The Rüdlingen Monitoring and Landslide Experiment

A large scale field experiment was conducted on a steep forested slope in north Switzerland to trigger a landslide by means of artificial rainfall. The experiment was successful and has delivered valuable knowledge about the behaviour of landslides.

by Sarah Springman, Amin Askarinejad, Peter Kienzler, Francesca Casini, Marco Sperl, Ernst Bleiker / IGT;
Devrim Akca, Armin Grün, Professur für Photogrammetrie / IGP

One of the many strengths of working in Switzerland and at the ETH Zurich is the many and varied possibilities to engage in 'big picture' research that offers an opportunity to contribute within a multidisciplinary environment to solve a problem of societal concern. In this case, civil and geomatic engineers were at the centre of a fascinating project that sought to expose the ways in which landslides would be triggered, leading to understanding about initiation of failure and the subsequent movement of the displaced soil. Earlier field experiments in Gruben (Teysseire, 2006) and Tössegg (Thielen, 2007) were forerunner doctoral projects that were largely focused on geotechnical aspects alone. Nonetheless, they contributed much useful knowledge for the planning and execution of this project as well as a clear understanding that we needed to incorporate input from colleagues in the fields of geology, hydrology, soil physics, geophysics, photogrammetry, bio-engineering and instrumentation and sensor technology.

The Competence Centre for Environmental Sustainability has provided the stimulus for an overarching project entitled TRAMM[1], Triggering of Rapid Mass Movements, in which groups from WSL, ETHZ and EPFL, coordinated by Dr Manfred Stähli, have focused their research on enhancing understanding of triggering and initiation mechanisms, including the transition from slow to fast mass movement processes, and flow characteristics of such catastrophic mass movements. The roles of heterogeneity of hydro-mechanical slope processes on the onset of snow avalanches, landslides, and debris flows are also being studied by other research groups.

The Rüdlingen Experiment was a sub-project within TRAMM, led by the first author. The express purpose was to trigger a rainfall induced landslide, having characterised the slope, instrumented it with a range of state of the art sensors to observe its response to the environmental loading and exposed it to 24 hour observation using high resolution cameras to witness the slide. Rüdlingen village (Fig. 1) was chosen following an extreme event in May 2002 in which 100 mm of rain had fallen in 40 minutes, leading to 42 landslides around the local area. Student projects were carried out in three of these locations in 2003 during the remediation period, in support of the local council. The Council President, Katy Leutenegger was open to the idea of a controlled experiment being conducted on a slope within their territory, when she was approached in 2007. Permission was obtained to fell a few trees, which were mainly at the boundaries of the slope. The Schaffhausen cantonal authorities, represented by their delegate for natural hazards, Jürg Schulthess, and the neighbouring Buchberg village were both supportive and interested in the outcomes of the research, which has already been reported back to the community in 2010. Local assistance was essential at a practical level during the period of the experiment and in the clean up afterwards!

Having identified a possible steep forested slope that would be susceptible to slope instability on the basis of geology, topography, accessibility, vegetation and expected ground profile (Fig. 2), it was necessary to characterise the layers of soil and determine depth to rock to decide whether the experiment would be feasible or not. A series of test pits were dug around the edges of the projected test field to determine soil layering, investigate the root systems, locate rock depth and extract soil samples to enable the relevant properties to be measured. Infiltration tests

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[1] http://www.cces.ethz.ch/projects/hazri/tramm

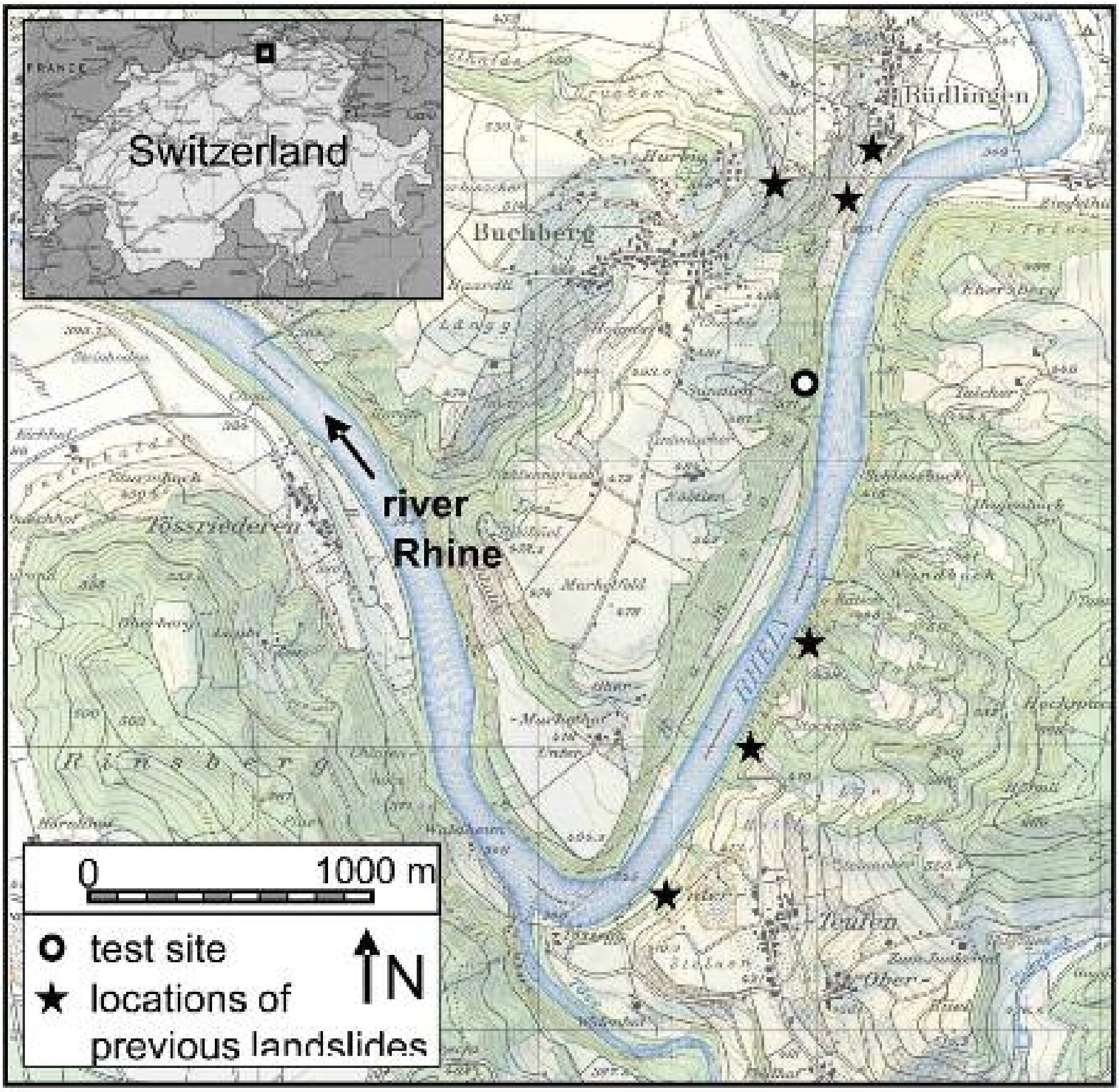

Fig. 1: Location of the test site, detailed map and map of Switzerland (after Sieber, 2003).

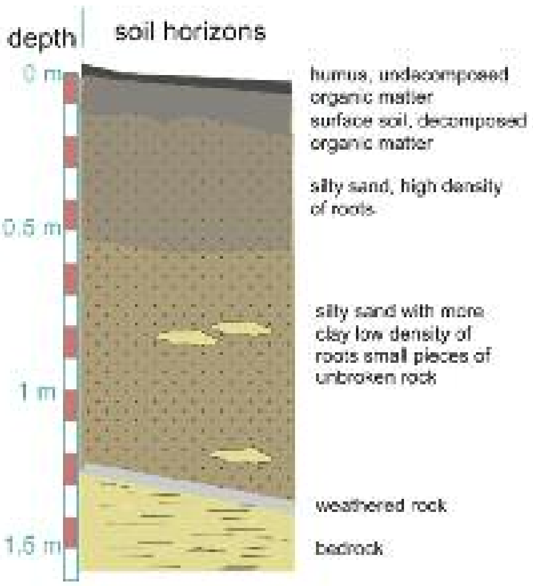

Fig. 2: Soil profile from upper part of the slope.

Fig. 3: Dye pattern in the middle section of a test pit (scale: from ground surface to 1.3 m depth).

were also carried out, using water coloured with brilliant blue dye, to investigate the mode and speed of infiltration of water into the ground (Fig. 3). These exhibited homogeneous saturation and staining of the soil profile (Fig. 3) with only little preferential flow and possible local build up of a perched water table at the transition to bedrock (here at 1 m depth), which confirmed the high vulnerability of the slope to a deep-seated failure above the transition to bedrock rather than a near-surface failure. Furthermore, since a small percentage of active clay minerals, increasing with depth, were found in the soil, and these would tend to reduce the soil strength and the permeability, it was quickly established that a likely failure surface would lie above the bedrock at between 1 and 2 m depth. State of the art seismic dilatometer testing was also conducted by Andreas Schmid and René Rohr (IGT: Chair Geomechanics) to deliver shear wave velocity near the surface. Combined with the planned area of the experimental test field of 35 m longitudinally and 7 m transversely on the slope, around 500 m^3 of debris could be mobilised in the worst case: a not insignificant amount! Since much of this could have been expected to flow over the road and into the Rhine, protection measures were sought with the help of GEOBRUGG, who generously donated two panels of their Swiss made ring net, instrumented to measure force at impact.

The reasons why a slope fails suddenly due to rainfall can be compared to the collapse of a sandcastle due rainfall or flooding. The capillary action of at the water-air-soil particle interface in partially saturated ground adds strength to the soil due to the suctions that increase contact stresses between the particles. As the ground saturates due to infiltration, the suctions reduce as does the shear resistance in the ground, with the reverse condition emerging as soil saturates and a groundwater table rises. In this case, increasing hydrostatic porewater pressures reduce contact stresses and hence the strength. The relationship between the degree of saturation and the suction becomes a critical means of evaluating the contribution to strength (see Fig. 6).

A 4-camera arrangement was adopted for the image acquisition. IDS cameras were placed in housing shields to protect them against environmental effects and two each were equipped with 8.0 mm and 12.0 mm C-mount lenses. They were fixed on two tall trees at the foot of the slope (Fig. 4) at approximately 25 metres height by a professional climber. Approximately 250 white ping-pong balls (with diameter 40 mm) were glued onto wooden pegs and embedded in the ground in a 1 m by 1 m grid (Fig. 4). 21 well distributed ground control points were established on the surrounding stable trees. The a priori point positioning accuracy of the ping-pong balls, using an in-house developed network simulation tool, was estimated as ± 10.3 mm along the horizontal direction and ± 3.5 mm along the vertical direction. In the second sprinkling experiment, the area of interest was moved ca. 5 metres up the slope. In order to make the targets more discernable on the image space, the ping-pong balls were replaced with approximately 80 white tennis balls. A posteriori point positioning accuracy obtained from bundle adjustment in the first sprinkling experiment was ± 16.5 mm along the horizontal direction and ± 3.4 mm along the vertical direction. For the second experiment, these values were ± 11.0 mm and ± 4.3 mm for the horizontal and vertical directions, respectively. Just prior to the monitoring experiment in October 2008, Cornelia Brönnimann (EPFL), conducted a pumping test close to the lowest instrument cluster above bedrock. No groundwater table could be sustained. This rejected one of the possible triggering mechanisms due to watertable rise. Furthermore, geophysical monitoring conducted by Klaus Holliger's group from Uni Lausanne, led by Barbara Suski with Francesca Gambazzi, indicated the likelihood of a strata change in the underlying Molasse rocks, which would confirm the presence of cracking in the more competent coarse grained Susswasser Molasse compared to the weaker, fine grained Meereswasser Molasse.

A safety concept was also set up to make sure that noone was buried during the landslide, since it was predicted that failure would occur within a matter of seconds, and it would not be possible to escape the muddy onslaught. The observational method was used as a decision-making framework depending on the degree of saturation and suction with depth, linked to stability calculations of a predicted failure mechanism (Fig. 6). A traffic light system backed up with appropriate observations, measurements and permitted actions at each level, set up clear command, control and communications between the team members and the local community. A 'red' state meant that the slope could fail at any time and so noone was permitted to pass below the net or within 20 m of the slope.

Connecting up the water supply (Figs. 7a, b, c) was successfully achieved. The first experiment ran in October 2008. After a preliminary testing phase, a total of 1.7 m of rainfall, calculated as an average over the slope area, was supplied over 3.5 days. The mode of saturation of the ground was observed and some deformations were measured in the top right quarter of the field, but failure did not occur. Furthermore, some extremely promising technology using acoustic sensors developed (Fig. 4) by D-BAUG Associate Dani Or's group, were installed by Gernot Michelmayr and hinted at some significant shear movement during one of the most extreme rainfall periods (at 40 mm/hour), that was supported by data from both the surface deformations and the inclinometers.

The research team concluded that failure had not occurred on two accounts, because of the leaky base rock in the lower half of the slope, where the greatest part of the water had been supplied so that a groundwater table could not rise and root reinforcement, characterised by WSL/STEP doctoral researcher Massimiliano Schwarz, from a tree stump in the lower left quadrant of the slope.

Measures taken included confirming that there was less permeable base rock underlying the top of slope to permit a groundwater table to rise during the rainfall event, and re-orienting the sprinklers at closer spacings, further up the

Fig. 4: Location of the instrumentation clusters (Cl. 1 – 3), the sprinklers and the photogrammetry cameras.

Fig. 5: Deformation probe.

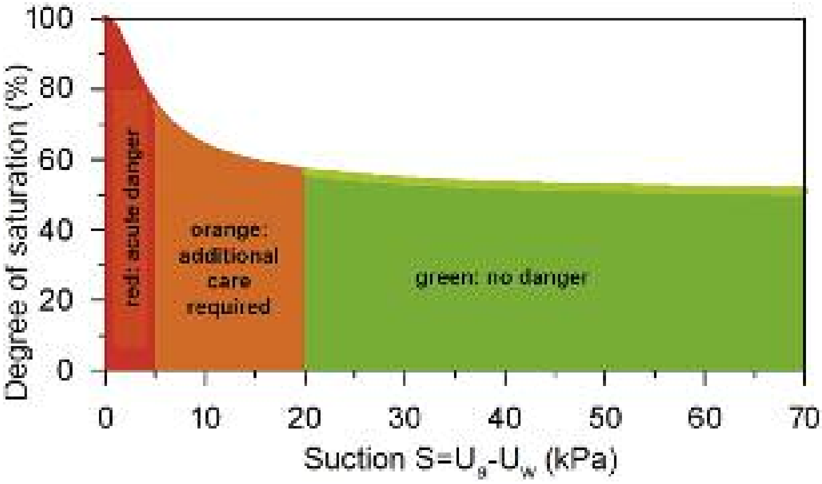

Fig. 6: Decision – making graph for the observational method.

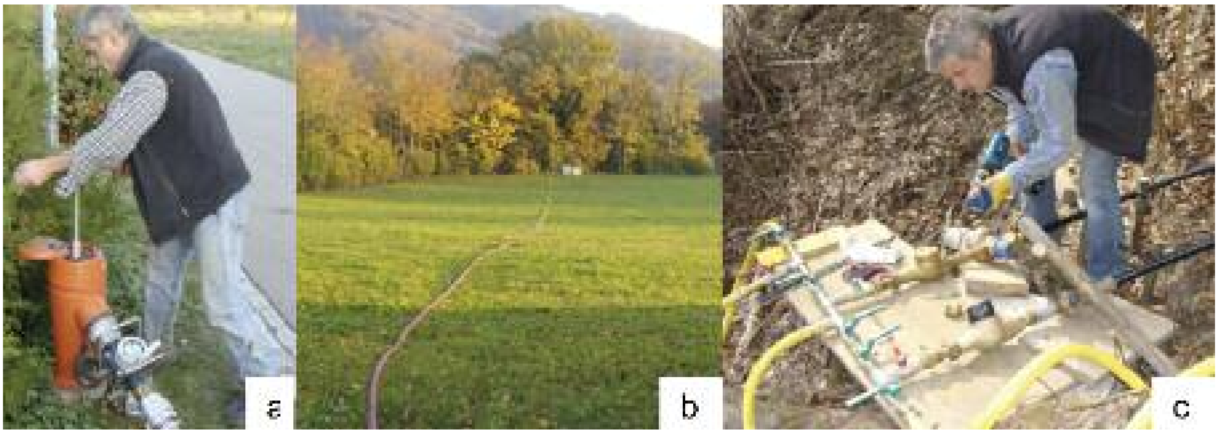

Fig. 7: a) Supply of water from a hydrant, b) long water pipe to the test field c) water-meters and main connections to the sprinklers.

slope (Fig. 8), where less influence was expected from the vegetation and a rising groundwater table would be possible. Roots were severed to a depth of 40 cm along the sides of the field and more extensive tracer / run-off experiments were planned for a follow-up experiment in March 2009 over 2 weeks, so that saturation could be achieved prior to initiating failure.

Pre-test predictions of a failure event were as follows: a landslide would be triggered towards the end of the first week, it would be initiated in the top right quadrant, and travel towards the bottom right of the field, with a failure surface at a depth of about 1.5 m, mobilising between 100–300m^3 of debris.

With newly aligned sprinklers, the rainfall was adjusted to an average distribution of 15 mm/h. There was an instant response in the upper part of the field as the saturation degree increased, suctions dropped and then the water table rose over 5 h to about 1.5 m below ground level, where it stayed for the next 10 h. 15 h after the rainfall had begun, at 3:00 am, the upper right quadrant started to creep downslope, with the rate increasing until 3:23 am (Fig. 9). A crack opened up parallel to the top of the test field, and as the failure surface spread through the ground, the right hand side of the landslide followed the scar made through the vegetation and the left ripped away from and through the surficial vegetation (Fig. 10). It took 36 seconds to mobilise about 130 m^3 (3 super script) of soil and roots, which travelled left towards the tree stump in the lower part of the field, which re-directed the flow to accelerate towards the bottom right, whereupon it took only 12 seconds more to impact on the protection net. Not one grain of debris reached the forest road below (Fig. 11). Water oozed out of the back scarp for several minutes after the event and the research team celebrated 'a bonnie slide', which was quite well predicted in size and shape. The difficulty of estimating the time to failure was emphasised however.

Lessons for the locals include that a cracked base rock is very effective at draining the overlying ground, rather like trying to fill up a bath when the plug is not in! The challenges of slope instabilities lie when shallow soil layers overly semi-impermeable rock so that a water table can build up locally or even flow out of the ground. Useful hints to such episodic springs can be obtained from vegetation and during winter from the build up of ice (Fig. 12). In general, vegetation has a very positive effect on slope stability, with tree roots acting as effective deep reinforcement, which could be quantified by the experiment.

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