Application of geotechnical and geophysical field measurements in an active alpine environment

D R Lucas¹, K Fankhauser¹ and S M Springman¹

¹ETH Zürich, Institute for Geotechnical Engineering, Wolfgang-Pauli-Str. 15, 8093, Zürich, Switzerland
daisy.lucas@igt.baug.ethz.ch, kerstin.fankhauser@igt.baug.ethz.ch, sarah.springman@igt.baug.ethz.ch

Abstract. Rainfall can trigger landslides, rockfalls and debris flow events. When rainfall infiltrates into the soil, the suction (if there is any) is reduced, until positive water pressure can be developed, decreasing the effective stresses and leading to a potential failure. A challenging site for the study of mass movement is the Meretschibach catchment, a location in the Swiss Alps in the vicinity of Agarn, Canton of Valais. To study the effect of rainfall on slope stabilities, the soil characterization provides valuable insight on soil properties, necessary to establish a realistic ground model. This model, together with an effective long term-field monitoring, deliver the essential information and boundary conditions for predicting and validating rainfall-induced slope instabilities using numerical and physical modelling. Geotechnical monitoring, including soil temperature and volumetric water content measurements, has been performed on the study site together with geophysical measurements (ERT) to study the effect of rainfall on the (potential) triggering of landslides on a scree slope composed of a surficial layer of gravelly soil. These techniques were combined to provide information on the soil characteristics and depth to the bedrock. Seasonal changes of precipitation and temperature were reflected in corresponding trends in all measurements. A comparison of volumetric water content records was obtained from decagons, time domain reflectometry (TDR) and electrical resistivity tomography (ERT) conducted throughout the spring and summer months of 2014, yielding a reasonable agreement.

1. Introduction

The Meretschibach catchment (figure 1), situated in the Swiss Alps, within the Canton of Valais, provides an environment in which different kinds of mass movements occur more or less frequently where the slope of inclination is steeper than the angle of repose. Furthermore, this complex field environment consists of a type of soil that is challenging for monitoring and characterisation. Shallow landslides can be triggered within this catchment by a decrease of suction due to rainfall, followed by an increase in pore water pressure with a consequent reduction in effective stress within the gravelly soil. Triggering of a mass movement event can generate debris flows, which have the potential to reach the village of Agarn and cause significant damage to infrastructure, as well as loss of life [1]. Some of these events have been documented [2], but little has been published in the case of slope instabilities triggered in gravelly soils. The project at Meretschibach involves the soil characterisation, including the determination of soil properties at different depths, thickness of soil (depth of bedrock) and the establishing of a realistic ground model. This characterisation forms the base of an effective field monitoring to observe and measure the response of the scree slope to rain infiltration and satura-
tion processes. A long-term monitoring campaign, integrating geotechnical and geophysical methods together with laboratory analyses, allows a progressively more detailed calibration and validation of the ground model. Ultimately a collection of all acquired data is used for numerical and physical modelling to study the mechanism of failure due to rainfall [3], hence enabling a hazard assessment to be made and the implementation of suitable safety measures, along with early warning systems.

Instrumentation is placed at shallow depths within three geotechnical trenches (IT1-3 at elevations of 1868-1914 m.a.s.l., figure 1) in one of the steep scree slopes in the catchment, to perform real-time monitoring of the volumetric water content (VWC), temperature and suction [4, 5]. Electrical resistivity tomography (ERT) measurements were conducted repeatedly throughout the summer months of 2014, on a profile located closely to IT1, to complement the geotechnical data [6], allowing the VWC recordings to be validated in specific locations. Furthermore, the precipitation in the area is measured at two weather stations located within 1 km, at an elevation of 2220 m.a.s.l., and of 1370 m.a.s.l., respectively.

The data acquired in two of the instrumented trenches (IT1 and IT3) are analysed separately and compared to the corresponding data in the other trench. Trends in temperature, as well as VWC in the scree slope’s gravelly soil, correspond well to expected seasonal changes. Peaks in VWC can be related to intense rainfall events. Unanticipated variations and deviations can be explained by isolated rockfall events and freezing/thawing cycles. A good correlation between the peaks in various measurements is observed for the times when debris flows occurred in the Meretschibach in July 2014.

A comparison between the VWC measurements performed by time domain reflectometry (TDR) and decagon sensors within each trench is made, and the degree of saturation is calculated. Furthermore, the VWC obtained from the two geotechnical instruments is compared to the VWC estimates obtained from the ERT acquisitions using Archie’s law [7, 8]. All trends and values agree well with each other, proving that the three different methods are consistent. The VWC and the suction measurements, provide valuable information to be able to assess changes in soil resistance, particularly in a partially saturated state.

Figure 1. Overview of the field area, located in the canton of Valais, Switzerland (small map). The left image looking to the south shows a view of Agarn, situated on the Rhone valley floor and the Meretschibach catchment on the mountain slopes behind. The most active area within the catchment, the Bochtür area, can be divided into an active channel and a scree slope. The right image shows an enlargement of the scree slope (yellow rectangle) and the locations of the instrumented trenches (IT1 and IT3) are indicated along with the ERT profile on which the monitoring was performed.
2. Soil and ground characteristics

2.1. Soil classification

Figure 1 shows the location of the research site and specifically the location of instrumented trenches 1 and 3 (IT1 – IT3). Samples were taken from three test pits TP1-3, near IT1 to perform grain size analysis. The work was carried out during dry summer weather conditions. The following characteristics were noted: the ground surface was considered to be ‘depth zero’ for each test pit, at least 4 kg of soil were extracted for each disturbed sample, some cobbles larger than 70 mm and any boulders were left at the site, and roots were found in almost all of the samples.

The soil is classified (figures 2, 3 and table 1) according to USCS and Swiss standard classification SN 670 004-2NA, as gravel with silt and sand (GM). Figure 2, shows the soil profiles at the trenches to a depth of 38 cm. IT1 on the left, consists of a layer of approximately 30 cm thickness (A and B, above the orange dashed line) of gravel with more fines, overlying coarser gravel. This upper layer can further be divided into an upper (A) and a lower (B) part with more and less roots respectively. At IT3, the top layer consists of finer gravel (D) and a transition to slightly coarser gravel (E) can be inferred.

![Figure 2](image)

**Figure 2.** Soil at instrumented trenches IT1 (left) and IT3 (right). The following description is based on field observations. IT1: A (~0-12 cm), gravel with silt, sand and roots; B (~12-25 cm), gravel with silt and sand; C (below ~25-30 cm), coarser gravelly soil with less fines. IT3: D (~0-25 cm), gravelly soil with little content of sand and silt; E (below ~25 cm) change to a coarser gravel.

| Test Pit | USCS Classification | Moisture content | Percent of fines | $C_u$ | $C_c$ | $G_s$ |
|----------|---------------------|------------------|------------------|------|-------|------|
| TP1      | GM                  | 2.9-3.7          | 5.7-8.2          | 73.6-139.3 | 8.3-14.4 |
| TP2      | GM                  | 3.0-5.4          | 5.5-10.8         | 33.3-105.1 | 7.9-11.2 |
| TP3      | GM                  | 3.7-4.3          | 6.7-16.4         | 72.8 | 9.1 |

$C_u$: Coefficient of uniformity, $C_c$: Coefficient of curvature; $G_s$: Specific gravity
Figure 3. Grain size distribution: samples from Meretschibach scree slope test pits 1-3. A range is marked in grey to illustrate the characteristics and content of fines for the entire set of samples. A sample in green from test pit 3 (TP3) at a depth of 30-40 cm and a sample in red from test pit 2 (TP2) at a depth of 20-40 cm set the upper and lower limit respectively.

3. Monitoring methodology

3.1. Instrumented trench

Selected spots on the slope(s) (i.e. landslide source areas) are monitored *in situ* to measure water infiltration-suction characteristics in the ground, to provide time-series data about infiltration quantities and rates, and the effect on the inter-particle suction, which directly affects the *in situ* effective stress. Suction is measured with tensiometers, providing complementary data to calculate effective stress and hence to assess changing shear stress conditions.

Two vertical monitoring profiles were installed (IT1-IT3), consisting of sets of co-located tensiometers, time domain reflectometry (TDR) soil moisture, decagons and temperature sensors. Freezing/thawing conditions, particularly during the crucial spring snowmelt period, can be identified through measurements of temperature, while the TDRs are calibrated to measure the volumetric water content. An SR50A Campbell weather station was installed and monitored within the study area (precipitation, ambient air temperature, humidity) by the Swiss Federal Institute for Forests, Snow and Landscape research, (WSL), and a Pluvio OTT2 (solid and liquid precipitation) was installed by ETH to measure total precipitation.

3.1.2. Sensors & calibration

The sensors used in this monitoring set up include: tensiometers, decagons, time domain reflectometry (TDR) and temperature devices. These have been described and used in previous landslide monitoring programmes [3]; technical details are given in table 2. TDR and decagon sensors measure the volumetric water content of the soil in the field and have been used in the past [3, 9], to measure the VWC in unsaturated silty sand, and alpine moraine with good results. The performance of both sensors will be evaluated and compared in the field for application in gravelly soils. The decagons and TDRs were calibrated using the gravelly soil from the field, over the range of volumetric water contents estimated for unsaturated conditions in gravel. However, when comparing measurements between these two types of sensors the cylinder of influence as well as sensitivity to temperature changes should be taken into account.
Table 2. Technical information about the sensors installed.

| Sensor        | Name       | Brand                  | Length | Measuring range                  |
|---------------|------------|------------------------|--------|----------------------------------|
| Decagon       | EC-5       | Decagon devices         | 0.089 m| Apparent dielectric permittivity $\xi_a$ 1-50. |
| TDR           | TDR100     | Campbell Scientific    | 0.15 m | Apparent dielectric constant $K_a^{0.5}$. |
| Tensiometers  |            | Keller AG Company Heraeus| 0.15, 0.30, 0.45 m | 80-85 centibar. |
| Temperature sensors | RTD PT100 |                        |        | -50 to 100 °C.                    |

3.2. *ERT*

A 2D electrical resistivity survey was carried out on a fixed profile line next to the instrumented trench 1 (figure 1) to complement the TDR and decagon point measurements, achieving a more widespread characterisation of the subsurface. The basic principle of geoelectrical resistivity measurements involves the injection of current into the ground through a pair of electrodes and measuring the resulting potential in the form of a voltage difference at another pair of electrodes along the subsurface current flow. 48 electrodes were planted along the profile line and the Syscal Pro system (IRIS instruments) was used to conduct six ERT measurements (three of which are presented here) in a monitoring phase from May to July, 2014. A Wenner configuration was used for all acquisitions due to the highly resistive environment. The inversion was performed using the BERT (Boundless Electrical Resistivity Tomography) software package [6, 10, 11, 12, 13].

3.3. *Archie’s law*

ERT measurements are highly susceptible to changes in the subsurface water content/saturation as the current injected during a geoelectrical survey flows mostly through the pore water. An empirical relationship between the resistivity of a porous medium to the amount of pores, their connectivity and saturation, as well as the resistivity of the pore filling fluids, was found by Archie [7]:

$$\rho = a \rho_w \Phi^{-m} S^{-n}$$  \hspace{1cm} (1)

where $\rho$ is the resistivity of the porous soil, $\rho_w$ is the resistivity of the pore filling fluid, $\Phi$ is the soil’s porosity and $S$ its saturation which can also be expressed as the ratio between the water content $\theta$ and the porosity (eq. 2). Furthermore, $a$ is the tortuosity factor set to 1 for granular soils, $m$ is the cementation factor and $n$ is the coefficient of saturation. The latter two factors are taken from literature (e.g. [7, 14, 15]) and are assumed to be constant: $m = 1.3$ and $n = 2$.

$$S = \frac{\theta}{\Phi}$$  \hspace{1cm} (2)

Archie’s law is considered to be valid in this case, as the soil consists mainly of gravel and sand and contains almost no fine material, especially clay (figures 2 and 3 and table 1) and has enabled effective comparisons between geotechnical soil moisture measurements and ERT acquisitions (e.g. [16, 17, 18]). The temporal variation of soil resistivities along the repeatedly measured profile can therefore be
related to the temporal variation of soil saturation or water content (under the assumption that the porosity and the pore water resistivity remains constant) as:

\[
\rho_t \frac{1}{n} - \rho_{t_0} \frac{1}{n} = \ln \left( \frac{\rho_t}{\rho_{t_0}} \right) - 1 = \frac{S_t - S_{t_0}}{S_{t_0}} = \frac{\Delta S}{S_{t_0}} = \frac{\Delta \theta}{\theta_{t_0}}
\]

(3)

The profile measured on May 15, 2014 was chosen as the baseline model (at time \( t_0 \)) and variations in saturation in later acquisitions are relative to this profile. The advantage of this approach is the fact, that none of the constants (except for \( n \)) nor the porosity or the resistivity of the pore water need to be estimated to see a seasonal variation in soil saturation. The resulting trend can relatively be compared to the readings obtained from TDR and decagon measurements.

To achieve a more detailed comparison however, the parameters in Archie’s law have to be estimated from soil and water samples extracted from the field and analysed through lab and field experiments. The values of the key parameters (\( \Phi \) and \( \rho_w \)) have been estimated at this stage of the project on the basis of preliminary tests and the literature. These can be refined to improve the calculated soil saturation (and VWC) for comparison with field measurements in the trenches.

4. Results and discussion

4.1. Instrumented trench IT1

The data recorded from the end of October 2013 to April 2015 are shown in figure 4, representing variations from four seasons with data from two winter’s. The change of volumetric water content at 25 cm depth shows a general agreement between the measurements from the TDRs and decagons for the first eight months. The decagon readings differ from the TDR recordings after the rockfall event (beginning of August), but it is not possible to affirm that the impact of the rockfall affected the results at this depth. Values decrease to a minimum VWC during winter time (end of December to end of March), probably due to the accumulation of snow, leading to a low or non-existent rate of rain infiltration. This situation changes from April 2014 (spring season) through snow melt and rainfall, and continues to fluctuate due to varying seasonal precipitation to the end of 2014. Changes in VWC occur following to rain peaks. There is a gap from October 12 to November 10, 2014, with no precipitation information available at this time. However, it is still possible to see the variations in VWC, most probably due to precipitation.

A comparison of the temperatures in the soil at 15 cm depth and in the data logger, which was considered to be the local exterior temperature on the soil’s surface, was also plotted in figure 4. Temperatures are around 0°C, with minimum variation, for both sensors during the winter season, and this trend continues until April 2014. The temperatures increase again in May (spring season), and stay mainly between 10 – 15°C until August 2014 (summer season). They decrease again during November 2014 (autumn) and remain near zero degrees, illustrating an annual temperature curve with a range from approximately -8 to +26 °C.

A rockfall happened at the beginning of August 2014 (figure 4) during an extended period of rain, with a debris flow observed (dashed brown line) at the end of July. At least one large boulder hit the trench breaking the stake and exposing the soil temperature sensor, causing some instability in the readings. An offset between the decagon and TDR readings was also observed. The boulder was removed and the sensor placed in the trench again on August 28, 2014, after which the temperature sensors (but not the decagons and TDRs) were recording similarly again. The VWC increased during January 2015, as water melted in the voids, when temperatures changed from a period of negative temperatures to above 0 °C.

Figure 5 shows the variation of pore water pressure with precipitation (SR50A weather station), recorded by the tensiometers, which were installed in June 2014 at depths of 15, 30 and 45 cm
approximately three meters uphill of IT1. The correlation between the loss in suction after rainfall events can clearly be observed, in particular after all tensiometers show a significant increase in pore water pressure during the period of higher frequency in precipitation (July 2014). In addition, it should be noted, that the shallower tensiometer reacts faster the deeper tensiometers after a rainfall event, according to the direction of infiltration with depth.

Figure 4. Measurements at IT1. From top to bottom: volumetric water content at 25 cm depth measured with TDR and decagons, temperature at 15 cm depth and in the data logger at the surface and daily total precipitation (28/10/2013-11/04/2015). Precipitation data were not recorded or not available during two periods, indicated in the bottom figure. A rockfall happened at the beginning of August (labelled black arrow), right after the second debris flow event (dashed brown lines indicate the two largest such events). Also indicated are the three ERT data acquisitions (magenta arrows), from which results are presented later (figure 8). The colour change in the background reflects time windows during which tensiometer measurements (orange, figure 5) or readings at instrumented trench IT3 (blue, figure 6) are available. Precipitation data were supplied by WSL during the period of 2013 to October 2014.

4.2. Instrumented trench IT3

IT3 was installed at the end of October of 2014, and mainly reflects the seasonal changes in volumetric water content and temperature during the most recent autumn and winter seasons, with a short
period corresponding to the beginning of the spring. Data from two sensors, a TDR and a decagon, located at depths of 15 and 20 cm respectively, are plotted in figure 6 to show the change in VWC with temperature and precipitation. A comparison between the VWC values indicates similar trends in the readings, whether they originated from TDR or decagon, however some discrepancies are noticeable in autumn and winter (December and January) and spring time (April). These changes could be due to a higher sensitivity of the decagons to a period of negative temperatures (from December to mid of January) and the differently sized cylinders of influence for the two types of sensors. TDRs have larger cylinders of influence and could therefore be considered as more representative measurement. Furthermore, a difference in readings might arise from the different installation depths of the two sensors.

![Figure 5. Tensiometer measurements at trench IT1](image)

**Figure 5.** Tensiometer measurements at IT1 and precipitation data (25/6/2014-11/10/2014). Two debris flow events in the Meretschibach are indicated (brown dashed lines) and the ERT acquisition (figure 8) on July 25, 2014 (magenta arrow). Precipitation data were supplied by WSL from the meteostation (SR50A) located at Meretschihorn 2220 m.a.s.l.

Temperatures remained near or below zero during the winter season (end of December to end of March), and the VWC reached minimum values due to minimal precipitation in form of rain (figure 6). An increase in VWC is observed during the beginning to mid-January in the form of two peaks. The occurrence can be explained due to ice or snow melting after a transition from a negative temperature period to 0 °C, or slightly above freezing temperatures. The increase in temperature manifests itself in two corresponding peaks within the surface temperature and a continuous period of higher values in the soil temperature near 0 °C. The peaks in VWC during winter do not correlate with peaks in precipitation, as no such peaks are observable in the remaining winter period (February-March 2015) even though peaks in precipitation (mostly snowfall) can be noted. Peaks of VWC at IT3 show up in a very similar manner in IT1 (figure 4 and 7, discussion in section 4.3).

Changes in VWC are also observed in April 2015 (figure 6), when spring starts, but temperatures still remain close to 0 °C. A correlation to (a) rainfall event(s) is obvious; however thawing cycles could play a role in the increase of VWC in the soil, as the snow at the higher elevation start to melt.

In IT3, the decagon appears to be more sensitive to variation of precipitation and temperature, compared to the TDR. The relatively higher sensitivity of the decagon device is not as clearly detectable in IT1. During winter, at the end of 2014 (figure 6), the decagon records more variation whereas the TDR device remains relatively steady at low VWC values over the entire season.
Figure 6. Measurements at IT3. From top to bottom: volumetric water content at 15 and 20 cm depth recorded with TDR and decagon sensors, temperature at 15 cm depth and in the data logger at the surface and daily total precipitation measured with Pluvio OTT at 1370 m.a.s.l. (11/11/2014 - 11/04/2015). It should be noted, that the meteostation failed to record data during a period of four days (December 18-21, 2014) for unknown reasons.

4.3. Comparison between instrumented trenches

Figure 7 shows the comparison of the volumetric water content at IT1-IT3, located at elevations of 1868 m.a.s.l. and 1914 m.a.s.l. respectively. TDR and decagons were plotted separately, one from each trench over the same period, (as shown in figure 4 and 7, marked with a blue background).

In addition, the precipitation and temperature are plotted in the same figure to facilitate a comparison in terms of correlation. The records of VWC agree within the seasonal changes: the changes in autumn (November- December 2014) are due to precipitation (rain/snow), and during winter when it reaches a minimum, the changes (e.g. the two peaks in beginning to mid-January 2015 marked in grey background) reflect rather temperature variations (thawing - freeze cycles) than actual increases in precipitation. Variations at the beginning of the spring season (April 2015) due to precipitation in the form of rainfall are again observed.

Most interestingly, the two large peaks in VWC data in January 2015 (figure 7, grey background) were recorded in a very similar manner in both trenches. This not only means that both types of instruments expressed a comparable sensitivity most likely to a temperature variation, resulting in thaw-
ing (as discussed in section 4.2), but also that this specific event influenced the entire scree slope instead of isolated locations.

Figure 7. Comparison between TDR and decagon measurements at IT1 and IT3 during the period of 11/11/2014-11/04/2015 (same length of time as in figure 6).

The possibility of isolated and sudden events such as avalanches on the scree slope is also considered for an explanation, although this scenario does not necessarily imply an increase of the VWC in the point of view of the authors. Instead, an explanation for this abrupt increase can be attributed to the difference in the dielectric constant of water and ice (approx., 80 and 3, respectively [6]). According to the Topp equation used for TDR calibration [3], the VWC increases with the dielectric constant. Since the total dielectric constant of a soil can be estimated from its components (solid, water and air), freez-
ing/thawing cycles have an impact on the magnitude of the calculated VWC. A better understanding of this widespread type of event will be possible when photographs from permanently installed cameras at the scree slope near IT3 are retrieved.

Furthermore, a third peak occurring at the end of December 2014 (grey background), was only detected by two decagons, but the peak remained smaller in IT1 compared to IT3. An increase in temperature was measured in both trenches at the same time. This again suggests a greater sensitivity of decagons (as an instrument type) to changes in temperature, in particular after longer periods of sub-zero conditions. Variations in VWC between trenches, as shown in figure 7, can be due to a difference in the gravel characteristics as described in figures 2 and 3.

4.4. Comparison between ERT and TDR

The resulting geoelectrical tomograms in figure 8, show the subsurface resistivities obtained from inversion of the ERT data acquired on May 15, June 16 and July 25, 2014. All models depict a two-layered subsurface: an upper, relatively low resistive layer, which can be attributed to the gravelly soil and a highly resistive layer underneath, which is assumed to represent the quartzite bedrock.

The precipitation data before each of the acquisitions (magenta arrows in figure 8) show that the conditions were dry and undergoing a drainage phase for the first two campaigns, whereas the data acquired in July was recorded within a period of heavy rainfalls. These seasonal changes are mostly reflected in resistivity changes within the soil layer, in particular as a significant reduction of resistivities in the July model. The saturation relative to the subsurface model obtained in May clearly reflects these conditions; there is a slight near-surface decrease in saturation in June, whereas an increase in saturation is observed within the soil layer in July. This trend in near-surface soil saturation corresponds very well to the volumetric water content measurements (which are directly proportional to saturation) from TDR and decagons installed at shallow depths within trench 1 (lowermost graph in figure 8).

5. Conclusions

Combining geotechnical and geophysical techniques, has lead to greater insight about the characterisation of the ground forming the scree slope and its response to rainfall and snow in terms of saturation and desaturation. A monitoring campaign was designed to investigate this, using different methods consisting of two types of sensors installed in instrumented trenches to determine the VWC. ERT was used to obtain resistivities which can be converted to VWC through Archie’s law.

The monitoring of two instrumented trenches (IT1-IT3) gives valuable information regarding the response of the volumetric water content and temperature in the soil due to seasonal weather changes. In this aspect, the VWC increases in spring due to thawing cycles and precipitation in the form of rain, and reaches the lowest values during winter when temperatures, that stay near 0 °C or below, could lead to soil freezing under the protective insulation of a snow cover. The occurrence of isolated peaks in VWC during winter can be explained by thawing after relatively extended periods of subzero temperatures.

There is a good agreement in the data trend between decagons and TDR, but some differences can be observed, either due to rockfall events (IT1) or a greater sensitivity of one of the sensors, e.g. decagons to temperature changes during thawing periods (IT3). Additional sensor specific conditions, such as the cylinder of influence, can account for variations in the readings. The data collected from VWC in both trenches show that the response to seasonal changes are similar for the shallower layers at two different elevations on the scree slope.

The analyses of the volumetric water content time series obtained from instrumentation in the trenches not only showed very plausible seasonal trends and a clear correlation to increases in precipitation, but also compared reasonably well to saturation trends calculated from ERT measurements, conducted on different dates from May-July 2014. Thus, these results illustrate how well geotechnical and geophysical measurements can complement each other. Furthermore, models obtained from dif-
ifferent ERT acquisitions consistently showed a subsurface separable into a highly resistive, underlying bedrock at shallow depths and a less resistive gravelly soil layer at the surface.

**Figure 8.** The uppermost row shows the resulting geoelectrical tomograms from May 15, June 16 and July 25, 2014. The resistivity scale beneath the tomograms is the same for every acquisition. The row below shows the increasing and decreasing saturation, relative to the subsurface model obtained on May 15. Finally, the three acquisition dates are indicated (purple arrows) within the precipitation and the volumetric water content measurements from TDR and decagon instrumentation in trench 1, shown in the lower most graphs from 01/05/2014-01/08/2014. Also indicated in both graphs are the debris flow events in July (see figure 4 for description).
6. References

[1] Oggier N 2011 Simulierung von Murgängen mit RAMMS am Beispiel des Meretschibachs
Master Thesis ETH Zürich & Forschungsanstalt für Wald Schnee und Landschaft (WSL)

[2] Rickenmann D and Zimmermann M 1993 The 1987 debris flows in Switzerland documentation
and analysis Geomorphology 8(2) 175-89

[3] Askarinejad A 2013 Failure mechanisms in unsaturated silty sand slopes triggered by rainfall
ETH Dissertation Nr. 21423

[4] Lucas D R, Askarinejad A A, Herzog R, Bleiker E and Springman S M 2015 Volumetric
water content determination by TDR sensors and decagons in gravelly soils submitted to the
XVI European Conference on Soil Mechanics & Geotechnical Engineering (ECSMGE)
Edinburgh

[5] Springman S M, Lucas D R, Oggier N C, Kos A, Fankhauser K and Mc Ardell B, 2015
Study of the seasonal response of a scree slope and debris flow catchment in the Swiss alps
submitted to the XVI European Conference on Soil Mechanics & Geotechnical Engineering
(ECSMGE) Edinburgh

[6] Fankhauser K 2014 Geophysical slope characterization using GPR and ERT in an active
debris flow catchment Master Thesis EEG ETH Zurich

[7] Archie G E 1942 The electrical resistivity log as an aid in determining some reservoir
characteristics AIME 146 54-62

[8] Friedel S, Thielen A, Springman S M 2006 Investigation of a slope endangered by
rainfall-induced landslides using 3D resistivity tomography and geotechnical testing J. of
Appl. Geophys. 60 100-14

[9] Teyssseire P 2005 Geotechnische Eigenschaften von Möranen ETH Dissertation Nr. 16322

[10] Günther T, Rücker C and Spitzer K 2006 Three-dimensional modelling and inversion of DC
resistivity data incorporating topography - II. Inversion Geophys. J. Int. 166 506-17

[11] Günther T and Rücker C 2013 Boundless electrical resistivity tomography - the user
tutorial available at: www.resistivity.net

[12] Rücker C, Günther T and Spitzer K 2006 Three-dimensional modelling of DC resistivity
data incorporating topography - I. Modelling Geophys. J. Int. 166 495-505

[13] Günther T 2011 Timelapse ERT inversion approaches and their applications Int. Workshop on
Geolectric Monitoring Within the Frame of the FW Project TEMPEL (TRP 175-n21) and the 7th
FP European Project SafeLand: Berichte der geologischen Bundesanstalt Nr.93
(Vienna, 30 November - 2 December 2011) pp 91-7

[14] Lowrie W 2007 Fundamentals of Geophysics (New York: Cambridge University Press)

[15] Schön J 1983 Petrophysik Physikalische Eigenschaften von Gesteinen und Mineralen
(Berlin: Akademie-Verlag)

[16] Brunet P, Clément R and Bouvier C 2010 Monitoring soil water content and deficit using
Electrical Resistivity Tomography (ERT)–a case study in the Cevennes area France J. of
Hydro. 380(1) 146-53

[17] Lehmann P, Gambazzi F, Suski B, Baron L, Askarinejad A, Springman S M and Or D 2013
Evolution of soil wetting patterns preceding a hydrologically induced landslide inferred from
a resistivity survey and point measurements of volumetric water content and pore
water pressure Water Resources Research 49(12) 7992-8004

[18] Springman S M, Thielen A, Kienzler P and Friedel S 2013 A long-term field study for the
investigation of rainfall-induced landslides Geotechnique 63(14) 1177-93

Acknowledgments
The authors are most grateful for funding from the SNF Project No. 200021_144326/1 and Canton
Valais, together with the Councils of Agarn and Leuk. The project also contributes to the TRAMM2
programme of the Competence Centre of Environmental Sustainability.
In particular, we wish to acknowledge the support from Pascal Stoebener, WSL, as well as to Professor Dr. Hansruedi Maurer (Exploration and Environmental Geophysics, EGG), Dipl. Ing. Ralf Herzog, Ernst Bleiker and to Nicole Oggier, for giving access to part of the rainfall data used in the analysis.