

MONITORING OF SUBSURFACE DEFORMATIONS USING TIME DOMAIN REFLECTOMETRY

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INTRODUCTION

In context of the global climate change an increase of extreme precipitation events is expected for Europe and the Alps (Alcamo et al. 2007). As heavy rainfall is an important trigger for landslides, the frequency of hazardous landslide events is also expected to rise. Luckily in most alpine regions the awareness of landslide hazards has risen in the last years, driven by national and regional hazard mapping programs (e.g. in Bavaria (LfU 2009), Switzerland (Lateltin et al. 2005) and South Tyrol (Willerich et al. 2008).

Although many potentially hazardous landslides have been identified, due to economic reasons only few are continuously monitored. In many cases only sporadic geodetic surveys are performed, which is not sufficient when infrastructure or even human life is at risk. In order to overcome this, efficient and economic measurement systems for landslide monitoring are needed.

In order to evaluate a deep seated landslide, observations from the surface are not sufficient. Detailed information about the depth of the slope movements and their changes through time are needed.

MONITORING OF SUBSURFACE DEFORMATIONS

The direct measurement of subsurface deformations is only possible in boreholes. To date, if continuous monitoring is required, usually inclinometer chains are used for this task. While these allow to determine subsurface deformations with high precision, the associated costs are quite high. So often continuous monitoring is rejected in favor of cheaper sporadic measurements.

With a Time Domain Reflectometry (TDR) measuring system continuous monitoring of subsurface deformation can be performed at 25 % and less of the costs compared to inclinometer chains. However the landslide mechanism has to meet some premises in order to be able to use this measuring system, as it is limited to the detection of localized shear zones.

TIME DOMAIN REFLECTOMETRY (TDR)

A TDR measuring system consists of three major elements (figure 1): 1. the measuring device (TDR cable tester including data logger and multiplexer), 2. the measuring cable (usually semi rigid coaxial cable for easy installation) and 3. the lead cable (low loss coaxial cable) which connects the measuring cable to the measuring device.

For landslide monitoring the measuring cable is installed into a borehole and connected to the rock mass with grout. When the rock mass starts to move in a shear zone, the coaxial cable is deformed, altering the distance between inner and outer conductor of the cable. This change in the cables geometry can be identified, localized and analyzed using a TDR cable tester (Singer et al. 2006).

TDR can simplified be described as “cable-based radar” (O’Conner & Dowding 1999): The TDR cable tester emits electric pulses which are sent through a coaxial cable. When these pulses approach a deformed portion of the coaxial cable a signal is reflected to the cable tester. As with radar, due to the known propagation velocity of the electromagnetic wave within the coaxial cable, by measuring the time span between emission and reception of the electric pulse, the distance to the deformation can be determined with high accuracy. Furthermore the analysis of the reflected signal (amplitude, width, etc.) can reveal information about the type and amount of deformation.

If the measuring cable is bent with a large radius (for landslides: gradual deformation over several decimeters or meters of soil) the distance between the inner and outer conductor of the coaxial cable is not changed sufficiently to produce a TDR signal. Therefore TDR measurements generally are limited to discrete deformation zones with a width of centimeters to decimeters. In this context the mechanical properties of the grout used to connect the measuring cable to the surrounding rock mass is of utmost importance.

But not only the grout composition (strength, mode of deformation) influences TDR measurements, also the measuring cable type (conductor material, diameter) and lead cable type and length (signal attenuation) have to be considered. Prior to installation all these parameters have to be chosen according to the expected deformation mechanism and velocity of the landslide.

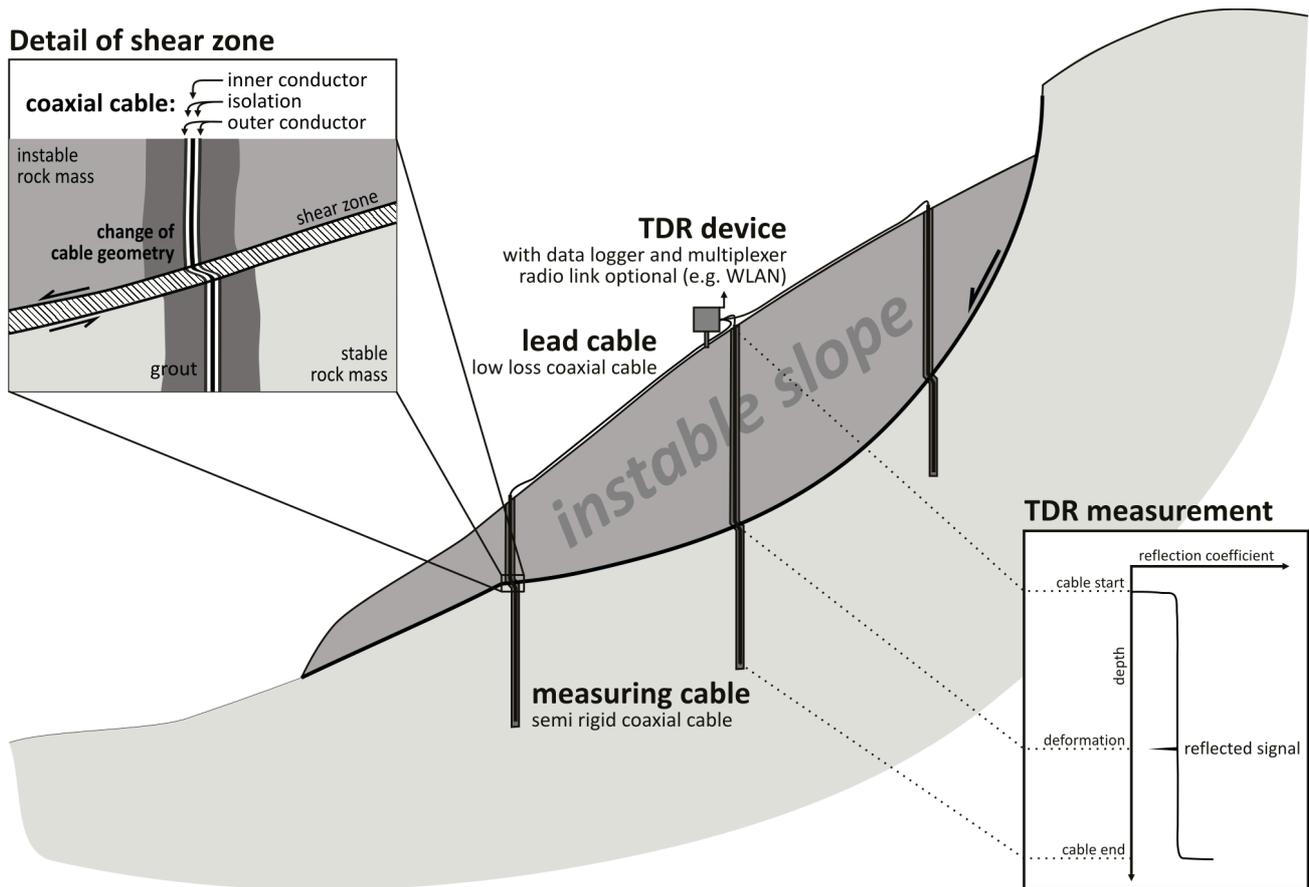


Figure 1 – Installation scheme of a TDR landslide monitoring system (according to Singer et al. 2006, edited).

LABORATORY SHEAR TESTS

In order to characterize and then optimize the installation parameters of the TDR measuring system, a large number of laboratory shear tests were conducted in an especially developed test stand (Singer et al. 2006), which allows to shear grout columns with varying diameters at different shear rates and with varying shear zone thicknesses.

GROUT

Main focus was thereby put on the grout: different cement-bentonite-water mixtures were analyzed (Festl 2008), starting from mixtures which usually are used when installing inclinometers. Considering also the viscosity and stability (shrinkage) of the grout, only a relatively small variety of mixtures seem suitable for TDR installation (figure 2).

Depending on the type and speed of the observed landslide different grout mixtures should be used. E.g. for a slow rock slide (> 1,6 m / year according to Cruden & Varnes 1996), mixtures with high water and bentonite content should be used, resulting in a higher measurement lifespan before cable failure. In an extremely slow earth slide (<

1,6 cm / year) a mixture with less water and medium bentonite content should be used, which leads to a high sensitivity but not too high strength of the grout. This ensures that the moving rock mass is able to fracture the grout and will not plastically flow around the grout column.

BOREHOLE DIAMETER

When selecting the grout mixture also the borehole diameter has to be considered as another factor controlling the total strength of the grout column. For good measuring results (especially in soft rocks) the coaxial cable should be covered by at least 1 cm of grout. For a typical 12 mm semi rigid coaxial cable (see below) the minimum drilling diameter thus would be 32 mm. The centered installation of the coaxial cable can be assured using spacers, as they are used for armored concrete.

Besides an exclusive borehole installation, TDR cables can often also be installed into sheared inclinometer casings, thereby considerably extending the usability of an existing borehole.

MEASURING CABLE

Generally any coaxial cable can be used as measuring cable. O'Connor & Dowding (1999)

suggest using semi rigid coaxial cables, as these on the one hand make an easy installation possible, and on the other hand seem to enable to achieve a relatively high reproducibility (and thus accuracy) in the TDR measurements. A well tried rigid coaxial cable for deformation measurements is the Commscope P3-500 JCA with 12 mm diameter, aluminium outer conductor, copper claded steel inner conductor and a PVC jacket, which is available at a comparable low price of about 3 €/m. The jacket protects the aluminium cable from corrosion, which is an issue especially when installed into ground water.

LEAD CABLE

One great advantage of the TDR measuring system is that multiple measuring cables can be read out with one measuring device, thereby drastically reducing the costs per measuring site. In order to achieve this, the different measuring sites have to be connected to the TDR measuring device using high quality low loss coaxial cables. However, with increasing length an exponential attenuation of the signal was observed, limiting the lead cable length depending on the type of cable used to under 150 m (Woytowitz 2008).

CALIBRATION

All the above installation parameters have to be considered, when analysing TDR signals. Based on the ongoing laboratory shear tests installation parameter combinations are currently being defined for typical landslide settings. For these combinations extensive calibration shear tests are performed in order to quantify the reproducibility and accuracy of the TDR measurements and to determine calibration curves as basis for an automated signal analysis, which will allow to not only determine the position of the deformation zone with high accuracy, but also the amount of deformation. In the laboratory environment accuracies below 5 mm have been achieved for the quantification of the deformation amount.

ANALYSIS SOFTWARE

With help of the newly developed TDR signal analysis software “tumTDR” the raw data received from the measuring device can be visualized in various different ways, allowing an experienced user to perform a first evaluation and interpretation of the collected data. After that an automated deformation analysis of the data is possible, whereby deformation zones are automatically identified and the deformation is quantified using the calibration curves determined in the laboratory shear tests (Singer et al. 2009). The software currently is in a beta status with all major functions operable.

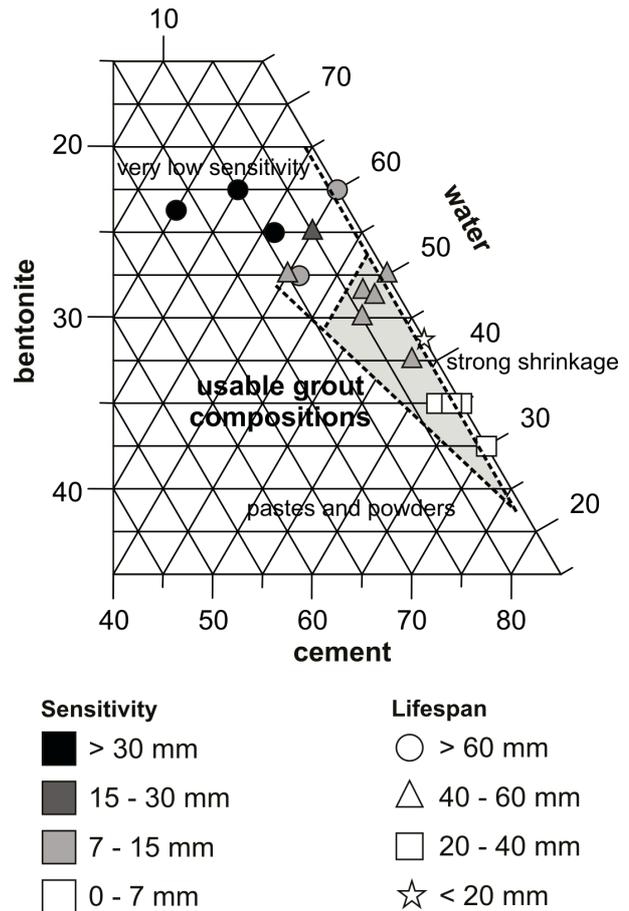


Figure 2 – Results of several TDR shear tests with different cement-bentonite-water mixtures (mass-%) (according to Festl 2008, edited). The shear tests were conducted with a shear width of 15 mm and a shear rate of 2 mm / min. In each test the sensitivity and the cable lifespan was determined. Additionally the shrinkage of the grout during hardening was measured. As the grout has to be pumpable during installation, also the viscosity limits the useable grout mixtures for TDR deformation measurements (grey area).

FIELD TEST

A calibrated TDR measuring system has been installed at the Aggenalm Landslide near Bayrischzell (Bavarian Alps) as part of a geo sensor network containing several other measuring devices for surface deformations and trigger factors (e.g. precipitation, ground water levels) (Thuro et al. 2009).

This installation is the first test for the signal analysis based on a calibrated installation setup. The parallel installation of TDR and inclinometers will make an evaluation of the measurement accuracy in field possible. In other actual landslide installations the TDR measuring system was proven functional (figure 3), but in lack of a calibrated setup the amount of deformation could not be determined accurately.

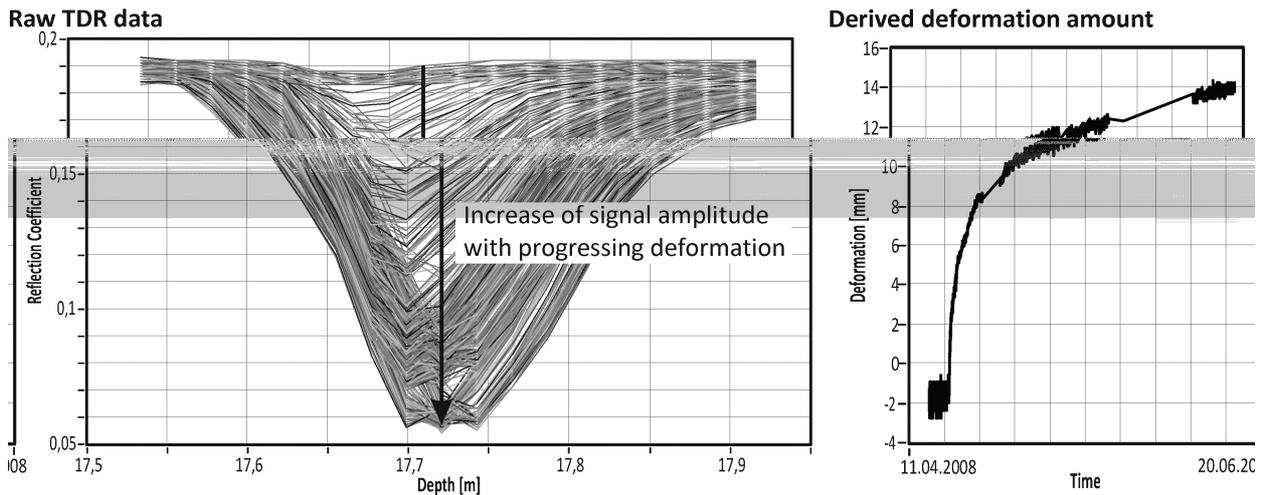


Figure 3 – Results of a TDR field test in a slow earth slide. The depth of the shear zone can be determined with high accuracy. In lack of a calibrated installation the accuracy of the deformation amount can not be stated, although the results were in compliance with inclinometer measurements conducted parallel to the TDR measurements.

CONCLUSION

If the Aggenalm Landslide field test is successful (especially regarding the measurement accuracy), the TDR measurement system will have proven to be a powerful technique for subsurface deformation monitoring if the landslide mechanism fulfills some premises (discrete shear zone) and calibrated installation setups are used. Compared to inclinometer the installation costs can be cut down by up to 75 % due to the low minimum borehole diameter, low material costs and the fast and easy installation. Also the expenses for a measurement device (including data logger) are reasonably lower than those for an inclinometer chain, which allows continuous monitoring – a task easily achieved with TDR. Continuous monitoring is generally strongly recommended when using TDR, since this leads to reduced personnel costs and at the same time provides the best data basis for an automated deformation analysis using the tumTDR software.

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