**ABSTRACT:** In recent years time domain reflectometry (TDR) has been introduced as a new system for subsurface deformation monitoring in boreholes. As TDR can easily be operated continuously using dataloggers it is an economic alternative to expensive inclinometer chains. To date TDR can identify and localize discrete deformation zones with high accuracy. As TDR measurements are influenced by a great variety of parameters, as for instance the used coaxial cable and grout type, they often are ambiguous, thereby hindering the quantification of the deformation. By the definition of calibrated installation standards and the usage of signal analysis software, it is possible to overcome this and reliably quantify deformation using TDR. Since TDR data can be acquired continuously as well as remotely, it is possible to integrate a TDR measuring system into a geo-sensor network.

1 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.

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.

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 determining 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.

2 TIME DOMAIN REFLECTOMETRY

A TDR measuring system consists of three major elements (Fig. 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 (O’Conner & Dowding 1999).
TDR can simplified be described as “cable-based radar”: 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 (Dowding et al. 1988): e.g. the amplitude of a TDR correlates to the amount of shear deformation the cable is subject to.

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 great importance.

3 CALIBRATION

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. O’Conner & Dowding 1999 already summarize several findings concerning the quantification of these parameters; however they are not directly applicable to practical field measurements. Therefore a calibration method based on empirical observations from laboratory shear tests has been developed (Fig. 2), which allows to easily account for most influences and leads to a more accurate quantification of deformation using TDR.

3.1 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 (Fig. 3).
3.2 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, aluminum outer conductor, copper cladded steel inner conductor and a PVC jacket, which is available at a comparable low price of about 3 €/m. The jacket protects the aluminum cable from corrosion, which is an issue especially when installed into ground water.

3.3 Grout

As stated earlier the grout plays an essential role, as it transmits the deformation of the surrounding rock/soil mass to the measuring cable and therefore influences the relation between deformation and the TDR signal amplitude, which is used for the quantification of the deformation. Furthermore within certain limits the grout controls the life span (amount of shear deformation a coaxial cable can be subject to before it severs) and sensitivity (shear deformation needed for detection) of the TDR measuring system.

In an extensive laboratory program several different cement-bentonite-water mixtures partly using cement admixtures were analyzed. Using the Commscope P3-500 JCA measuring cable and considering...
the limits in grout composition due to the viscosity and stability (shrinkage) of the grout, sensitivities of 3 to 35 mm (high to low grout strength) and life spans from 7 to above 160 mm (limit of the laboratory shear apparatus) were determined for different grout mixtures.

The grout used in a field installation should therefore be adapted to fit the expected rate of deformation.

3.4 Standardized installation setups

As the calibration procedure depicted in figure 2 is elaborate, standardized installation setups (combination of grout mixture and cable) have been defined for typical landslide mechanisms and speeds (Table 1). As these have been calibrated, they are ready to use for field measurements.

<table>
<thead>
<tr>
<th>Rock slide velocity</th>
<th>Coaxial cable</th>
<th>Grout mixtures*</th>
<th>Life span &amp; Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>extremely slow</td>
<td>semi rigid, small diameter (&lt; 12 mm)</td>
<td>CBW 60-35-05</td>
<td>30 / 3</td>
</tr>
<tr>
<td>slow</td>
<td>medium diam. (12 mm)</td>
<td>CBW 55-40-05</td>
<td>50 / 6</td>
</tr>
<tr>
<td>very slow</td>
<td>semi rigid, large diameter (&gt; 12 mm)</td>
<td>CBW 50-45-05</td>
<td>55 / 8</td>
</tr>
<tr>
<td>“cm/year”</td>
<td>flexible, large diameter (&gt; 12 mm)</td>
<td>CBW 40-50-10</td>
<td>&gt;60 / 10</td>
</tr>
<tr>
<td>slow</td>
<td>medium “m/month”</td>
<td>any</td>
<td>any</td>
</tr>
<tr>
<td>“m/year”</td>
<td>fast, very fast, extr. fast</td>
<td>event detection only</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Simplified example of standardized installation setups for rock slides.

4 SIGNAL ANALYSIS

Using the newly developed TDR signal analysis software “tumTDR” the raw data received from the measuring device can be visualized, 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 (Figure 2 and Singer et al. 2009). The software currently is in a beta status with all major functions operable. In the laboratory environment accuracies below 5 mm have been achieved for the quantification of the deformation amount.

5 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).

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, but in lack of a calibrated setup the amount of deformation could not be determined accurately.

6 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 drastically reduced 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 recommended when using TDR, since this leads to reduced personnel costs and provides the best data basis for an automated deformation analysis using the tumTDR software.

REFERENCES

