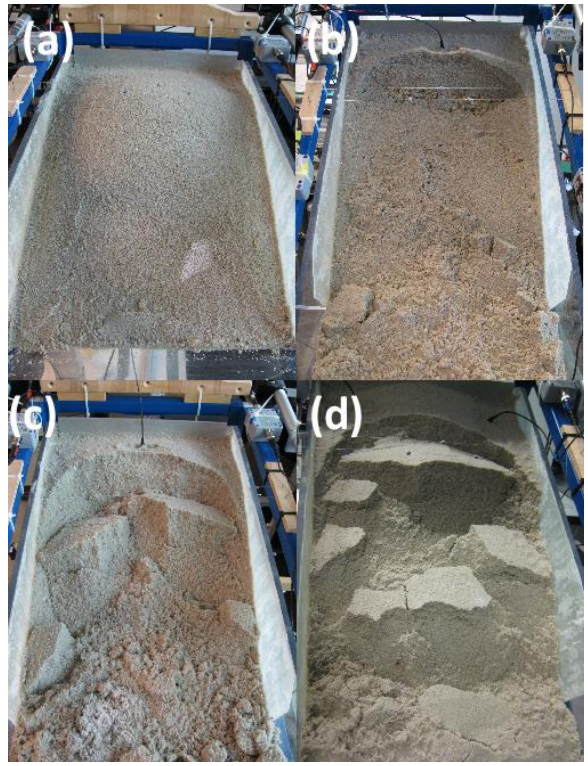
Tilt-box with video camera and surface laser profiler. Desktop computer for acoustic emission acquisition is visible in the background left of the tilt-box. Acoustic emission sensors and tensiometers are hidden inside the sand. Sprinkler system not shown.

Objective of the experiment

Shallow landslides triggered by rainfall are sudden events yet often represent the culmination of numerous small progressive failure events that eventually coalesce to form a continuous failure surface. We investigated characteristics of such precursory events during failure of laboratory-scale sand and soil landslides in a tilt-box by monitoring: (1) acoustic emissions; (2) matric suction; and (3) rapid imaging of tension-crack formation. The objective was to capture key morpho-hydrological characteristics and statistics of precursor events preceding rainfall-induced shallow landslides.

Set-up

Wet or dry sand or soil filled a 20x40x100 cm box. Four acoustic emission sensors with peak sensitivities of 70 kHz and 3 tensiometers were located at the bottom of the box to continuously record acoustic emissions and matric suction. A high-speed video camera recorded images of the top surface at rates of 200-500 frames per second. The top surface of the material was convex and tapered toward one end of the box. A motor lifted the other end of the box to an inclination of 30-40 degrees. A sprinkler delivered the equivalent of 50 mm/hour until failure of the material occurred. Three-dimensional surface laser scans were captured before and after failure to estimate morphological characteristics and failed volume.



Failure morphology of sand in tilt-box experiments. (a) Before failure, (b) failure with 5% volumetric water content (w.w.c.), (c) 15% v.w.c., and (d) 20% v.w.c.

Experiments

We carried about 20 experiments with medium sand or a loamy soil to explore the effect of initial water content, compaction, and tilt angle on the morpho-hydrological characteristics of small landslides. For sand, initial volumetric water content varied between 0 and 20%. For soil we used 20% volumetric water content. The soil was first sieved and only aggregate fraction greater than 10 mm was retained. Material was deposited in the box in layers and hand compacted. Initial tilt angle before sprinkling varied between 30 and 40 degrees.

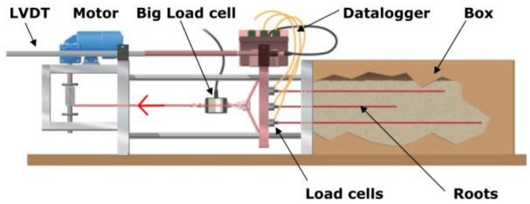
Data availability

Data can be obtained by contacting Denis Cohen (see below)

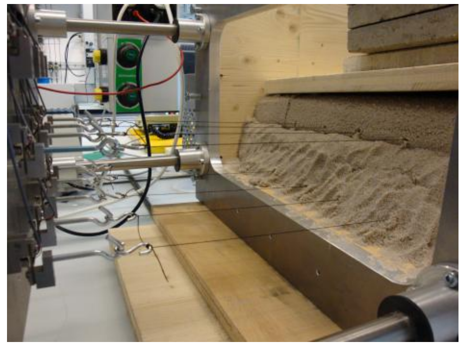
Contact

Denis Cohen, Soil and Terrestrial Environmental Physics (STEP), ETH Zurich, Universitätstrasse 16, 8092 Zürich, denis.cohen@env.ethz.ch

Lab-experiment mechanics of roots



Pullout machine. In red are evidenced the parts which are pulled.



Pullout experiment with cotton fibers in sand.

Objective of the experiment

The primary objective of this study is to quantify parameters controlling root bundle mechanical behavior by means of field and laboratory measurements. Experimental data obtained by these measurements are used for calibration and validation of the Root Bundle Model.

Set-up (sensors, constructions)

We designed a novel apparatus to collect data on the pullout behavior of a root bundle in the lab or in the field. The apparatus is capable of measuring simultaneously the pullout forces and displacement of each single elements of the bundle. It runs displacement controlled experiments and can pull up to 13 roots/fibers simultaneously. The pullout apparatus consists of a rigid structure (400 x 600 x 800 mm) where a rigid plate (400 x 600 x 25 mm) moves along four parallel guides with a circular cross section (diameter 30 mm). On the stiff plate we installed 13 load cells (Omega engineering, LCL-040) to which individual roots/fibers are attached. The load cells were connected to a data logger which collected forces and displacement data every second. The displacement of the plate was measured using a LVDT (SigmaEpsilon, AS-630), which has a linear accuracy of 0.3%. The plate was pulled with an electric motor positioned at the back of the machine. The pullout apparatus was designed and constructed to remain stiff with negligible internal elastic deformations. The friction of the plate on the four guides during the experiments varied between 20 and 60 N for a pulling velocity of 0.44 mm/sec. The variation in friction depends on the asymmetry of load due to the irregular distribution of roots on the plate that causes a turning moment on the four guides of the plates. The tested roots or fibers were embedded in a soil within a wooden box or in a natural soil profile. In the field the roots prepared on a face of soil profile were attached directly to the plate of the machine, whereas in the laboratory experiments the roots/fibers were prepared in a soil-filled horizontally-oriented box.

Experiments

Laboratory experiments consisted of three types of tests. First, we used cotton fibers in wet or dry sand in order to investigate the influence of tortuosity and branching points on the global pullout behavior of each individual fiber. The tortuosity was established by laying the fibers in a prescribed zig-zag shape, formed 200 mm segment lengths at 90° angles. The branching points were simulated by crimping a 4 mm diameter fishing lead bead at 200 mm interval along the fiber. The second type of tests consisted of straight root segments which were pulled out from sand or soil under different moisture and confining pressure conditions. This type of tests aims to quantify the root-soil friction in different conditions, verifying how it changes in function of soil moisture. Finally, we tested real roots in soil by changing parameters like tortuosity and branching points. In this later type of experiment we eliminated the influence of the branching points cutting the lateral branched roots and polishing the branching point. With these experiments we provide a basis for models estimating root reinforcement in vegetated slopes.

Data availability

All the raw data can be requested from Schwarz M. and are available as ascii files.

Contact

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Main results

In the following section, the main results and lessons learned from the different sub-projects of TRAMM are summarized. For more details on the results we refer to original publications in national and international journals.

The Rüdlingen Experiment - Landslide triggering by artificial rainfall: hydrological aspects

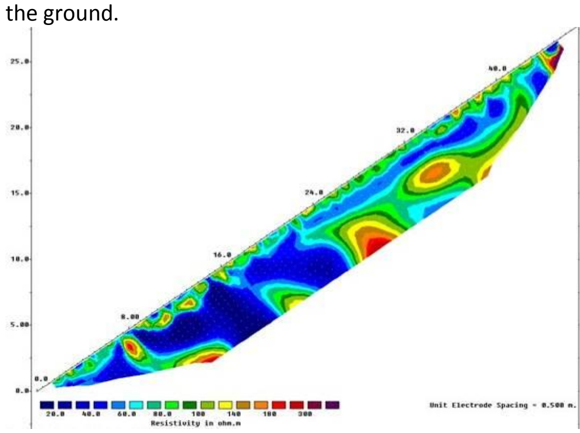
***Summary*: The purpose of this project was to trigger a rainfall induced landslide. Slope failure may be triggered by saturation of the ground, which leads to increase of weight and decrease of frictional resistance. Hence, saturation and drainage characteristics of the experimental slope were closely monitored, as they may exert significant control on the prevention or triggering, as well as the shape, of the failure mechanism. In a first monitoring experiment in October 2008, a total of 1.7 m of rainfall, calculated as an average over the slope area, was supplied over 3.5 days. The degree of saturation of the ground was determined from measurements and some deformations were measured, but there was no failure event. A follow-up experiment in March 2009, with an optimised sprinkling layout, resulted in slope failure that mobilised 130 m^3 of soil after 25 cm rainfall in 14 hours of sprinkling. The experiments allowed detailed insight into how the hydrological response influenced the deformation of a slope during extreme rainfall.

Methods

A detailed description of the instrumentation can be found above, see "Rüdlingen (SH) - Landslide triggering by artificial rainfall".

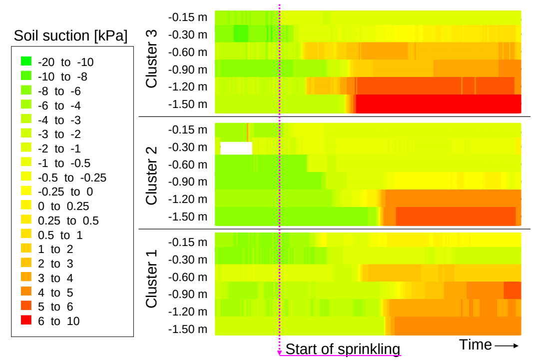
Important results

Time-lapse ERT-monitoring was carried out, every hour, along a transect on the experimental slope to visualize the temporal development of saturation of the ground.



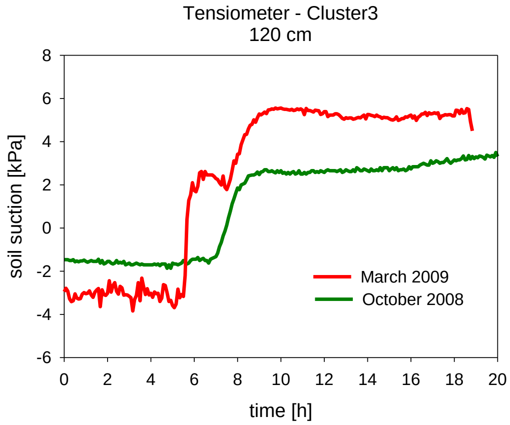
Results from time-lapse ERT-monitoring to visualise the saturation of the ground.

Tensiometer measurements of soil suction at different depths and locations (Cluster 1 to Cluster 3) showed the development of positive pore pressures in the subsoil above the Molasse bedrock during the triggering experiment in March 2009. Highest pore pressures occurred in the upper part of the slope (Cluster 3).

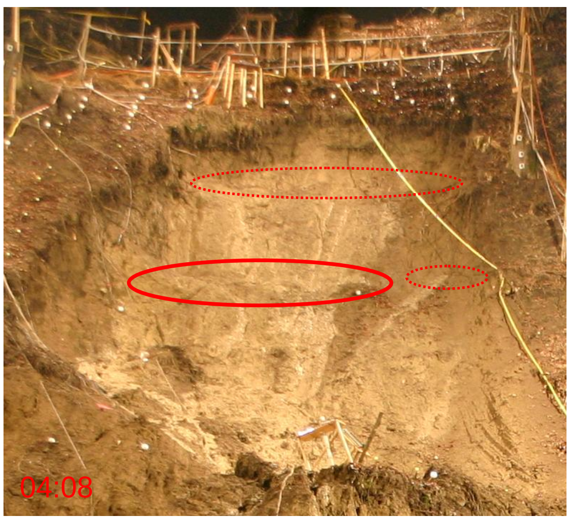


Results from tensiometer measurements during the landslide triggering experiment in March 2009. Green colours indicate high soil suctions, red colours indicate positive pore pressures.

In comparison with the first experiment, higher pore pressures were achieved during the follow-up experiment in March 2009 that resulted in slope failure. It can be concluded that the optimised sprinkling layout enabled higher pore pressures through the development of a perched water table and of lateral subsurface flow above the Molasse bedrock. These are indicated by water level readings in piezometers as well as post-failure observations of subsurface water flow at the failure surface.



Comparison of tensiometer readings at the same location during the two different experiments in October 2008 (green) and March 2009 (red).



Post-failure observations of subsurface water flow at the failure surface at three different locations (red ellipses).

Major outcome

The experiments allowed detailed insight into the hydrology and deformation of a slope during extreme rainfall. Further analysis and interpretation of this unique data set will lead to an improved understanding of triggering mechanisms as well as of hillslope hydrology and the interrelation between them.

Contact

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The Rüdlingen Experiment - Landslide triggering by artificial rainfall: geotechnical aspects

***Summary*:** The twentieth century is notable for a number of catastrophic landslides induced by rainfall in many parts of the world, including Switzerland. They are often devastating, causing many casualties and significant damage. A 38° steep slope has been chosen in Ruedlingen in Canton Schaffhausen, North Switzerland to carry out an artificial rainfall experiment to investigate the mechanisms of triggering and pre-failure behaviour of the slope in hydrological, and geotechnical terms. The initiation and propagation of the slip surface(s) has been studied. A three dimensional model of the ground properties was developed from non-invasive geophysical surveys, insitu probing, combined sprinkling and dye tracer tests and shallow test pits. Laboratory tests were carried out on undisturbed samples under various degrees of saturation. A sprinkling experiment was carried out on the heavily instrumented slope in autumn 2008. This test was followed by a triggering experiment in spring 2009, which mobilised about 130 m3 of debris.

It can be concluded from these two sprinkling experiments that a combination of unsaturated properties of the soil in terms of shear strength and permeability, geological and hydrogeological characteristics of the region, and the existing vegetation determines the stability of a slope subjected to a heavy rainfall.

Methods

See above "Rüdlingen (SH) - Landslide triggering by artificial rainfall".

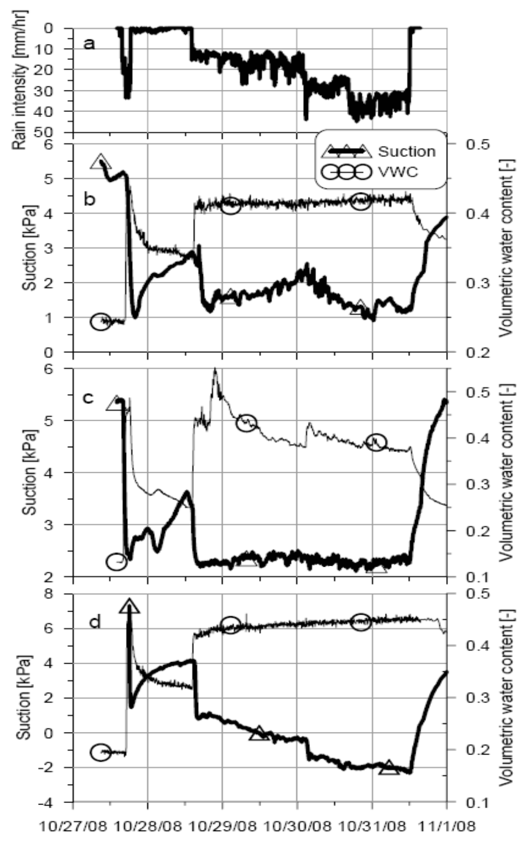
Important results

a) Insitu measurements of water content and pore pressure

The average applied rain intensity in the first sprinkling experiment is shown in the figure to the right. It also shows the variations of volumetric water content (VWC) and matric suction at three different depths of 30, 60, and 120 cm in the middle (cluster 2) and lower part (cluster 1) of the slope. After changes in the intensity of applied rainfall, the suction and volumetric water content measurements respond without significant time discrepancy at all 3 depths. This verifies the high infiltration capacity of the soil noted from the earlier hydrological investigations.

The changes in VWC and suction are not always contemporaneous during the second wetting phase of the rainfall. This can be due to either the hysteretic effect of the soil–water retention curve or the difference in the location of the sensors at each depth.

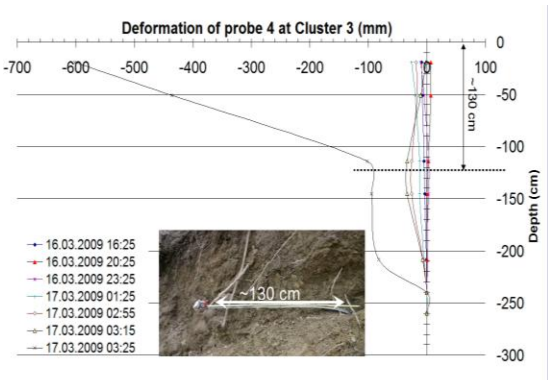
After stopping the rain, the VWC drops as the suction increases, but the suction increases in cluster 2 at a depth of 120 cm up to 2.5 kPa and the VWC starts to decrease only after this point. This point can be described as the air entry value of the WRC, which is consistent with the suction value derived from the laboratory test (s_{aev} = 2.7 kPa).



(a) Average applied rain intensity, (b) Variations of volumetric water content and matric suction in cluster 1 at depth of 60 cm, (c) cluster 2 at depth of 30 cm, and (d) cluster 2 at depth of 120 cm.

b) Monitoring of surface and subsurface movements
An aluminium deformation probe was developed in this project. It has a rectangular cross section of 40 X 2 mm. Several pairs of strain gauges were installed on the aluminium plate at predetermined spacings to measure bending strains. They were connected as “half bridges” to minimise the temperature effects. It is assumed that the deformation of that part of the plate on which one strain gauge is mounted forms a circular arc. The bending of the deformed plate can be calculated and the deformation curve will be derived by integration. Bending strains at different points and the inclination at the top of the probe are sampled at a frequency of 100 Hz.

The depth of the failure surface calculated from this approach is in good agreement with the field observations after failure.



Deformation of the probe and location of the failure surface.

Two slip surfaces can be determined by tracking changes in the shape of the deformed probe, one at the depth of ~50 cm and other at ~130 cm. Due to differences in the time and speed of propagation, these two surfaces have interactive effects on the behaviour of the deformation probe.

Comparing the results of the photogrammetrical analysis with the bending strain approach, it can be determined that the order of the magnitude of movements and the trends in changes indicate good agreement. However, the measured values are not exactly the same. This difference can be due to using different coordinate systems, and possible effects of the strain gauge cables and sealings at the upper and lower parts of the probe which can impose minor constraints against bending.

Major outcome

These experiments have provided detailed data of pore pressure changes, build-up of water table and soil movements in the slope at different stages during heavy rainfall events. Analysis and interpretation of these data, together with the geological and hydrogeological information from the region, and characteristics of root reinforcement, will deliver a clearer understanding of the triggering mechanisms of fast rainfall induced landslides.

Some novel techniques were used to monitor the slope failures, including the development of flexible deformation probes that can measure fast subsurface deformations over the bedrock. A network of these probes has provided detailed information about the location of the development and propagation of slip surface(s).

Another promising technique in monitoring the initiation of the movements was the use of acoustic emissions to detect accumulation of microscopic failure events that can lead to global slope failure.

Further reading

Askarinejad, A., Casini F., Kienzler, P., Springman, S. M., 2010. Comparison between the in situ and laboratory water retention curves for a silty sand. *5th International Conference on Unsaturated Soils*, Barcelona, Spain: in print.

Casini, F., Jommi, C., Springman, S.M. 2010. A laboratory investigation on an undisturbed silty sand from a slope prone to landsliding. *Granular Matter*, DOI: 10.1007/s10035-010- 0182-y.

Michlmayr, G K., Or, D., Cohen, D., Schwarz, M., Lehmann, P., 2008. Acoustic Emissions from Hydro-mechanical Perturbation of Natural and Artificial Slopes, *Eos Trans. AGU*, 89(53), Fall Meet.

Springman, S.M., Kienzler, P., Casini, F., Asakrinejad, A., 2009. Landslide triggering experiment in a steep forested slope in Switzerland. *17th International Conference of Soil Mech. & Geot. Eng*. Alexandria, Egypt: 1698 - 1701.

Tacher, L., Locher, D. 2008. Geological Characterization of the Buchberg field site (Ruedlingen). *Internal TRAMM report.*

http://www.cces.ethz.ch/projects/hazri/tramm/Field_experiments/Ruedlingen-field-site

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Role of bedrock hydrogeology for the occurrence of landslides

***Summary*:** The objective of this subproject is to estimate the effect of groundwater coming from the bedrock and water infiltrating into the bedrock to the triggering of shallow landslides. Where does such groundwater build up pore water pressure from below of the landslide? Can we locate a preferential water flow path in the bedrock or springs in the area of the landslide? Which type of bedrock favors exfiltration/infiltration? The bedrock at the Wiler experimental site showed to be extremely permeable preventing the build-up of a water table in the soil. In the area of the Rüdlingen landslide triggering experiment permeable and partly saturated sandstone layers are outcropping. Nevertheless, for the experiment, they played a minor role. At the second study site, the Rufiberg slope in the Canton of Schwyz, there is evidence for local water circulation in the fractured conglomerate bedrock and extruding under pressure during heavy rainfall events. Studies are going on to locate such groundwater containing layers and to measure the groundwater water level in boreholes as a basis to calculate the porewater pressure distribution in the slope.

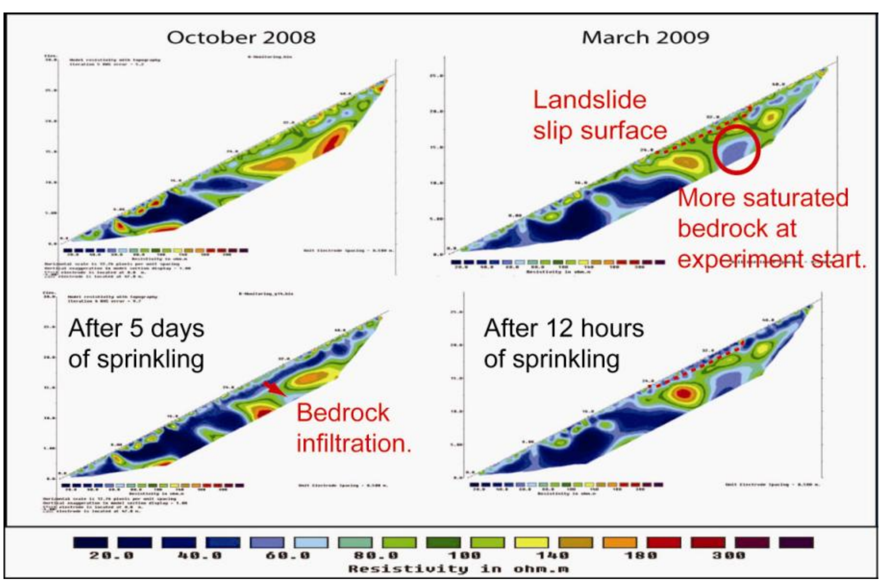
Left side: Ice indicates sandstone layers in whose groundwater is circulating (Rüdlingen). Right: Conglomerate with large joints in which water is circulating (Rufiberg).

Methods

A 23 m deep borehole was drilled at the top of the Rüdlingen experiment and equipped with pore water pressure sensors. Piezometric and Electrical Resistivity Tomography (ERT) monitoring during the sprinkling shed light on the soil saturation and water infiltration into the bedrock. Springs around the landslide and in the slip surface were mapped to locate groundwater exfiltration. At Rufiberg, the flux of a spring is measured and compared with natural precipitation. ERT profiles were performed before and after wet periods and piezometers will be installed at the interface between the bedrock and the soil in order to measure groundwater pressures.

Important results

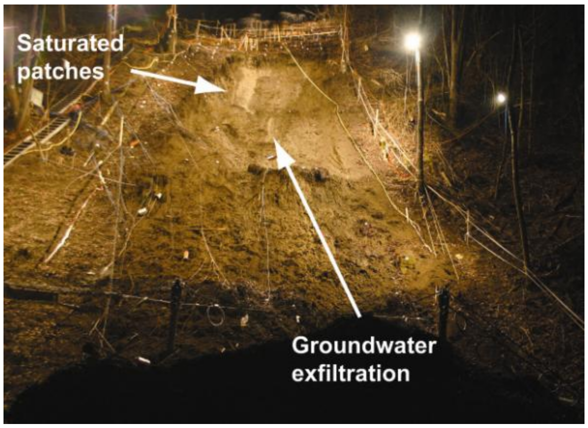
The ERT profiles from Rüdlingen and Wiler, canton of Vallis (third experiment site of TRAMM), showed, that during the sprinkling experiments, water was infiltrating into the bedrock. The water efflux immediately after the slope failure was clearly visible.



Electric Resistivity Tomography profiles of the experiment slope in Rüdlingen before and after sprinkling. Blue color means low resistivity, thus more saturation of the soil/colluvium and bedrock. We can observe, that after the sprinkling, the soil (1-2 m depth9 was more saturated and part of the water was infiltrating into the bedrock.

Major outcome

For landslide studies, the bedrock should not be assumed to be an impermeable model boundary. On one hand, the presence of groundwater and springs in the near surface bedrock may build up pore water pressure from below and favor the triggering of shallow landslides. On the other hand, water may infiltrate into the bedrock and prevent the triggering of landslides.



Artificially triggered landslide, Rüdlingen: after the triggering, sprinkling water which was trapped in the weathered sandstone was extruding.

Further reading

http://geolep.epfl.ch/page27704.html

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Root reinforcement

***Summary*:** The objective of this subproject was to develop a new model for the quantification of root reinforcement in vegetates hillslope and implement it in a framework for the simulation of the triggering mechanisms of shallow landslides. We included the effects of root geometrical and mechanical parameters into a numerical fiber bundle model that describes the mechanical dynamic pullout behavior of roots embedded in a soil matrix during strain-controlled deformation. The model strikes a compromise between complexity arising from root-soil interactions and oversimplifications of previous models by judicious selection of a minimum number of parameters needed to describe key features of the geometry and mechanics of pulled roots. The laboratory experiments (described in section 4) were used to calibrate the RBM that was later validated using six field-measured natural root bundles of spruce (*Picea abies* L.). These tests demonstrate the progressive nature of root bundle failure under strain-controlled pullout force and provide new insights regarding force-displacement behavior of root reinforcement, highlighting the importance of considering displacement in slope stability models. The force-displacement relations characterized in this study are fundamental inputs for the quantification of force redistribution on vegetated slopes and may provide explanation for abrupt loss of strength and landslide initiation.

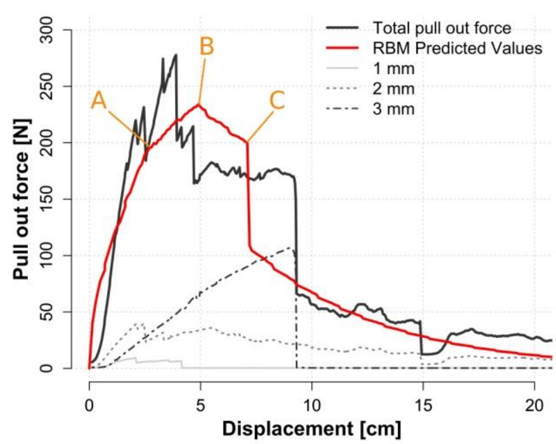
Methods

We developed a detailed model for quantitative description of mechanical behavior of a bundle of roots under strain-controlled mechanical forcing. The Root Bundle Model (RBM) explicitly considers typical values of root-size spatial distribution (number and dimension of roots), geometric factors (diameter-length proportion, tortuosity, and branching characteristics), and mechanical characteristics (tensile strength, Young's modulus) and interactions under various soil conditions (soil type, confining pressure, and soil moisture). The model considers how a bundle of lateral roots of different diameters contributes to the global reinforcement at different strain increments during the failure of a shallow landslide.

The model is built on a hierarchy of sub-models [Schwarz et al., 2010]: (1) a detailed description of the geometry and mechanics of individual roots; (2) a root frequency-size distribution model; (3) a strain-controlled pullout model of a bundle of roots that includes the effects of root elongation, root-soil friction, and root failure.

Important results

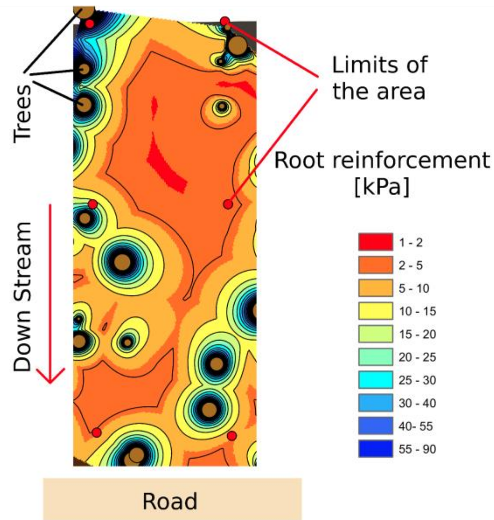
The simulations with the RBM of the mechanical behavior of the root bundles tested in the field show a nice prediction of the main characteristics of the root reinforcement (see figure). The global pullout of the root bundle exhibit a continuous increase in the first part of the force-displacement curve until the first root (or class of root diameter) breaks or slips out (point A in figure). In many cases it is possible to observe the presence of multiple peaks before the pullout force start to decrease gradually (point B in figure). The breakage of a class of roots, which dominates the bundle, may result in an abrupt decrease in pullout forces (point C in figure). The high variability in the behavior of individual roots may strongly influence the global behavior of a root bundle with a limited number of roots. The application of the RBM allows for a more realistic quantification of maximal root reinforcement and provides an indication of the stress-strain behavior of root reinforcement. The results of this study highlight the importance of two mechanical variables for slope stability calculations: a) displacement and b) variations in root reinforcement as a function of displacement.



Pull out forces versus displacement of the experiment N°1, showing the global behaviors versus the model behaviors and the single roots behaviors. The orange capitol letter indicates the three failure phase which are determined by the failure of the three class of root diameter (A = 1mm, B = 2 mm, C = 3 mm).

Major outcome

We have shown that previous formulations of safety factor calculation with infinite slope approach that consider lateral root reinforcement as a cohesion term added to soil intrinsic cohesion, clearly overestimate slope stability because these two components of the stabilizing force are activated at different displacements, hence can not be simply additive. Moreover, our results confirm that lateral root reinforcement may play an important role in the stabilization of small shallow landslide and that a realistic implementation of root reinforcement in a slope stability calculation is possible only with a spatial resolution at the single tree scale. The application of the RBM allows for complete description of root reinforcement evolution from progressive to abrupt failure, hence links root mechanical behavior with triggering mechanism of shallow landslide in vegetated slopes.



Spatial distribution of maximal root reinforcement in the study area in Ruedlingen.

Further reading

Schwarz, M., F. Preti, F. Giadrossich, P. Lehmann, and D. Or 2009. Quantifying the role of vegetation in slope stability: A case study in Tuscany (Italy). *Ecological Engineering*, 36: 285–291.

Schwarz, M., P. Lehmann, and D. Or. 2010. Quantifying lateral root reinforcement in steep slopes – from a bundle of roots to tree stands. *Earth Surface Processes and Landform*. 35(3): 354-367. doi: 10.1002/esp.1927.

Schwarz, M., D. Cohen, and D. Or. In press. Soil-Root Mechanical Interactions During Pullout and Failure of Root Bundles. *J. Geophys. Res.*, (in press).

Schwarz, M., D. Cohen, and D. Or. In review. Pullout tests of root analogs and natural root bundles in soil - experiments and modeling. *J. Geophys. Res.*, (in review).

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Geomechanical prediction of slope failure

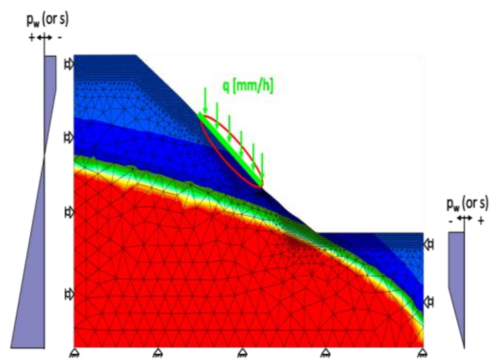
***Summary*:** The hazard analysis is one of the main steps in the risk assessment process. Regarding the hazard of slope failure and landslide triggering, one needs to evaluate the probability of the slope instability to occur. A quantitative assessment of the intensity of the eventual landslide is also required. Our capabilities of prediction lie upon better understanding of the physical processes involved in landslide triggering. The quantity of water entrapped in the soil is one of the key factors driving the slope instability. The analysis thus relies on the concepts of unsaturated soil mechanics.Taking explicitly into account the effects of the evolution of water content and capillary pressure within the slope helps dealing more accurately with phenomena such as the effect of rainfall infiltration on slope stability and the acceleration of slow-moving landslide. Hence, landslide physics require a description that goes beyond the conventional concepts of stability in soil mechanics. The developed numerical tool, using finite element discretization, offers a comprehensive understanding of both the hydraulic processes and stress-strain behaviours by the means of advanced hydro-mechanical couplings. As a consequence, the modelling tool can deal with any landslide geometry, provided that the geological, geotechnical and hydraulic information is available. In conclusion, the main objectives of the presented subproject were (i) to improve the modelling of mechanisms within unsaturated soils and (ii) to show the added value of such an approach in landslide triggering analysis. The practical hydro-mechanical modelling tool was applied to the TRAMM instrumented field case of landslide triggering.

Methods

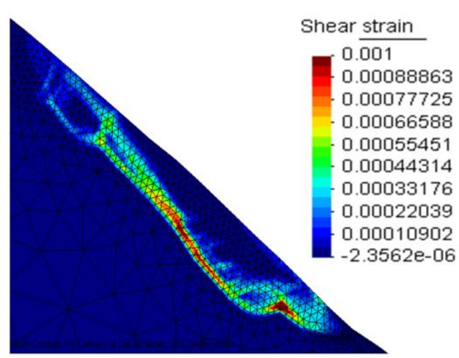
The analysis comprises three main aspects: A new geomechanical model, including a dependency on the hydraulic processes, has been developed. The model parameters have been determined by the means of laboratory tests carried out on samples taken from the field sites. The finite element method has been employed to enable the spatial and temporal discretization of land-slides problems.

Important results

The figures to the right show typical results obtained with the proposed model. On the one hand, it is possible to model the infiltration process within the soil mass resulting from the rainfall at the surface, and hence to predict the content of water and pore pressures. Simultaneously, the numerical tool computes the deformations induced by the changes in moisture, which provides information on the localization of the maximum deformation (sliding plane(s)).



Contours of saturation at the initialization of the calculation. The red map indicates full saturation.



Localization of the shear strains during the infiltration phase (prediction – Rüdlingen case)

Major outcome

A new tool for the numerical simulation of landslides has been developed in the frame-work of the sub-project. The tool enables to visualize the processes of deformation occurring during the change of pore pressure and water content. The simulations also provide a better insight into the localization of the maximum deformations which are characteristic of the failure surface.

Further reading

Nuth, M., Laloui, L. "Advanced hydro-mechanical coupling for unified constitutive modelling of unsaturated soils", Proc. of the First European Conference on Unsaturated Soils, Durham, 2nd-4th July 2008.

Nuth M., Laloui L., "Advances in modelling hysteretic water retention curve in deformable soils", Computers and Geotechnics, vol. 35, num. 6, 2008, p. 835-844.

Laloui L., Nuth M., "On the use of the generalised effective stress in the constitutive modelling of unsaturated soils", Computers and Geotechnics, vol. 36, num. 1-2, 2009, p. 20-23.

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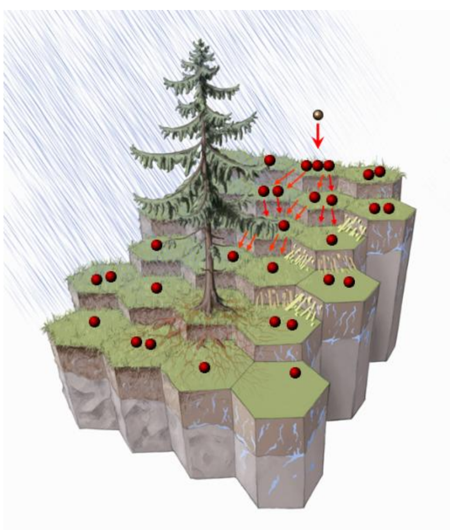
Concept of Self-Organized Criticality applied for modeling initiation of landslides

***Summary*:** Shallow landslides are rare events occurring in case of unfavorable combination of high water loads, weak mechanical forces and local failure that may culminate to hazardous mass release. To model such 'accident' we must incorporate spatial distribution of water, stress and propagation of local failure. In this subproject we combined a hydro-mechanical hillslope model with concepts of Self-Organized Criticality to describe landslide triggering. A hillslope is modeled as composite of many interacting elements that may break due to high water loads. Such 'local' perturbation can propagate across the entire system culminating to global failure (landslide).

Methods

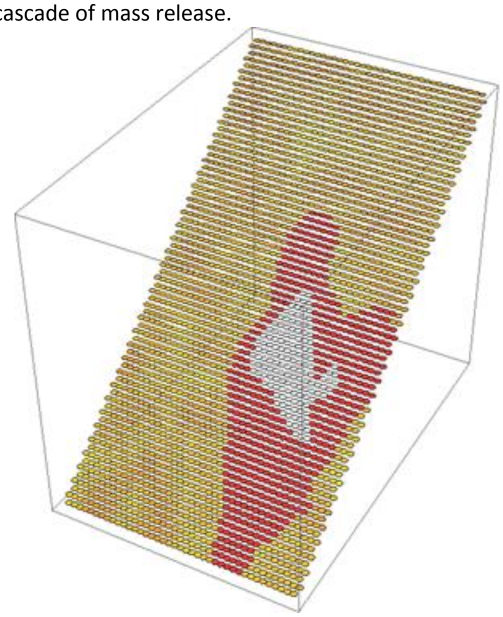
The concept of Self-Organized Criticality (SOC) was introduced by Bak et al. (1987) to reveal that complex and critical system behavior can emerge from simple interactions of many connected elements. They modeled a growing sandpile determining the number of 'sand avalanches' when adding randomly an additional particle to the pile. In this subproject we translated the SOC concept to a model of landslide triggering. The figure below indicates the relationship between landslide triggering and SOC models.



Schematic of SOC concepts applied for modeling landslide triggering. A hillslope is modeled as network of soil volumes with hexagonal cross-sections connected by mechanical bonds (fiber bundle model, Cohen et al. 2009). During intense rainfall events, water loads (red balls) are added to the slope. At certain spot (incoming black ball) water load exceeds the mechanical strength of an element and its load is redistributed in a cascade of failure events.

Important results

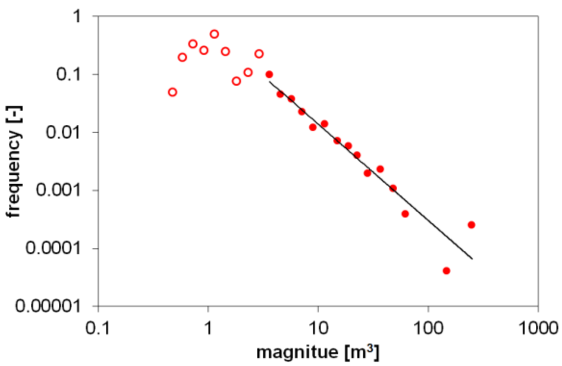
To model load redistribution based on SOC concepts we must understand where and when local perturbations occur. Local perturbations are related to high water loads and weak mechanical strength. Our model incorporates simulation of water distribution within the slope and its effect on mechanical forces. When driving forces exceeds friction and cohesion at the base of a soil element, it can be stabilized by intact neighbors. In the figure below a failure pattern for wet slope is shown. When stress on soil element becomes too high it fails entirely destabilizing upslope region and initiating a cascade of mass release.



A landslide (white) of about 100 m^3 computed with model based on SOC concept for a system of 40 x 60 m with slope angle 45˚. Red cells with unfavorable factor of safety are stabilized by cells in the neighborhood.

Major outcome

The model based on SOC was applied to analyze landslide triggering in slopes of different geometry and soil properties. As shown in the figure below the model reproduces power-law relationship between landslide size and frequency that is documented for various landslide inventories.



Size (magnitude) and frequency of modeled landslides for loamy soil with power-law relationship valid for large landslides. Similar statistics are reported for landslide inventories.

By characterizing mechanical connections between soil elements and at soil-bedrock interface with fiber bundles, it is possible to simulate occurrence and propagation of local failures before a slope element is released and will help to interpret measurements of precursor events for example by acoustic emission.

Further reading

Bak, P., Tang, C., and Wiesenfeld, K, 1987. Self-organized criticality: an explanation of 1/f noise, *Physical Review Letters*, 59 (4), 381-384.

Lehmann, P., and Or, D., 2010. The role of Self-Organization on triggering of shallow landslides (in preparation).

Cohen, D., Lehmann, P., and Or, D., 2009. Fiber bundle model for multiscale modeling of hydromechanical triggering of shallow landslides, *Water Resources Research*, 45, W10436.

http://www.step.ethz.ch/research/active-research-project/landslide-triggering

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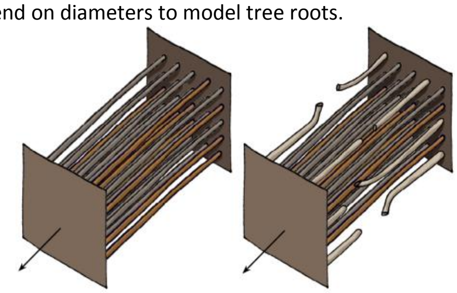
Fiber bundle models for snow avalanches and landslides

***Summary*:** We developed new fiber bundle models for snow avalanches and landslides. Using concepts of statistical fracture mechanics of disordered media, fiber bundle models can describe the progressive failure of highly heterogeneous materials such as snow and soils. Bundles of fibers are used as analogs of snow grains in a weak layer, soil particles and associated binding elements in a soil, or tree roots on a slope. Through various combinations of fiber rheology and fiber strength distribution, fiber bundle models can describe the brittle to ductile transition in snow and soils, model the progressive failure of root bundles, estimate root reinforcement and root failure dynamics for rooted soils on slopes, and predict time and location of failure for rainfall-induced landslides in shallow unsaturated soils. Comparisons of model results with data are promising but more data are needed to validate concepts and apply the fiber bundle model to real-case mass failures.

Methods

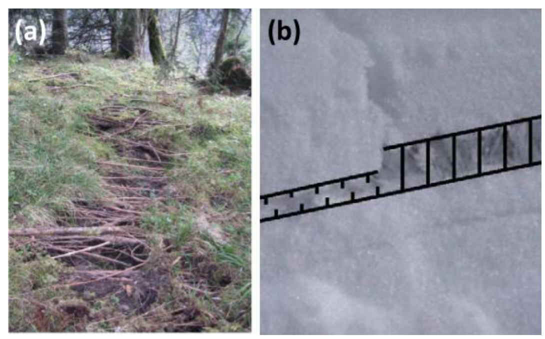
Fiber bundle models (FBM) were used to describe various aspects of triggering of rapid mass movements, from soil and snow rheology, to root mechanical reinforcement, to prediction of time and location of hydrologically-triggered landslides. FBM are statistical fracture models that can describe the progressive failure of a heterogeneous material like snow or soil. The basic model consists of a set of elastic-brittle fibers whose strengths are drawn randomly from a probability density function. Fibers are then pulled between parallel plates. Fibers represent roots in soil, single snow grains in a weak layer, cement, water, or biological bonds between soil particles, or frictional contacts between grains. Loading of the bundle causes weak fibers to break and load redistribution among surviving fibers can trigger secondary, tertiary, and so on, failures, a process known as an avalanche. Avalanches exhibit power-law frequency-size distribution. In specific applications, fibers can heal to model snow sintering, fail plastically to model soils in shear, or have lengths and elastic moduli that depend on diameters to model tree roots.



Bundle of fibers loaded in tension between two rigid plates.

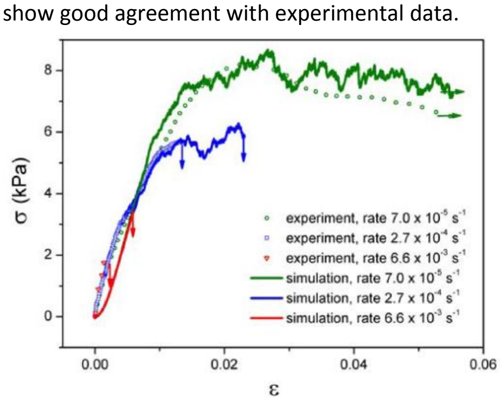
Important results

Snow: Dry-snow avalanches initiate from the failure of a weak snow layer. The failure behavior of snow is highly rate dependent and snow is considered a highly disordered



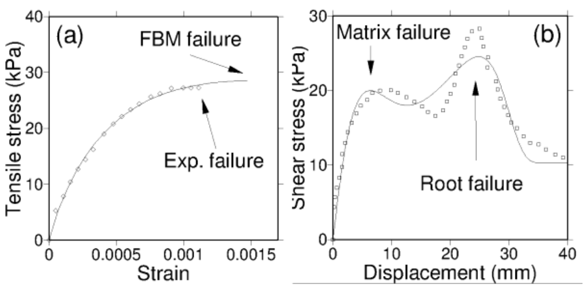
Roots stretched across a tension crack. (b) Buried surface hoar layer with fiber bundle representation. Layer is fractured on the left and intact on the right.

material. On a microstructural level, the failure process is believed to start if the fracturing of bonds between snow grains is greater than the formation of new bonds. Using fibers with different characteristic times for breaking and sintering, the strain-rate dependence of snow strength can be modeled and the ductile-to-brittle transition reproduced. FBM results of stress-strain curves for different strain rates show good agreement with experimental data.



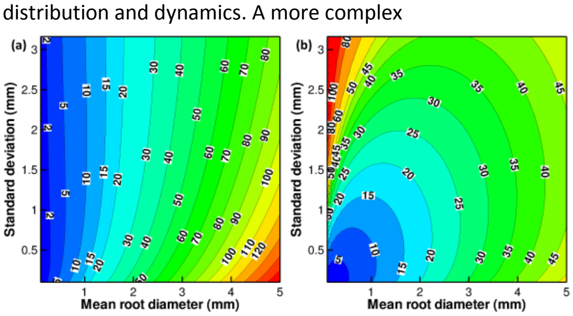
Comparison of stress-strain data for snow at different strain rates with FBM.

Soil: Using a combination of brittle and plastic fibers, the fiber bundle model can reproduce the rheological behavior of soils under tension and in shear, and of rooted soils. FBM results are obtained by fitting experimental stress-strain data to analytical expressions for stress-strain using a Weibull distribution of fiber threshold strength. Some parameters such as a fiber elastic modulus and fiber strength distribution (heterogeneity) can be extracted directly from data and thus are not fitted parameters. The representation of soil behavior with the FBM allows us to describe soil deformation in terms of failure of individual soil elements (aggregates, water bridges, biological binders and cements) and seamlessly simulate the brittle-to-ductile transition. In the future, it may be possible to predict soil bulk behavior from the deformation and failure of its individual components with the fiber bundle model.



Comparison of stress-strain data with FBM for (a) a soil in tension, and (b) a rooted soil.

Roots: Fibers are obvious analogs of tree roots. We developed two fiber bundle models of roots that include the effects of root diameter on root length, elastic modulus, and threshold strength. In a first model, neglecting root-soil interactions, an analytical expression for the pullout force as a function of displacement for a bundle of roots was obtained and results compared with field and laboratory pullout tests. Maps of maximum reinforcement and displacement at maximum reinforcement highlight the importance of diameter distribution and dynamics. A more complex



(a) Root reinforcement in kPa and (b) displacement in mm at maximum reinforcement as a function of mean root diameter and diameter standard deviation for 1000 roots of spruce.

numerical fiber bundle model (the Root Bundle Model) that included root-soil interfacial friction, root slippage, soil moisture, root tortuosity, and branching points was also developed to analyze pullout tests under various soil type and moisture conditions. Experimental and model results show that maximum root reinforcement of basal and lateral roots should not be added because not all root strengths are mobilized together at a particular displacement. Thus, previous root reinforcement models usually overestimated root reinforcement. Both fiber bundle models explicitly estimate root reinforcement as a function of displacement, an important parameter for slope stability calculations of rooted soils.

Hydrologic triggering: Hydrologically-triggered shallow landslides can fail when soil strength is reduced during water infiltration in shallow layers because soil constituents such as aggregates, water capillaries, and other binders become weaker with increasing water content. To model such water-induced weakening, the strengths distribution of fibers in the FBM can be made to depend on water content. Combining this effect with a model of time-dependent infiltration allows the estimation of the time to failure and the depth of failure.

Major outcome

Because they can describe progressive failure and heterogeneities, fiber bundle models are effective tools to simulate triggering of rapid mass movements such as snow avalanches and landslides. To our knowledge, we have developed the first fiber bundle models that: (1) describe the brittle to ductile transition in snow and the rheological behavior of soils; (2) include root geometrical and mechanical properties to estimate root reinforcement and dynamics; (3) predict time to failure of rainfall-induced shallow landslides.

Further reading

- Cohen, D., P. Lehmann, and D. Or. 2009. Fiber bundle model for multiscale modeling of hydromechanical triggering of shallow landslides, *Water Resour. Res.*, **45**, W10436, doi:10.1029/2009WR007889.
- Cohen, D., M. Schwarz, and D. Or. *In prep*. An analytical model of root reinforcement using a fiber bundle approach.
- Cohen, D., and D. Or. *In prep*. A fiber bundle model of landslides triggered by rainfall-induced soil weakening.
- Reiweger, I., J. Schweizer, J. Dual, and H.-J. Herrmann. 2009. Modelling snow failure with a fibre bundle model, *J. Glaciol.*, **55**(194), 997-1002.
- Schwarz, M., D. Cohen, and D. Or. 2010. Soil-root mechanical interactions during pullout and failure of root bundles, *J. Geophys. Res.*, in press.

www.step.ethz.ch/research/active-research-project/landslide-triggering

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Capturing precursor events of mass movements with acoustic sensors

***Summary*:** The objective of this subproject was to develop sensor systems to capture precursor events for two types of mass movements, namely landslides and snow avalanches. When deformed or broken, almost all materials emit elastic waves in the form of so called acoustic emissions. Some studies on hazardous gravitational processes, such as cliff collapses and landslides, suggest that an increase in acoustic emissions (AE) precedes major failure. If increased acoustic activity could be detected, such events might be used for better prediction of mass movements and early warning systems. The goal of this subproject was therefore to monitor acoustic emissions in snow and earth material (sand, soil). For snow avalanches an avalanche start zone was instrumented with an array of geophones. Acoustic signals were continuously recorded and a microphone as well as several cameras were installed to identify sources of background noise and avalanches. The seismic system has been in operation for two consecutive winters. Identifying signals originating from the snow cover is however very difficult due to the amount of background noise. The first large avalanche which released directly above the sensor array occurred on 22 February 2010 and was clearly recorded by the sensor array. However, no clear precursor signals were observed, suggesting that in snow low frequency precursors might not exist. The triggering of landslides is typically preceded by soil deformation, the occurrence of shear bands and soil micro-structure rearrangements – all of which release elastic waves. Acoustic emissions generated from such processes were investigated experimentally using a specially designed shear frame. During the onset of shear deformation a significant increase of acoustic events can be observed. Field tests showed that the use of waveguides is an effective measure to solve the issue of high attenuation of signals in earth material, which states a challenge especially for operational landslide monitoring applications.

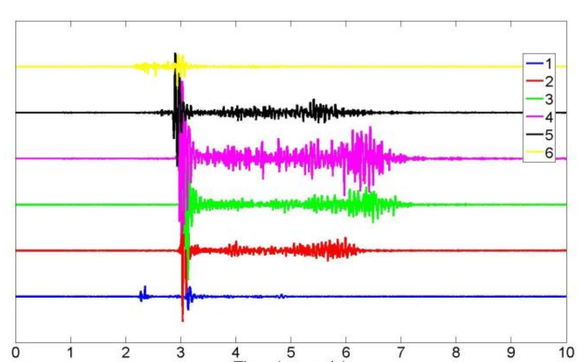
Methods

a) snow avalanches

A low power, high precision sensor array was developed to monitor acoustic emissions in an avalanche start zone. Given the high attenuation of elastic waves in snow, especially in the high frequency range low frequency seismic sensors were used.Since the nature of signals emanating from a natural snow cover was unknown, waveforms were continuously recorded at a sampling frequency of 500 Hz. The development of the sensor array was a significant technological challenge. After the deployment of a prototype system in March 2008 it became clear that additional observation methods were required to characterize background noise and to identify signals associated with avalanches. A microphone as well as several cameras were therefore installed during the winter of 2008-2009. The seismic sensor array has now been in operation for 2 full winters and vast amounts of data have been collected.

b) soil deformation

Acoustic emissions (elastic waves in the kHz range) in granular material were studied towards the imminence of failure. The aim was to link the occurrence of AE to progressive shear zone development in granular geo-material, such as soil or sand. To capture acoustic emissions piezoelectric sensors were placed into a specially designed shear frame, which permitted concurrent measurements of AE and forces during controlled shear. Single acoustic events were analyzed by their magnitude and shape. Occurrence frequency of events was evaluated as well as the distribution of event magnitudes at different stages of the tests.



Seismic signals associated with the release of a natural snow slab avalanche recorded by six geophones in the snow cover.

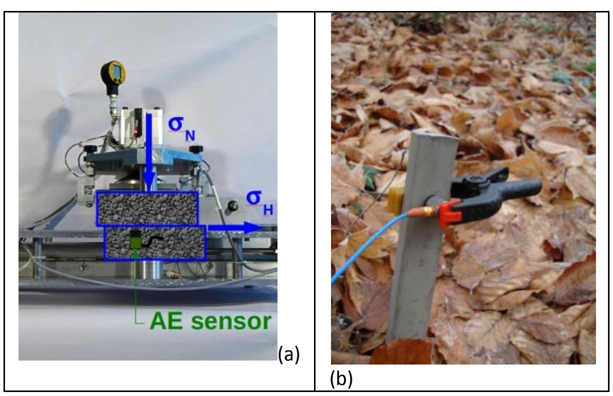
Important results

a) snow avalanches

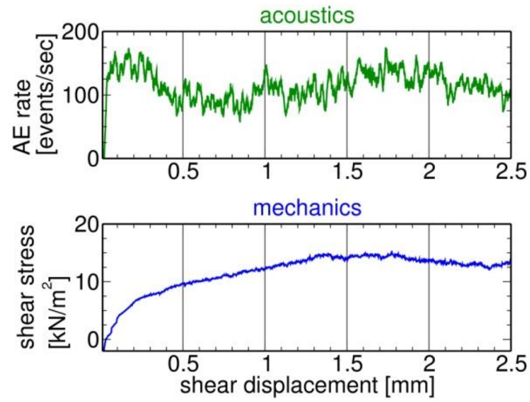
Preliminary analysis of the seismic data recorded on the avalanche start zone has shown that during the winter there are very little low frequency signals originating from the snow cover. Most all recorded signals were classified as background noise: airplanes, skiers, ski lifts, trains, animals, ect. Avalanches, on the other hand, are very well recorded by the seismic sensors and their distinct frequency content can be used to automatically detect these events. In the spring, on the other hand, many signals originate from the snow cover. These signals are very likely related to snow settlement, and are therefore of less importance for avalanche formation.

b) soil deformation

From shear tests with loose sand it was found that the occurrence of acoustic emissions is clearly related with shear deformation. Already small deformation is sufficient to trigger more than 100 signals per second. Results suggest that source mechanisms (frictional sliding, grain collisions) determine the shape of the corresponding acoustic signals: while frictional sliding of grains is presumably associated with low amplitude signals ("grinding"), collapse of highly stressed grain contacts and grain collisions produce signals with high initial amplitude ("bursting"). It was also found that signals are attenuated strongly by the granular material which states a major challenge for field application of this system.



A special shear box (a) was constructed to measure mechanical and acoustic properties of different granular geo-materials. (b) Acoustic sensor attached to a waveguide (a steel rod driven into the ground) for detecting sub surface deformation and slip plane development.



Measurements of acoustic emission event rate (number of AE events per second) and stress during a shear box experiment. A sudden increase of AE rate is visible already at the onset of shear.

Major outcome

We have developed a flexible, low power, high precision seismic sensor array which can reliably be used to continuously monitor acoustic emissions in a harsh environment. Preliminary analysis of data from an avalanche start zone suggests that the system can be used to automatically detect avalanches. However, precursor events to snow avalanches have thus far not been identified.

For monitoring of landslide prone slopes AE offer a promising possibility to complement existing measurement tools. Field tests showed that external noise sources (rain, ambient noise) can be canceled with a simple sensor casing. To overcome the issue of strong signal attenuation wave guides can be deployed.

Further reading

van Herwijnen, A.; Schweizer, J., 2008. Continuous monitoring of acoustic emissions in an avalanche start zone. Geophys. Res. Abstr. 10: 09762

van Herwijnen, A., Schweizer, J., submitted. Seismic sensor array for monitoring an avalanche start zone: design, deployment and preliminary results. Journal of Glaciology.

http://www.step.ethz.ch/research/active-research-project/landslide-triggering

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Spatial statistical modeling of shallow landslides

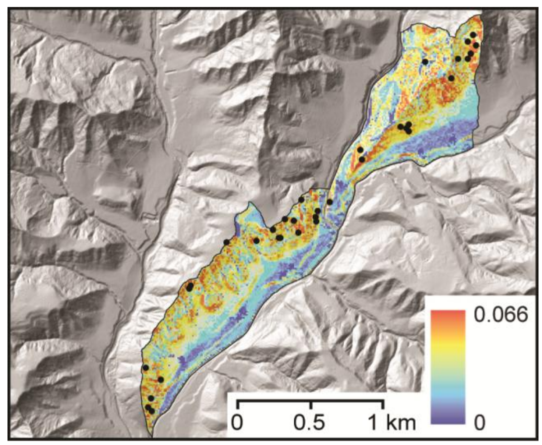
***Summary*:** Prediction of shallow landslides remains a difficult task because of our limited understanding of the triggering processes and insufficient information on the spatial distribution of relevant soil properties and rainfall patterns. Landslide susceptibility can be determined by statistical models based on the association of landslide occurrence with characteristic geomorphic features. In this subproject we used logistic regression to model landslide susceptibility. We analyzed data from an inventory of landslides triggered in Napf region after heavy rainfalls in 2005 (Napf 2005) and employed geomorphologic parameters deduced from digital elevation models. The model was validated for two other study areas with landslides inventories (Napf 2002, Entlebuch 2005). The validation of the predicted susceptibility with the observed landslide incidence showed that the statistical model successfully predicted zones prone to landslide release.

Method

We used three inventories with information about 132 shallow landslides to relate patterns of landslide occurrence to the spatial distribution of geomorphologic parameters. Eight attributes relevant for water flow and slope stability were computed from high-resolution digital elevation data and were tested with respect to their significance to explain observed landslide occurrence. We used logistic regression (Hosmer and Lemeshow, 2000) which is an established method to model binary data (landslide/no landslide) for the statistical analyses.

Important results

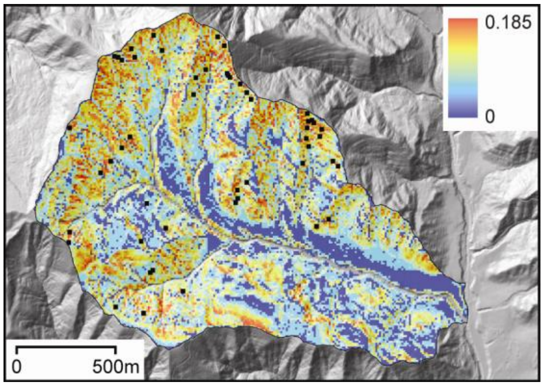
The logistic regression model was fitted for landslides triggered 2005 in Napf region (see Figure to the right). The selected model included the three variables slope, planform curvature (shape of contour lines) and vegetation type (forest or grassland). These three attributes are 'local properties' with values computed by analyzing the height of a pixel and its eight closest neighbors. Landslide susceptibility was high for steep slopes, negative curvature (converging water flow) and grassland lacking the reinforcing effects of tree roots. Other parameters (distance to flow paths, contributing area …) that depend on large scale properties of the study area were statistically not significant. The statistical model was then used to predict landslide susceptibility in two other study areas (Napf region, for a rainfall event in 2002; Entlebuch region for same rainfall event as Napf 2005). As shown in the figures on following page, the observed landslides occurred mostly in regions with high predicted susceptibility. In Entlebuch 2005 there is a tendency to over-predict landslide susceptibility, nevertheless all observed landslides lay in high susceptibility areas (red zones).

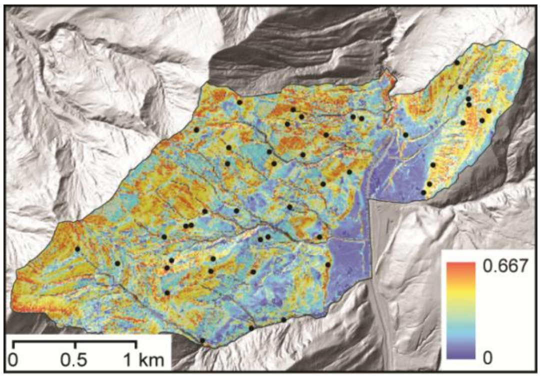


Landslide susceptibility map for study area Napf 2005 that was used to calibrate the logistic regression model. Black dots are the landslides triggered in 2005. Areas with high landslide susceptibility (red zones) are mainly located on steep slopes.

Major outcome

The best logistic regression model expresses landslide susceptibility as a function of slope angle, planform curvature and surface cover. Because these attributes are 'local properties', the model can be applied for other study areas with different large scale characteristics. While the predictions for both validation areas (Napf 2002 and Entlebuch 2005) identified correctly landslide prone areas, the prediction for the Napf 2002 area was better. This finding might indicate that similar geological and geomorphologic conditions are more important for landslide occurrence than the spatio-temporal patterns (rainfall intensity and duration) of the heavy rainfall event.





Susceptibility maps for the validation sets Napf 2002 (top) and Entlebuch 2005 (bottom), where black dots are the actual landslides and red color represent regions with highest landslide susceptibility.

Further reading

Hosmer, D. W., and Lemeshow, S., 2000. Applied logistic regression. John Wiley and Sons, New York, 375 pp.

Rickli, C., and Graf, F., 2009. Effects of forests on shallow landslides – case studies in Switzerland. Forest, Snow and Landscape Research, 82 (1), 33-44.

Von Ruette, J., Papritz, A., Lehmann, P., Rickli C., and Or, D., 2010. Spatial statistical modeling of shallow landslides – Validating predictions for different geologic formations and rainfall events. Geomorphology (in review).

Contact

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http://www.step.ethz.ch/research/active-research-project/landslide-triggering

Simulating debris flows in the laboratory

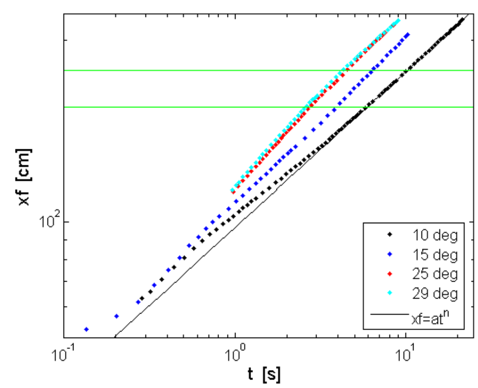
***Summary*:** The objective of this subproject was to gain physical insight into the dynamics of highly concentrated particulate flows by conducting "dam-break" experiments. The experimental setting is the idealization of debris flows involving saturated poorly consolidated materials. The dam-break experiment consists in releasing a fixed volume of material and tracking the subsequent motion. The experimental facility is made up of a flume and a reservoir, from which the material is released. Using high-speed cameras and special image processing techniques, we were able to measure the flow features (such as the flow depth profile over time) together with the flow inner structure (e.g., velocity and density profiles). In our experiments, the particle concentration was close to the maximum packing fraction and we observed that minutes changes in this concentration caused tremendous changes in flow dynamics. For concentrations in excess of a critical value (0.59 for our suspensions), stick-slip motion was observed (succession of resting and flowing phases), which confirmed the role of pore pressure. For lower solid concentration, the debris flow took the appearance of a highly viscous flow.

Methods

Flow visualization is essential to understanding how complex fluids organize when flowing in the form of a 'rapid' surge down a flume. Going inside the flow requires special techniques. First, the fluids had to be made transparent; we used PMMA particles mixed with various fluids to obtain transparent suspensions that looked like saturated granular soils. Second, particle imaging techniques were employed to measure the velocity (and perhaps density profiles) inside the flow, far from the sidewall. Additional sensors (bottom pore pressure, flow depth profile) were also used.

Important results

We found that the solid concentration is a key parameter that controls flow dynamics. For solid concentration in excess of a critical values (close to 0.59 with our suspensions), flow is unstable and characterized by stick-slip motion. This observation is consistent with Schaeffer and Iverson's theory [Steady and Intermittent Slipping in a Model of Landslide Motion Regulated by Pore-Pressure Feedback, *SIAM J. Appl. Math*. **69**, 769–786 (2008)] and shows how important the excess pore pressure is in causing material 'liquefaction'. For lower solid concentrations, we retrieved a viscous flow behavior, as documented by other authors [e.g., Bonnoit et al., Inclined plane rheometry of a dense granular suspension, *J. Rheol.* **54** 65-79 (2010)]. Some features are noteworthy. For instance, as reported on the figure thereafter, the front position scales as a power function of time, but the exponent (n = 0.41) differs from the value found for dilute suspensions (n = 1/3). The reason for this mismatch is still unclear.



Position of the front of a sliding mass of PMMA suspension as a function of time and for various flume inclinations in a log-log diagram.

Major outcome

The facility built within the framework of the TRAMM project is unique in that it allows to visualizing what occurs inside the flow (without disturbing flows). Although many teams in the world have conducted dam-break experiments with various flumes and materials, there is no other instance where both details of the inner flow structure (e.g., particle arrangement, velocity and density profiles) and bulk flow features (e.g., flow depth profile) can be measured at the same time. The experimental protocol was delicate to define, but after many trials and errors, we are now able to run experiments on the laboratory scale, which mimic the behavior of flows on larger scales, with the great advantage that a wealth of information can be measured in our setup.

Further reading

Ancey, C., S. Cochard, and N. Andreini, The dam-break problem for viscous fluids in the high-capillary-number limit, *Journal of Fluid Mechanics*, *624*, 1-22, 2009.

Wiederseiner, S., N. Andreini, G. Épely-Chauvin, and C. Ancey, Refractive index matching in concentrated particle suspensions: A review, submitted to *Experiments in Fluids*, 2010.

A paper is in preparation for the Journal of Fluid Mechanics.

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Debris flow erosion

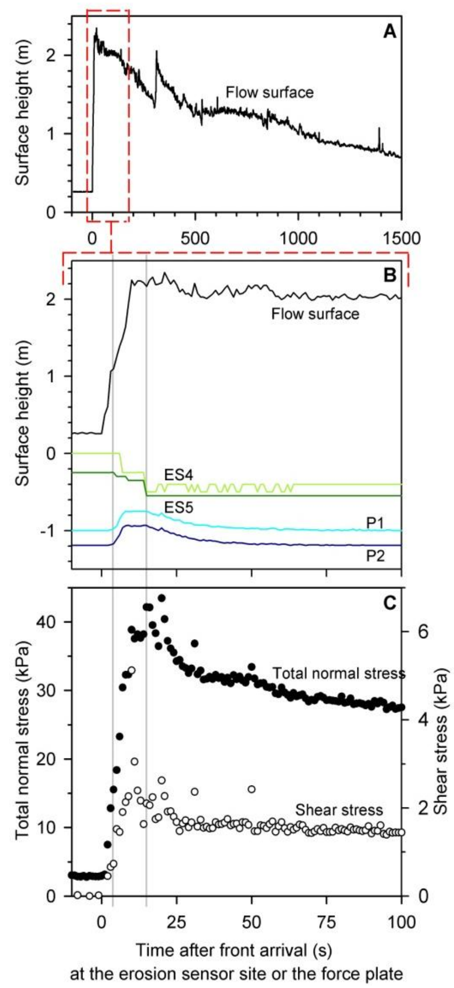
***Summary*:** Entrainment of sediment by debris flows is an important yet not well understood process. We investigated two aspects of entrainment at the Illgraben catchment, the details of the entrainment process using novel entrainment sensors, and the generation of sediment within the catchment. Within large debris flows, it was observed that significant entrainment occurs at the leading edge of large debris flows (within the first ~30 seconds), at the distal end of the fan. Sediment within the catchment was generated through bedrock landslides (volumes of up to several thousands of m^3), which were stored within the channel and mobilized by subsequent debris flows. Comparison of the volumes of the landslides or in-channel sediment deposits and the typical volumes of debris flows, which are typically an order of magnitude larger in volume than the landslides, clearly shows the importance of the entrainment process in generating large debris flows. Collectively the results confirm that debris flow entrainment should be considered in hazard assessment and mitigation.

Methods

Detailed measurements of the timing and magnitude of channel-bed erosion by debris flows were made at the Illgraben field site using novel erosion sensors developed within TRAMM. The data were compared with data on flow depth as well as normal and shear forces from a pre-existing force plate which is part of the Illgraben observation station. To explore larger-scale erosional changes, landscape change was measured through photogrammetric analysis of aerial images from Fall 2007, Summer and Fall 2008, and Fall 2009, and then compared with data on event volume from the debris flow observation station.

Important results

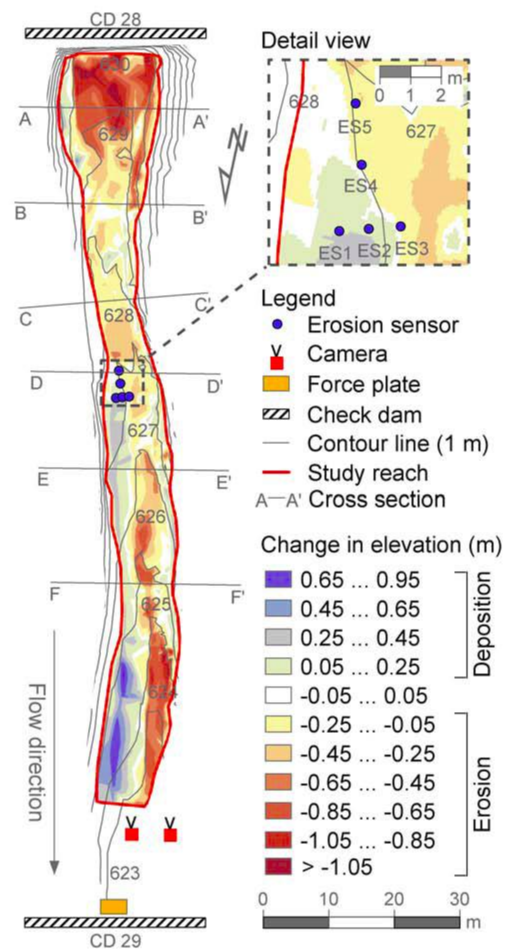
The timing and magnitude of channel-bed erosion were measured in 2008 at the erosion sensor site for three debris flows and four floods. During two debris flows erosion was detected at the leading edge of the flow within 10 to 20 s after front arrival and before maximum flow depth, shear and normal stress, measured nearby, were reached (see figure to the left, data from the largest debris flow). Coincident changes in fluid pore pressure were observed at two pressure probes buried at 1 and 1.2 m depth in the channel bed at the erosion sensor site, however the channel bed was not fully saturated to it is difficult to unambiguously interpret these data as true fluid pore pressures. A sediment layer covered the uppermost elements of the erosion sensors before the one of the debris flows, so the time of erosion of this layer could not be determined. Terrestrial surveys of the channel bed before and after the debris flows showed that sediment was deposited on top of the sensor columns after erosion was recorded at the head of the flows. This indicates that the bed was reworked to a larger depth than directly visible at the surface after the event. Observations from elsewhere in the channel on the fan support our measurements of the magnitude of debris flow erosion and demonstrate that debris flows may cause extensive



Debris flow data for 1 July 2008. A: Flow depth until 1500 s after front arrival. B: Flow depth, level of topmost erosion sensor element ES, and level of pore water pressure P (all with respect to the channel surface at h=0). C: Normal stress and shear stress. Measurements are from both the erosion sensor site and observation station, with t=0 defined when the debris flow front arrived at the point of interest.

erosion under channelized flow conditions, even on relatively gentle slopes on distal channels on the fan.

The photogrammetry showed that the debris, often originating from bedrock landslides, was transported stepwise in a complex sequence of erosion, storage, and re-mobilization. The magnitude and nature of sediment transfer processes displayed large spatial and temporal variability, and the residence time of the deposits was generally shorter than one year. The observed landslides with volumes of 500 to 4400 m^3 did not transform directly into debris flows but stopped in the downslope channels. The landslides were an order of magnitude smaller than the debris flows at the Illgraben outlet. While the mechanism of debris flow initiation could not be determined unambiguously, it is clear that the debris flows had to entrain substantial amounts of sediment along the flow path to reach the volumes estimated at the distal end of the fan.



Net elevation change after the debris flow on 1 July 2008 between check dams 28 and 29, and detailed view of the erosion sensor site (from Berger et al., in revision).

Major outcome

The findings of this subproject confirm that erosion by debris flows can be significant even on distal parts of alluvial or debris fans, and furthermore that erosion, at least by large debris flows, takes place near the leading edge of debris flows. We were able to document that in-channel sediment deposits from landslides can be rapidly incorporated into debris flows by entrainment. The results generally show the importance of debris flow erosion for the generation of large debris flows, a process which should be considered as part of a hazard assessment or mitigation work.

Further reading

Berger, C. McArdell, B.W., Fritschi, B., and Schlunegger, F. 2010. A novel method for measuring the timing of bed erosion during debris flows and floods, Water Resources Research, 46: W02502.

Berger, C., McArdell, B.W., and Schlunegger, F., 2010. Sediment transfer patterns at the Illgraben catchment, Switzerland: Implications for the time scales of debris flow activities. Geomorphology, Article in Press, doi: 10.1016/j.geomorph.2010.10.019

Berger, C., McArdell, B.W., and Schlunegger, F., 2010. Direct measurement of channel erosion by debris flows, Illgraben, Switzerland. Journal of Geophysical Research - Earth Surface, Article in press.

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Evaluation of project TRAMM

Reflecting on the project's original goals and subsequent project evolution during the past four years, the following statements on the overall outcome of TRAMM can be made:

The original goals of the project have been attained. New models and monitoring systems (sensors) applicable to different rapid mass movements have been developed. New insights into the triggering mechanisms and flow controls have been gained. The project successfully fostered and benefited from synergies between research activities of the different partner groups.

TRAMM was instrumental in creating unique opportunities for large-scale field experiments. The three major hillslope experiments (Wiler, Rüdlingen, Rufiberg) designed and conducted during the project were supported by different institutions. The leveraging of common resources and benefiting from multifaceted expertise made such complex experiments possible and lead to new understandings of key hydro-mechanical controls at these sites.

A common language and cross-disciplinary understanding were established among TRAMM partners. Over time we were able to reconcile different terminology used to describe 'stability', 'cohesion' or 'material failure' in the various scientific communities.

The TRAMM project strengthened collaboration between researchers and students at ETH Zürich, EPF Lausanne and WSL. The regular meetings and common field experiments provided a basis for collaboration and discussion among the eight ETH domain institutes previously non-existent.

The project provided a stimulating platform for PhD students. More than ten PhD students were involved in the TRAMM project. Four of them have accomplished their dissertation by now. Their contribution was decisive for the outcome of the project. Being a part of this interdisciplinary consortium and working together with other PhD students was very much appreciated.

The interdisciplinary view of rapid mass movements enhanced educational programs and teaching. Several project partners involved in the Bachelor and Masters courses at EPFL and ETHZ confirmed that the project had a positive impact on their teaching. With the experience from TRAMM they were able to include more interdisciplinary aspects into course materials.

Lessons learned from TRAMM were successfully disseminated to practitioners. With the special issue in the FAN-Agenda and the practitioners day at Monte Verità we were able to get in contact with natural hazard experts in Switzerland. This dissemination was expressed in many other occasions where decision makers, practitioners and the general public were informed about the project objectives and findings.

Finally, despite the project many achievements, the prediction of rapid mass movements remains a challenge. The problem of predicting the temporal and spatial occurrence and propagation of rapid mass movements is too complex to be solved in a four-year research initiative. Small steps have been made by TRAMM towards an improved understanding and potential solutions, but important key-questions are still open.

It is hoped that a follow-up of this research can generate a further big step forward on the way towards a save and foresighted management of rapid mass movements in Switzerland.

The TRAMM consortium is grateful to ....

Das TRAMM-Team bedankt sich herzlich bei ...

TRAMM remercie cordialement ....

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- The Swiss National Foundation (SNF) for funding of grants No. 206021-117407 / 1 (R'Equip) and 200021-122299 / 1 (Dissertation Jonas Von Rütte)
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List of publications

Peer-reviewed journal publications

Bellaire, S., Pielmeier, C., Schneebeli, M., and Schweizer, J. 2009. Stability algorithm for snow micro-penetrometer measurements, J. Glaciol., 55(193): 805-813.

Berger, C., B. W. McArdell, B. Fritschi, and F. Schlunegger. 2010. A novel method for measuring the timing of bed erosion during debris flows and floods, Water Resour. Res., 46, W02502, doi:10.1029/2009WR007993.

Berger, C., McArdell, B.W., and Schlunegger, F., 2010. Sediment transfer patterns at the Illgraben catchment, Switzerland: Implications for the time scales of debris flow activities. Geomorphology, Article in Press, doi: 10.1016/j.geomorph.2010.10.019

Berger, C., McArdell, B.W., and Schlunegger, F., 2010. Direct measurement of channel erosion by debris flows, Illgraben, Switzerland. Journal of Geophysical Research - Earth Surface, Article in press.

Casini, F., Jommi, C., and Springman, S.M., A laboratory investigation on an undisturbed silty sand from a slope prone to landsliding, Granular Matter, in 2nd review

Cohen D., P. Lehmann, D. Or. 2009. Fiber bundle model for multiscale modeling of hydromechanical triggering of shallow landslides, Water Resour. Res., 45, W10436, doi:10.1029/2009WR007889.

Cohen, D., M. Schwarz, and D. Or, An analytical fiber bundle model for pullout mechanics of root bundles, J. Geophys. Res., submitted.

Cochard, S, Ancey, C. 2009. Experimental investigation of the spreading of viscoplastic fluids on inclined planes, Journal of Non-Newtonian Fluid Mechanics 158: 18-35.

Friedel, S., Thielen, A., and Springman, S.M. 2006. Investigation of a slope endangered by rainfall-induced landslides using 3D resistivity tomography and geotechnical testing. Journal of Applied Geophysics 60(2): 100-114.

Gray, N., Ancey, C. 2009. Segregation, recirculation and deposition of coarse particles near two-dimensional avalanche fronts, Journal of Fluid Mechanics 629: 387–423.

Imre, B., S. Räbsamen, S.M. Springman. 2008. A Coefficient of Restitution of Rock Materials. Computers & Geosciences 34: 339-350, doi:10.1016/j.cageo.2007.04.004.

Laloui, L., and Nuth, M., 2009. On the use of the generalised effective stress in the constitutive modelling of unsatu-rated soils, Computer and Geotechnics, 36 (1-2) : 20-23

Mitterer, C., Hirashima, H. and Schweizer, J., 2010. Wet-snow instabilities: Comparison of measured and modelled liquid water content and snow stratigraphy. Ann. Glaciol., 52: submitted.

Ng, C.W.W., S.M. Springman & E.E. Alonso. 2008 Monitoring the performance of unsaturated soil slopes. Geotechnical and Geological Engineering, 26:799–816.

Nuth, M., and Laloui, L. 2008. Advances in modelling hysteretic water retention curve in deformable soils. Com-puters and Geotechnics, DOI 10.1016/j.compgeo.2008.08.001.

Reiweger, I., Schweizer, J., Dual, J. and Herrmann, H.J., 2009. Modelling snow failure with a fiber bundle model. J. Glaciol., 55(194): 997-1002.

Reiweger, I. and Schweizer, J., 2010. Failure of a layer of buried surface hoar. Geophys. Res. Lett.: in press, doi: 10.1029/2010GL045433.

Schwarz, M., Preti, F., Giadrossich, F., Lehmann, P., and Or, D., Quantifying the role of vegetation in slope stability: the Vinchiana case study (Tuscany, Italy), Ecological Engineering, in press, doi: 10.1016/j.ecoleng.2009.06.014

Schwarz, M., Lehmann, P., and Or, D., Quantifying lateral root reinforcement in steep slopes - from a bundle of roots to forest stands, Earth Surfaces Processes and Landforms, doi: 10.1002/esp.1927, in press.

Schwarz, M., Cohen, D., and Or, D., Soil-root mechanical interactions during pullout and failure of root bundles, J. Geophys.Res., doi:10.1029/2009JF001603, in press.

Schwarz, M., Cohen, D. and Or, D., Pullout tests of root analogs and natural root bundles -- experiments and modeling, J. Geophys. Res., submitted.

Schweizer, J. and Jamieson, J.B., 2010. Snowpack tests for assessing snow-slope instability. Ann. Glaciol., 51(54): 187-194.

Thielen, A., Springman, S.M., and Friedel, S., A long term field study for the investigation of rainfall induced landslides, Géotechnique, submitted

van Herwijnen, A., Bellaire, S., and Schweizer, J. 2009. Comparison of micro-structural snowpack parameters derived from penetration resistance measurements with fracture character observations from compression tests, Cold Reg. Sci. Technol., 59(2-3): 193-201.

van Herwijnen, A. and Schweizer, J., 2010. Seismic sensor array for monitoring an avalanche start zone: design, deployment and preliminary results. J. Glaciol.: submitted.

PhD theses

Berger, C. 2010. Debris flow entrainment and sediment transfer processes at the Illgraben catchment, Switzerland, Universität Bern, Institut für Geologie, 156 pp.

Nuth, M. 2009. Constitutive modelling of unsaturated soils with hydro-geomechanical couplings. EPF Lausanne.

Schwarz, M. 2010. Hydro-mechanical characterization of rooted hillslope failure: from field investigations to fiber bundle modeling. ETH Zürich.

Thielen, A. 2007. Einfluss der Bodensättigung auf die Stabilität von Hängen, ETH-Diss. Nr. 17303. http://e-collection.ethbib.ethz.ch/view/eth:29862

Master and diploma theses

Gilgen,M. 2008. Hydrological simulations of a hillslope prone to shallow landslides. ETH, Eidgenössische Technische Hochschule Zürich,Department of Environmental Sciences, 76 pp. http://e-collection.ethbib.ethz.ch/view/eth:30789

Kauer, S. 2010. Monitoring soil moisture dynamics on a hillslope prone to slide. Master thesis, University of Zurich, Department of Geography, 61 pp.

Umsetzungs-Veröffentlichungen (deutsch/französich)

Ancey, C., Andreini, N., Rentschler, M., and Wiederseiner, S., Laves torrentielles en laboratoire, FAN-Agenda 2/08: 28-32

Berger, C., and McArdell, B., Murgangerosion - Prozesse und Mechanismen, FAN-Agenda 2/08: 25-28

Cohen, D., Or, D., and Lehmann, P., Le modèle du faisceau de fibres pour l'étude des mécanismes de déclenchements rapides des glissements de Terrain, FAN-Agenda 2/08: 22-25

Lehmann, P., Rickli, C., and Or, D., Neue Konzepte zur Modellierung der Auslösung von flachgründigen Rutschungen, FAN Agenda 2/08: 17-21

Nuth, M., Ferrari, A., and Laloui, L., Prédiction numérique des mouvements et ruptures de pentes naturelles à l'origine de l'aléa glissement de terrain, FAN-Agenda 2/08: 17-18

Schwarz, M., Lehmann, P., Cohen, D., and Or, D., Neue Ansätze zur Quantifizierung des Wurzeleinflusses auf die Stabilität von Rutschhängen, FAN Agenda 2/08: 11-14, December 2008

Schweizer, J., and van Herwjinen, A., Auslösung von Schneebrettlawinen, FAN-Agenda 2/08: 15-16

Springman, S.M., Einfache Hangstabilitätsanalyse mit Berücksichtigung ungesättigter Verhältnisse, FAN Agenda 02/08: 7-11

Stähli, M., TRAMM - Triggering of Rapid Mass Movements in Steep Terrain: Ein interdisziplinäres Forschungsprojekt des ETH Kompetenzzentrums für Umwelt und Nachhaltigkeit (CCES), FAN-Agenda 2/08: 5-7

List of project partners

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