Mountain Risks: two case histories of landslides induced by artificial rainfall on steep slopes

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Mountainous areas tend to be exposed to an enhanced risk of damage caused by natural hazards. In addition to general risks such as earthquakes and storms, risks are exacerbated by the topography (leading to gravitational mass movements such as avalanches, mud and debris flows). Six percent of the area of Switzerland is prone to slope instability (BUWAL 1997, Lateltin et al. 2005).

This contribution compares the landslides induced by artificial rainfall on two different areas located in Switzerland. The first field test (slope of 42° and ~55 m^2 plan area) is located at about 2800 m above sea level (masl) at Gruben (Canton Wallis, Switzerland). To investigate the hydro-mechanical mechanisms, the slope was instrumented with devices to measure suctions and volumetric water content, pore water pressures and rainfall intensity. Artificial rainfall tests were carried out in the summers of 1999 and 2000. The slope was provided with sprinklers to create artificial rain as uniformly as possible (Teysseire et al. 2000).

The second test field (average slope of 38° and ~250 m^2 area) is located near Ruedlingen (Canton Schaffhausen, Switzerland) where a landslide triggering experiment was carried out in autumn 2008 and spring 2009 to replicate the effects of a heavy rainfall event of May 2002, in which 100 mm rain fell in 40 minutes, causing 42 superficial landslides. The slope was subjected to extreme rainfall by artificial means in October 2008 over a period of 4 days, with an average rainfall intensity of 15 mm/h for the first two days and an average intensity of 30 mm/h for the last two days. The sprinklers were distributed at constant spacing along the central line of the slope. Some surface movements were detected during this extreme event, although failure did not occur (Springman et al. 2009). Subsequently, a range of measures was implemented, such as relocating the distribution of the sprinklers to provide more rainfall to the upper part of the slope, so that a failure was triggered in March 2009, incorporating about 130 m^3 of debris.

Infiltration of rainfall has led to surface instability in a moraine slope (Grüben) and in silty sand (Rüdlingen). In both cases, the slopes are steeper than the internal angle of friction having different initial degrees of saturation and suction. The hydromechanical behaviour of these two field full scale landslides will be compared, trying to deliver a deeper underestanding of the rainfall induced failure mechanisms.

Introduction:

Due to the complexity of the infiltration processes of water in soils, one of the biggest challenges for the geotechnical engineer is to establish relationships existing between hydrologic conditions, pore pressures, strength, factor of safety, and, possibly the rate of movement (Leroueil, 2001).

Casagrande (1975) observed that the brooks emerging from the toe of the rather dense talus deposits in the Alps stoped to flow before the failure of large masses of granular talus. Also, Harp et al. (1990) reported a consistent trend of pore pressure increases during the early stages of infiltration and of abrubt decreases in pore pressure 5 to 50 min prior to failure in two landslides. Several researchers (e.g. Lee et al. 1988; Iverson et al., 2000; Wang & Sassa 2001) attributed the mentioned observations to the volumetric strains of the soil while shearing.

The initiation mechanisem of failures due to infiltration is a drained process, but as soon as the movements start (yielding), depending on the paricles speed and the permeabilty of the material an undrained condition can be developed. Under undrained conditions if the soil is contractant the initiated failure can trigger a rapid mass movement due to the sudden collaps of the soil structure and increase of pore pressure. On the other hand a dilative behavioure at yielding state of the soil may retard continued deformation by increasing normal stresses and frictional strength at grain contacts (Iverson et al., 2000).

However, Harp et al. (1990) suggest that the dramatic drops in pore pressure prior to failure, as well as dilatation and failure itself, may be due to the piping of fine-grained soil particles.

In this paper the changes in pore pressure and water content of two artificially induced landslies are presented and compared.

Gruben

To investigate slope stability in moraine as a function of degree of saturation and relative density of the soil, an alpine moraine slope at about 2800 m above sea level (masl) at Gruben (Canton Wallis) was selected as field test site and instrumented for artificial rainfall test in the summer 2000. The slope is 42° steep with ~55 m^2 plan area. The moraine from the glacier forefield is composed from parent rocks, based on faulted muscovite-rich gneiss or slate with some albite, chlorite and biotite present.

Seismic refraction, D.C. resistivity and gravimetry soundings were performed during a former geophysical campaign (Vonder Mühll et al. 1996). The results indicated a maximum thickness of nearly 100 m of moraine, with looser packing in a top layer (low compression velocities v_p = 400-600 m/s in the top 5 m at the site and v_p = 700–1400 m/s for the next 15 m and v_p = 1100–1400 m/s over the next 80 m), whereas the underlying moraine appears to have been well compacted with v_p increasing with depth (Springman et al. 2001, 2003).

Grain size distributions were determined from representative surface samples (originally 1-2 to., up to 1 m depth). Typical grain size distribution are given in Figure 1a for unlimited maximum fraction and for three fractions extracted from the “whole“ sample and restricted to < 45 mm, < 16 mm, and < 2 mm. The fines content is significant.

A layout of the instrumentation installed is given in Figure 1. Runoff was ~ 80% for this slope and type of storm. Time domain reflectometry (TDR) and moisture point (MP) devices were installed for accurate measurement of changes in volumetric water content (θ) and determination of S_r in the top 20 cm and top 1 m respectively. Suctions were also measured by tensiometers (T), although some difficulties were experienced in the harsh alpine conditions, which led to the malfunction of a number of instruments (Springman & Teysseire 2001).

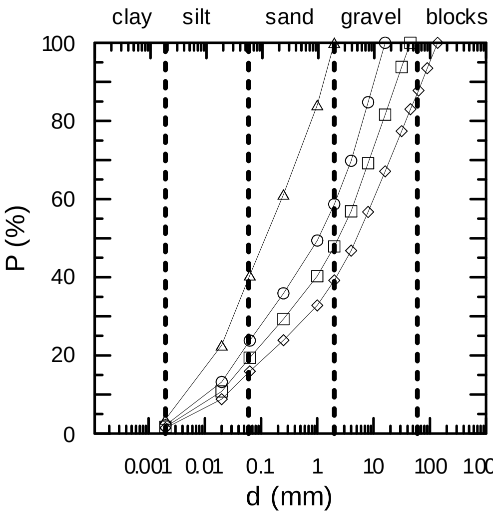

Figure 1 Grain size distributions

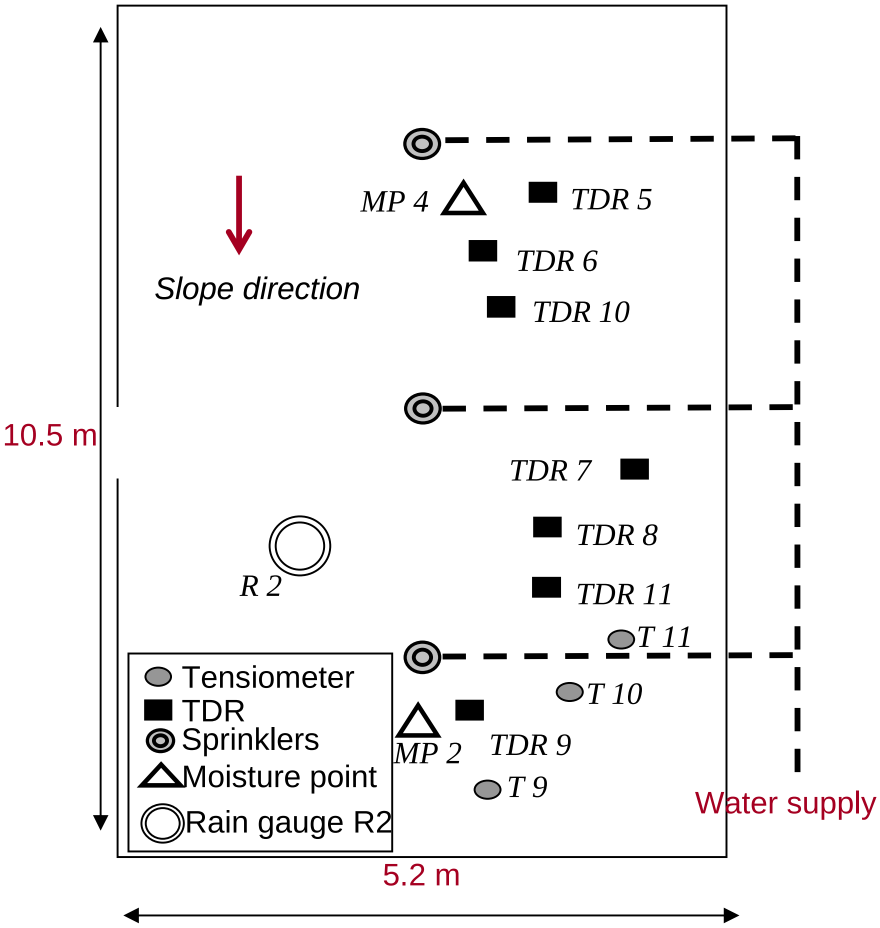

Figure 2: Test field and instrumentation layout (after Springman et al. 2001)

A sprinkler system was constructed to supply controlled artificial rainfall, the intensity of which was also measured. Rainfall was applied in 2000, for 50 hours, with an average of 16 mm/h for the first day and 12 mm/h for the second day. After ~2 days, the 42° slope failed and the tests were stopped (Figure 3).

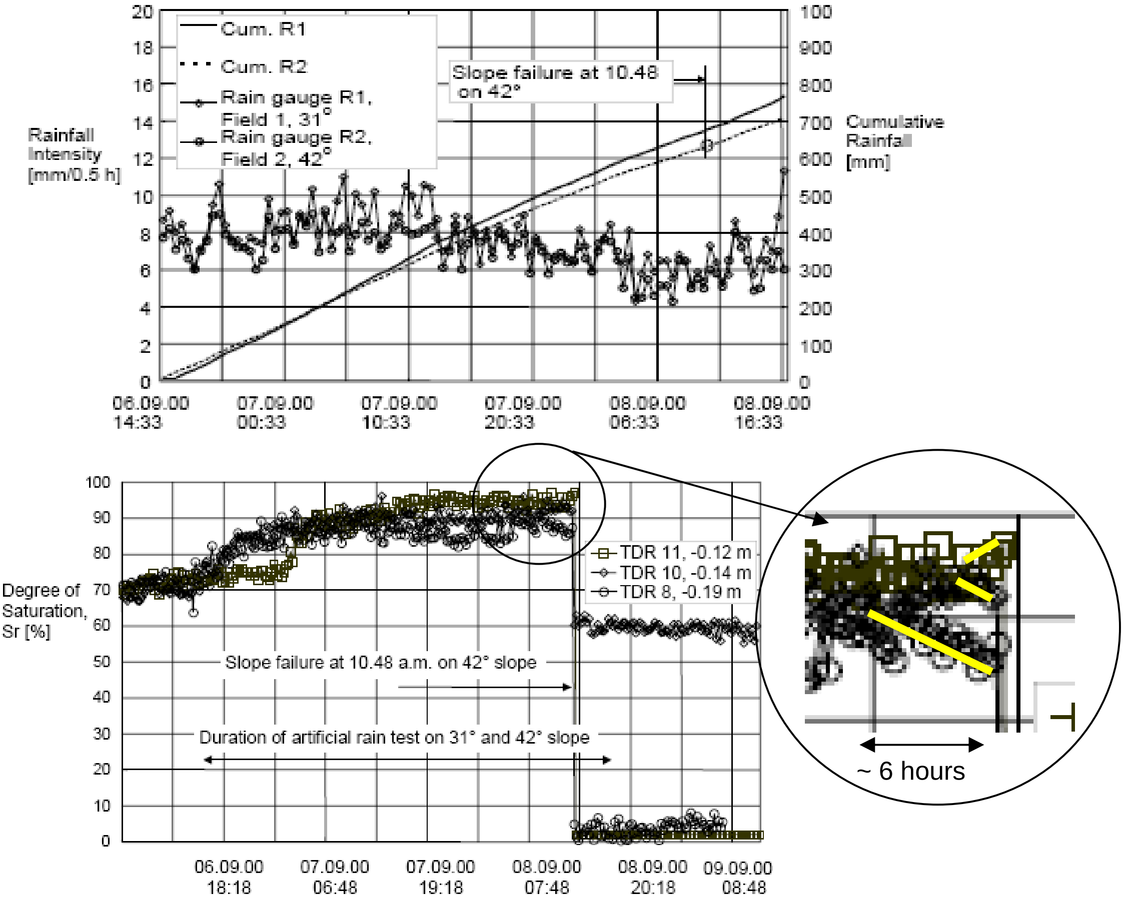

Figure.2 a) Figure 3 Rainfall intensity for 2000 b)TDR measurements

Figure 3b shows three sets of TDR measurements (TDR 8, 10, 11) over 2 days of intense rainfall. Instability occurred in the slope when S_r approached 0.95. The slip surface was located at the depth of 0.2 m. TDRs 8 and 10 show a decrease in the degree of saturation 6 hours and 1.5 hours before the failure, respectively. This observation can be attributed to the dilative behavioure of the soil, which was observed during a series of insitu direct shear box tests (Figure 4), or to the piping of fine-grained soil particles.

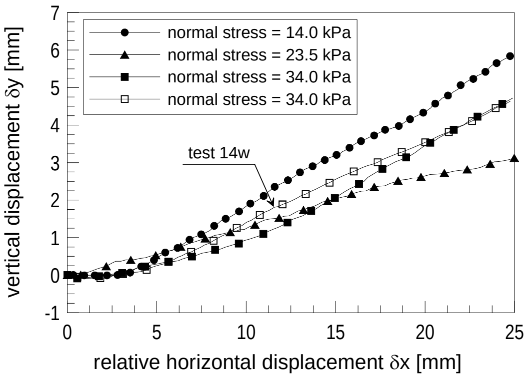

Figure 4 vertical displacements against relative horizontal displacements of insitu direct shear box, Gruben

Ruedlingen:

The selected experimental site is a steep, forested slope in Ruedlingen, North Switzerland, where more than 40 surficial landslides occurred in this area after an extreme rainfall event in spring 2002 (Fischer et al. 2003).

To investigate the hydrological and mechanical behaviour of the slope, a sprinkling experiment was carried out in autumn 2008, followed by a triggering experiment in spring 2009.

The selected experimental area is located on an east facing slope on the banks of the river Rhine. The altitude is about 350 masl. The average gradient of the slope is 38° (Springman et al. 2009). During the preliminary investigations, sandstone and marlstone were located at a depth of between 0.5 m to more than 5 m along the 30 m x 8 m plan section. The soil behaviour was investigated in the laboratory under saturated and unsaturated conditions (Springman et al 2009, Casini et al. 2010 a&b, $\varphi'=31°$ for remoulded soils and $\varphi'=32.5°$ for natural soils). The average saturated permeability of the soil is $k_{sat}=1*10^{-7}$ m/s. The soil can be classified as medium-low plasticity silty sand (ML) according to USCS.

An extensive instrumentation plan was designed to measure hydrological and geo-mechanical responses of the slope. Detailed measurements of soil suction, water level and soil volumetric water content were combined with an investigation of subsurface flow at the lowest part of the slope 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 a two axis inclinometer on the top (Askarinejad 2009). The instruments were installed mainly in three clusters over the slope. The instruments included jet-fill tensiometers, TDRs, Decagons, TDRs, piezometers, soil temperature sensor, deformation probes, earth pressure cells, acoustic sensors and rain gauges (Figure 7). The tensiometers were installed at depths of 15, 30, 60, 90, 120, and 150 cm below the ground surface in each cluster. Decagons were installed at shallow depths of 15 to 60 cm every 15cm, and TDRs from 60 cm to 150 cm, with a spacing of 30 cm. All the instruments were calibrated and checked in the laboratory for proper functioning before installation in the field. The hydrological responses of the soil were measured during the experiment with a logging interval of 5 minutes and the subsurface movement measurements were carried out at a frequency of 100 Hz (Askarinejad 2010).

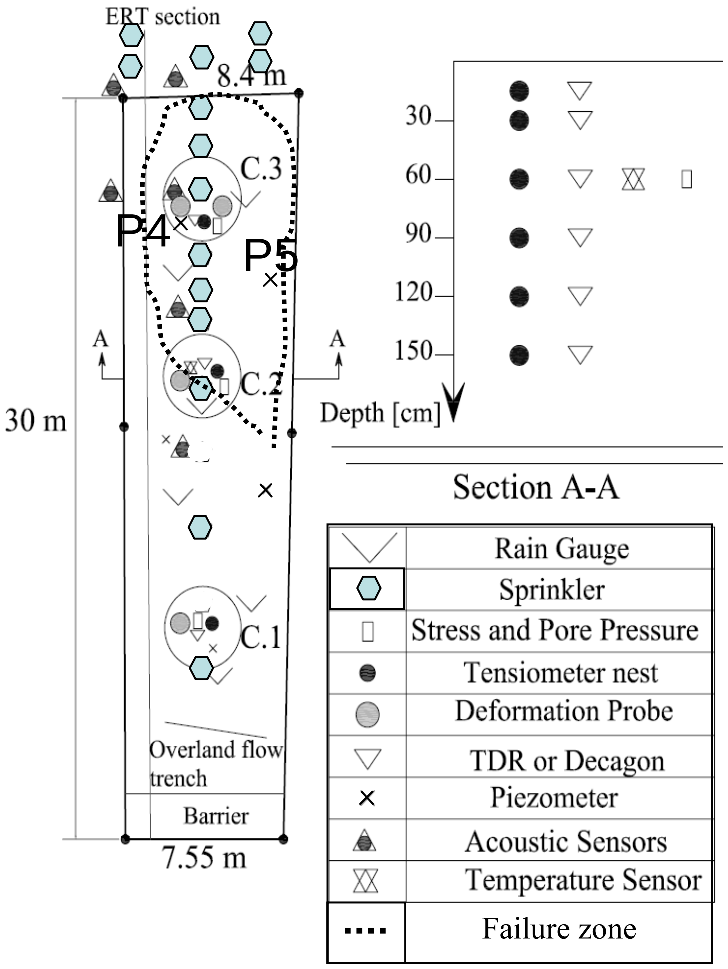

Figure 5 Instrumentation plan and section (after Askarinejad et al. 2009)

The sprinklers were aligned on the middle longitudinal line of the slope with different spacings to provide more rainfall to the upper part of the slope (Figure 5). The rainfall was adjusted to an average distribution between 10 to 15 mm/h (Figure 6). 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 hours to about 1.5 m below ground level, where it stayed for the next 10 hours (Figure 7). Fifteen hours 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 (Springman et al. 2010) The depth of the slip surface changes over the length of the failure zone ranging between 1.3 m on top to 0.3 m at the lower parts of the failure wedge.

Pore water pressures were measured at six depths between 0.15 m-1.5 m. After the beginning of the rainfall, pore water pressures reduced most quickly in the deeper layers, from roughly –7 kPa to a maximum value value of 9 kPa. The increase in pore water pressure and its positive value (saturated conditions) is particularly important given the accompanying decrease in effective stress and hence reduction in mobilised shear strength which leads to failure.

Figure 6 shows the changes in Volumetric Water Content (VWC) over 15 hours of intense rainfall. During this period the volumetric water content of the surface layers increased from ~28% to around 45% while in the deeper parts this change was from arround 0.25% to maximum value of 55%. The shallower TDRs at 60 and 90 cm first responded to the rainfall after 50 and 100 minutes, respectively. The deeper TDRs at 120 and 150 cm showed an increase in VWC after 100 and 140 minutes. The TDR at the depth of 120 cm measured higher values of water content compared to the one at 150 cm. This can be due to difference in porosity of the soil at these two depths, or local perched water table at the depth of 120 cm. After about 11 hours of constant VWC, the TDR at the depth of 120 cm, which was the nearest instrument to the slip surface, measured a decrease in water content. This decrease occured about 1 hour before the failure. This observed decrease can be attributed to the dilation of the soil at the failure surface or piping of the fine grained material. More or less at the same time the piezometers P4 and P5 which were inside the failure zone and had been installed at depths of 3 m and 1.4 m, respectively, showed a decrease in the piezometric level (Figure 7).

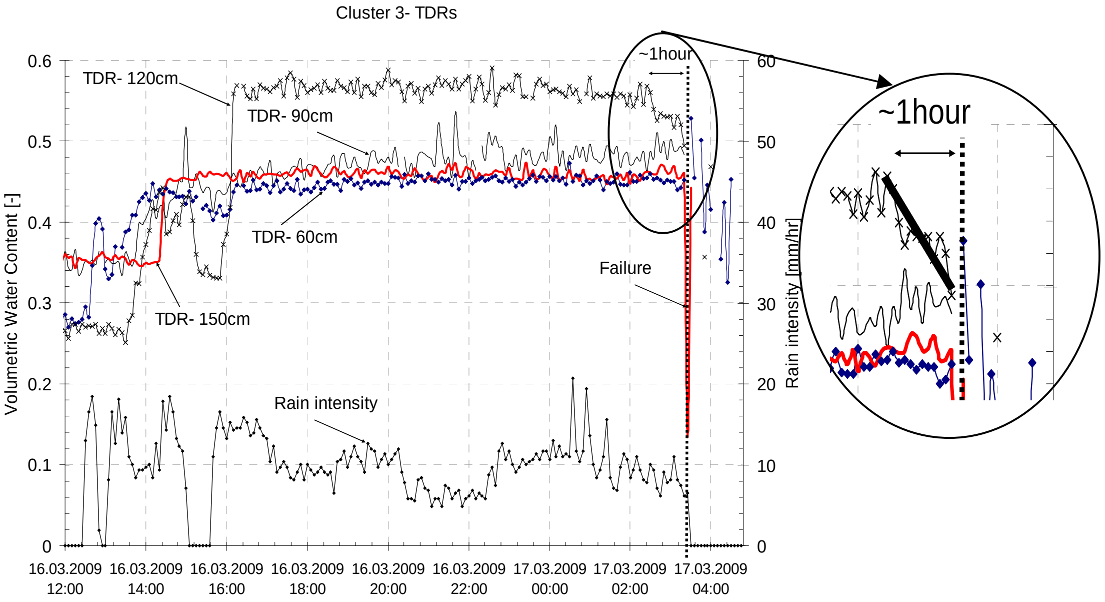

Figure 6 Applied rainfall and changes in the volumetric water content profile on the upper part of the slope

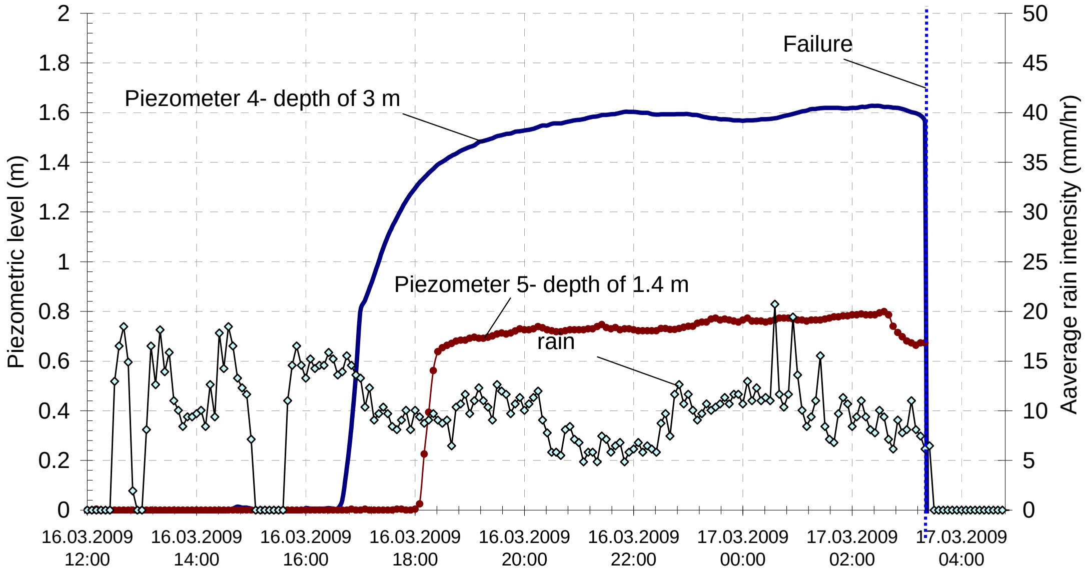

Figure 7 Changes in the piezometric level at two points on the upper part of the slope

To simulate the stress path experienced by a soil element in a slope during infiltration, Casini et al. (2010) performed drained triaxial tests on undisturbed samples under constant axial load and increasing water pressure after anisotropic compression (CADCAL).

The results of two CADCAL drained tests are reported in (figure 8). Specimens TX9 and TX10 were compressed anisotropically up to p'≈100 kPa with η=0.95 and η=0.44, respectively. Increasing the pore water pressure promotes a slight increase in volumetric strain, which is likely to be result of elastic swelling as the stress path moves inside the yield locus. For the sample TX10 a definite increase in shear strain was observed just after the critical state stress ratio, characterised by an increase in volumetric strain. The latter denotes a dilatant mode of ultimate failure with plastic volume increase. The sample TX9 eventually reached a dilatant mode of failure, but after a first contractant stage.

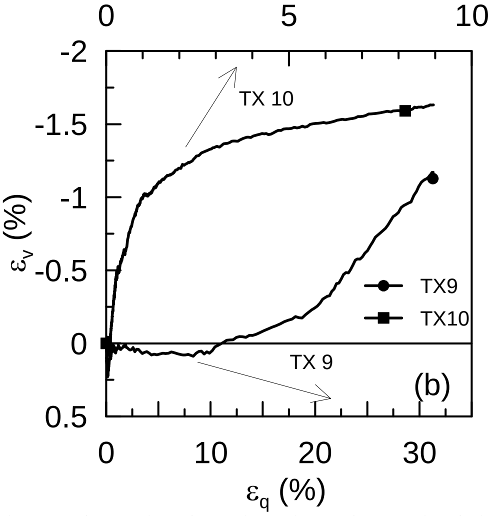

Figure 8 Changes in volumetric strain vs. shear strain of triaxial tests under constant axial load and increasing water pressure

Conclusion

Infiltration of rainfall has led to surface instability in a moraine slope (Gruben) and in a silty sand (Rüdlingen). In both cases the slopes are steeper than the internal angle of friction. Field and laboratory tests have provided data for comparison with a limit equilibrium analyses. In Grüben despite the simplicity of the limit equilibrium analyses and extreme heterogeneity of the moraine, it was found that the factor of safety reduced almost to unity at depths < 0:5 m for the 42° slope, as had been observed from the field test. An extended analyses to a laterally limited slide as been performed for the Rüdlingen site. A critical depth z = 1.12 m is obtained for a suction of 2.9 kPa. All the other depths investigated needed less suction for a safety of factor FoS = 1.The approach used is quite simple but it can be applied to predict the zone of potential failure, which in the field experiment was located at a depth z ~ 1.25 m. The suction mobilised at failure was lower than the critical value determined here. This is due to a more complex response of the soil in the field in comparison to the simple hypothesis of the analyses as also confirmed by the laboratory investigation. The response of the undisturbed samples suggests that the Rüdlingen soil may be typically classified into the so-called transitional soil, which shares some typical features of loose granular soils, such as strain induced anisotropy and potential for instability. A dilatant mode of failure is also confirmed by the readings of pore water pressure for the piezometer at a depth z=1.4m where a decrease was registered.

A more complex analyses musts be performed in order to take into account the complex behavior of soils and the contribution of all the factor that lead to failures as typical volumetric behaviour of fine grained soils, strain induced anisotropy, and possibly time dependence. This are basic requirements in the choice of a reference model for saturated conditions which will be accommodated to unsaturated conditions.

References

BUWAL (1997). Massenbewegungen von nationaler Bedeutung

Lateltin O., · Haemmig C.,· Raetzo H.,· Bonnard C. (2005). Landslide risk management in Switzerland. Landslides (2): 313-320.

Springman, S.M., Kienzler, P., Casini, F., Askarinejad, A.:Landslide triggering experiment in a steep forested slope in Switzerland. In: 17th International Conference on Soil Mechanics and Geotechnical Engineering, 5–9 Oct, Alexandria (2009)

Teysseire, P., Cortona, L. & Springman, S. M. (2000). Water retention in a steep moraine slope during periods of heavy rain. Proceedings of Unsaturated Soils for Asia (eds H. Rahardjo, D. Toll and C. Leong), pp. 831–836. Rotterdam: Balkema.