Development of a continuous 3D-monitoring system for unstable slopes using Time Domain Reflectometry

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Abstract: In recent years Time Domain Reflectometry (TDR) has been introduced as a new system for landslide monitoring. Until now there have been no standards to define how to install cables or how to process the received data, especially when multiple TDR measuring points are connected to produce a 3D model of the deformation zone.

A TDR system basically consists of two components: a coaxial cable and a TDR measuring device ("cable tester"). The cable is installed in a borehole and coupled to the surrounding rock with grout. If the cable is subject to deformation, this can be measured using the TDR cable tester. An electric pulse with an ultra-fast rise is applied to the cable and a reflection is detected. Changes in geometry caused by deformation produce characteristic TDR signatures. Since the propagation velocity of the signal is constant, the distance is determined by measuring the time between initiation of the pulse and detection of its reflection. TDR measurements are influenced by a great variety of parameters. Cable and grout type, water content in the surrounding ground and the number and type of deformation are a few examples.

In the ongoing research attempts are made to define several different TDR measuring-system configurations (especially cable and grout type) where each is designated for a specific geological environment. These configurations are then calibrated in laboratory shear tests and finally tested in the field in real landslides, if possible by comparing them with inclinometer measurements.

By combining several of these calibrated TDR measurements positioned in a pattern or along a profile within a landslide, better knowledge of the position, width and type of the deformation zone can be achieved. Since the TDR data can be acquired remotely, a continuous collection of data also is possible. Thereby, outside influences (e.g. rainfall) on the landslide can be observed in real time.

Résumé: Au cours des dernières années, Time Domain Reflectometry (TDR) a été introduit comme un nouveau système de surveillance des éboulements (O'Connor & Dowding 1999). Jusqu'à présent, il n'existe aucun standard définissant comment installer les câbles ou comment traiter les données reçues, tout particulièrement lorsque de multiples points de mesure TDR sont connectés afin de produire une image 3D de la zone de déformation.

Un système TDR comprend globalement deux composants: un câble coaxial et un testeur de câble TDR. Le câble est installé dans un trou de forage et relié à la roche environnante à l'aide d'un enduit fixant. Si le câble est soumis à une déformation, celle-ci peut être mesurée à l'aide du testeur de câble TDR. Une impulsion électrique de fréquence très rapide est appliquée au câble et la réflexion est ainsi identifiée. Des changements dans la géométrie, causés par déformation, produisent des signaux TDR caractéristiques. Lorsque la vitesse de propagation du signal est constante, la distance est déterminée en mesurant la durée entre l'émission de l'impulsion et la détection de sa réflexion. Les mesures TDR sont influencées par de nombreux paramètres, tel que le type de câble, le type d'enduit fixant, la teneur en eau de la roche environnante, etc.

Dans la recherche actuelle, nous essayons de concevoir différents types de systèmes de mesure TDR (notamment, différents types de câbles et d'enduit), chacun étant adapté à un environnement géologique spécifique. Ces différentes variantes sont ensuite calibrées lors d'essais en laboratoire de cisaillement et finalement testés sur le terrain dans de réels éboulements. Si possible, les mesures seront comparées à des mesures d'inclinomètre.

En combinant plusieurs de ces mesures calibrées de TDR, positionnées sur un modèle ou le long d'un profil au sein d'un éboulement, une meilleur connaissance de la position, de la largeur et du type de zone de déformation peut être atteinte. Depuis que les données TDR peuvent être acquises à distance, une prise de mesures continuelle peut également être effectuée. De ce fait, des influences extérieures (pluies) sur l'éboulement peuvent être observées en temps réel.

Keywords: monitoring, landslides, mass movement, slope stability, grouting, underground installations

INTRODUCTION

Time Domain Reflectometry (TDR) is widely known as a system for the measurement of soil moisture (e.g. Topp, Davis & Annan 1980). With few modifications TDR can also be used for the monitoring of localized deformation in rock and soil. To date this application has only found wider acceptance in North America, while it is still largely unknown in Europe. This is surely based on the fact that so far most of the research has been carried out at the Northwestern University (Evanston/Chicago, Illinois) under the leadership of Dowding and O'Connor, who have without doubt proved the usability of TDR in landslide monitoring (O'Connor & Dowding 1999).

Especially the comparably low installation costs and the possibility to perform continuous measurements make TDR an interesting alternative to classic inclinometers. Presently, TDR landslide monitoring systems are capable of determining the exact depth of the observed deformation zone, while only a semi quantitative statement can be made of the amount of movement. The orientation of the movement can not be determined at all. Furthermore in most instances the application is limited to the measurement of localized deformation as it is typically observed in rock (e.g. localized shearing alongside joints) (Kane, Beck & Hughes 2001).

In the opinion of the authors some of these disadvantages can be overcome by defining standardized installation procedures (e.g. grout type, coaxial cable type) adjusted for different geologic settings. Furthermore new methods for the analysis of the received TDR data under development, especially when multiple TDR measuring points are connected to produce a 3D model of the deformation zone. This paper presents the planned research project as well as the preliminary results.

BASIC PRINCIPLES OF LANDSLIDE MONITORING WITH TDR

The monitoring of deformation in rock/soil using TDR is based on an indirect measuring method: the deformation itself is not measured (as with an inclinometer) but a directly dependant value, the change in impedance of a coaxial cable as a result of deformation, is measured.

Basic principle

The basic function of a TDR system is comparable to that of a radar system. In radar systems electromagnetic waves are emitted from a transceiver. As soon as the electromagnetic waves encounter an object (such as an aeroplane) they are partly reflected back to the transceiver where they are recorded and analysed. Since the propagation velocity of the electromagnetic wave is known (speed of light) the distance to the object can be determined by measuring the time delay between the emission of the signal and the reception of its reflection. Furthermore, by analysing the received signals certain information about the object, such as its size and shape, can be determined.

TDR can be described as “cable-based radar” and consists of two basic components: a combined transmitter/receiver (TDR cable tester) and a coaxial cable (Figure 1). The TDR cable tester produces electric impulses, which are sent down the coaxial cable. When these pulses approach a deformed portion of the coaxial cable an electric pulse is reflected and sent back to the TDR Cable Tester. The reflected signals are collected and analysed. As with radar, by measuring the time span between emission and reception of the signal the distance between the TDR Cable Tester and the deformation can be determined. Furthermore by analysing the reflected pulse (amplitude, width, form etc.) information about the type and amount of deformation can be obtained.

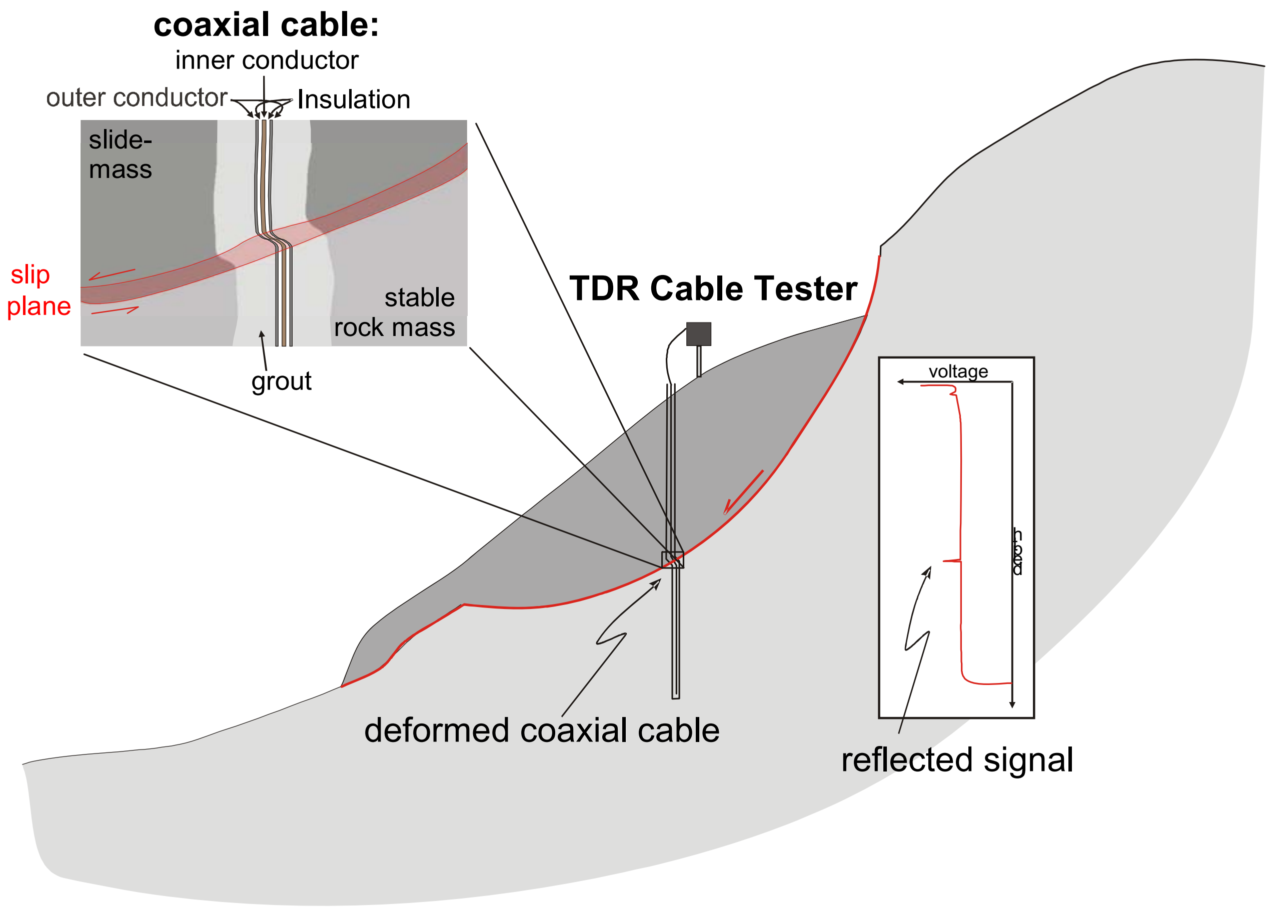

Figure 1. Basic setup of a TDR measuring site. The coaxial cable is installed into an instable slope and connected to the TDR cable tester. As soon as the coaxial cable is deformed by the mass movement a peak can be seen in the reflected signal. Its amplitude is directly dependant to the amount of deformation taking place.

Installation

As already mentioned, a TDR system for deformation measurements consists of two components: A TDR Cable Tester and a coaxial cable. A coaxial cable consists of an inner conductor which is surrounded by a cylindrical outer conductor. Both are separated by an insulating material, such as PE foam. TV cables are a typical example for coaxial cables.

For landslide monitoring the coaxial cable is installed into a borehole and connected to the rock mass with grout. There are basically three different installation methods (Figure 2): 1. The TDR cable is installed parallel to an inclinometer within the same borehole; 2. the coaxial cable is installed into a sheared inclinometer casing, therefore extending the lifespan of an inclinometer borehole; 3. the coaxial cable is installed into a borehole of its own.

The installation parallel to an inclinometer in the same borehole is primarily for research purposes, since a direct comparison of inclinometer measurements (direct measuring method) with the TDR readings (indirect measuring method) is made possible. For this reason this method will be a main part of the ongoing research. Nevertheless options 2 and 3 are probably the most appropriate installation methods for commercial use: option 2 because it extends the lifespan of an existing inclinometer borehole, and option 3 because a sole TDR installation can be established at comparably low costs, because of the relative small boring diameters required and the low cost of the coaxial cable.

Careful calibration of the entire system is a pre-requisite for ensuring the maximum quantity and quality of information (especially the deformation type and amount) through the indirect measurement of deformation with a TDR system.

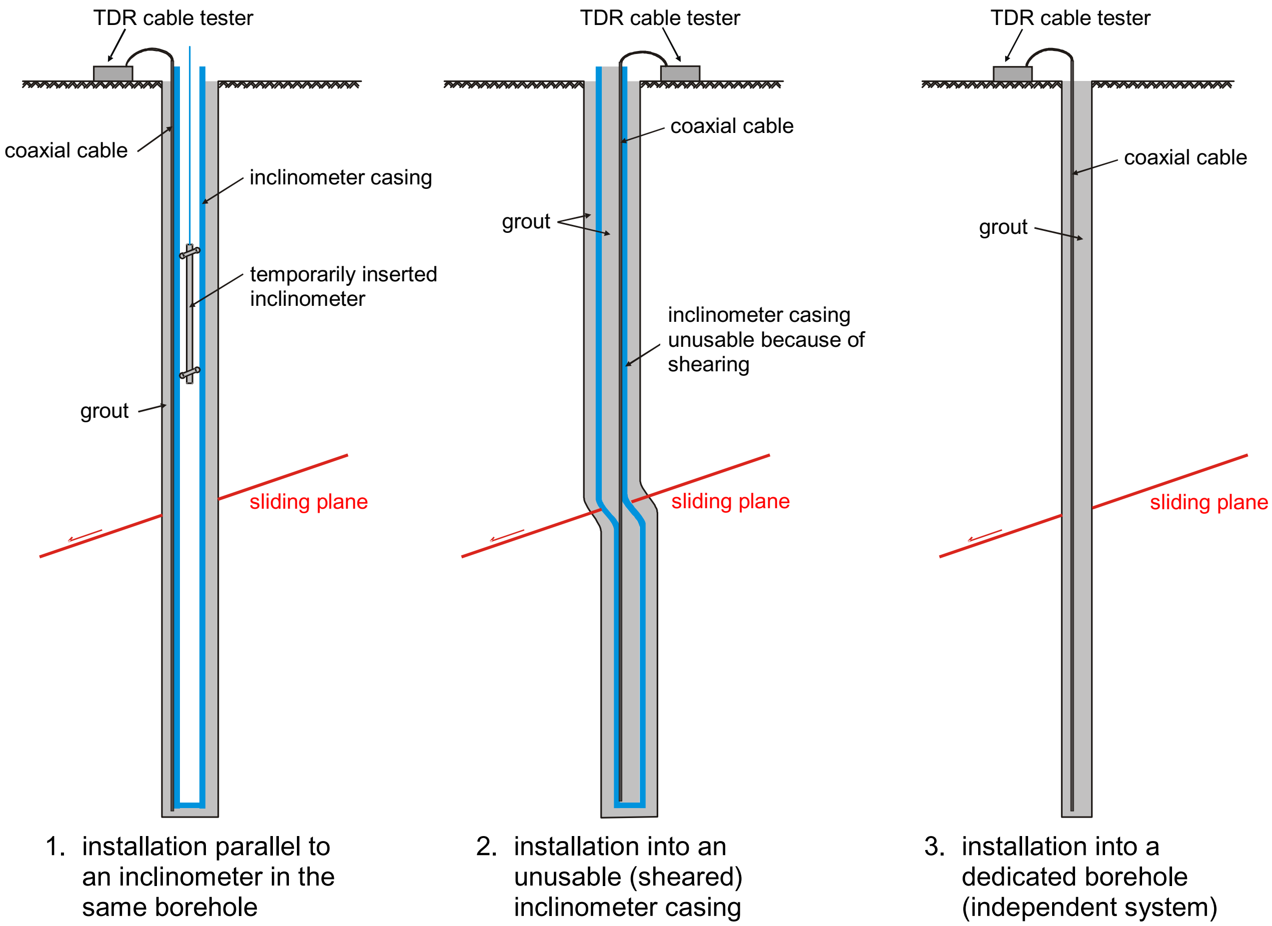

Figure 2. Possible installation setups for a TDR coaxial cable into a borehole with and without an inclinometer.

Influencing factors

Many different factors influence the measurement of deformation with TDR (O'Connor & Dowding 1999). Generally two groups of effects can be distinguished: the influence of the deformation itself and the installation parameters of the TDR system.

Deformation

TDR measurements are influenced greatly by changes in the geometry of the measurement cable. The type (shearing, extension and compression) and the amount of deformation, as well as the width of the deformation zone, affect the received signals. Prliminary simple tests have shown that discerning the different types of deformation is not always possible. However, especially with progressive deformation, a determination of the deformation type is sometimes possible (Figure 3).

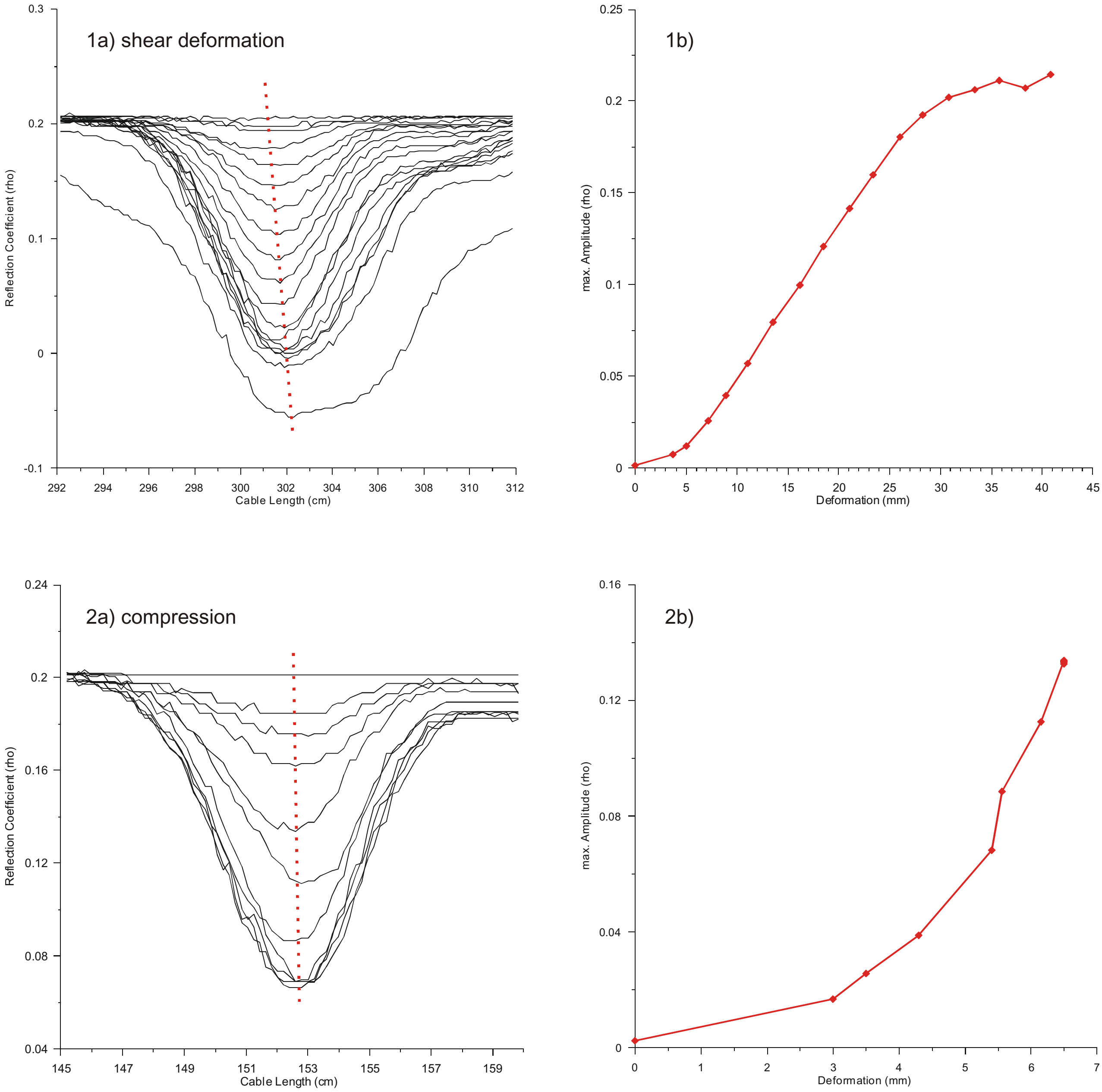

Figure 3. Comparison of TDR measurement results when shearing (1) and compressing (2) the coaxial cable. Note the progressive displacement of the peak maximum (shown by the red dotted lone) with proceeding deformation when the cable is sheared (1a), whereas it stays more or less static when the coaxial cable is compressed (2a). This suggests a likely method for distinguishing the deformation mechanism. The increase of maximum amplitude with progressive deformation is shown in diagrams 1b and 2b for shear deformation and compression, respectively. Measurements were made with a Campbell Scientific TDR 100 Time Domain Reflectometer and a CommScope P3 500 CA coaxial cable of 12 mm diameter.

Su (1987) has shown that with increasing shear deformation the amplitude of the observed peak rises. The dependence between the amount of deformation and the amplitude of the received signal is presented in Figure 3(1b) for a simple shear test. It can be seen that this dependence is not linear. The amplitude / deformation ratio is strongly reduced at the beginning and end of a test, and is therefore less sensitive.

With increasing width of the deformation zone, the sensitivity of the measurement is reduced. In the extreme condition, when the coaxial cable is bent slowly over a larger radius (rather than sheared in a narrow zone), the deformation can not be determined at all. This limits the application of TDR to landslides with a relatively localized shear zones (O'Connor & Dowding 1999).

Additionally, the distance between the Cable Tester and the deformation zone has a large influence on the measurement. The amplitude of the signal is reduced with increasing distance as a result of the attenuation of the signal along the cable (Pierce et al. 1994).

Installation parameters

It is evident from the preceding discussion that the components used in a TDR system, and the way it is installed into a landslide, influence the measurement. In particular, two parameters stand out in their importance: the type of coaxial cable used and the physical properties of the grout. The material from which the cable is made, its diameter and the length all influence the measurements. Generally, when using thicker cables, larger total deformations can be observed before the cable is severed. At the same time, the sensitivity of the system to small movements is reduced. Accordingly, thinner cables should be used for landslides with low deformation rates, and thicker cables for "faster" landslides.

The grout is the interface between the cable and the rock mass. It is, therefore, important to match the physical properties of the grout to the particular geology, especially when working in soil. If, for example, the grout is too strong, a pillar-effect might occur whereby soil moves around a pillar over-stiff grout, resulting in too little or no deformation of the TDR cable.

Varying the type of cable and the grout mix to suit the surrounding geology and the anticipated deformation rates will enhance the quality of the received TDR measurements. This is the main task of the ongoing research: defining certain installation procedures for different geological settings and deformation rates.

DEVELOPMENT OF INSTALLATION STANDARDS

The ongoing research comprises of two main phases. Firstly, influencing factors to TDR deformation measurements are to be determined from laboratory tests and initial installation standards are being developed. Secondly, the standards are to be tested in the field in real landslide monitoring projects.

Laboratory tests

It is planned to conduct shear tests on grouted cable assemblies in the laboratory. This approach was also made by Su (1987) and Blackburn (2002). The planned test apparatus is shown in Figure 4. It is integrated in an unconfined compressive strength testing machine and it will be possible to shear grouted cable assemblies with diameters of up to 80 mm. The maximum amount of shear deformation that can be applied will be 150 mm. The width of the shear zone will be variable from 0 to 60 mm. By using the equipment of the unconfined compressive strength testing machine an exact determination of the deformation amount and the force applied to the cable assembly can be measured. Parallel to this the corresponding TDR signals will be collected with a Campbell Scientific TDR 100 Time Domain Reflectometer.

A large combination of different cable types and grout mixtures will be tested using varying deformation rates and widths. The main aspect of the research is to increase the accuracy of the TDR measurements. Furthermore, special installation setups will be developed which are especially suitable for certain geological settings. For example, for the monitoring of slowly moving landslides a high sensitivity is needed, which can be achieved by using special coaxial cables with a small diameter. For fast moving landslides, less sensitive, but more durable, cables are needed.

While performing the laboratory shear tests, work will be started on the development of an automated analysis software for TDR deformation measurements.

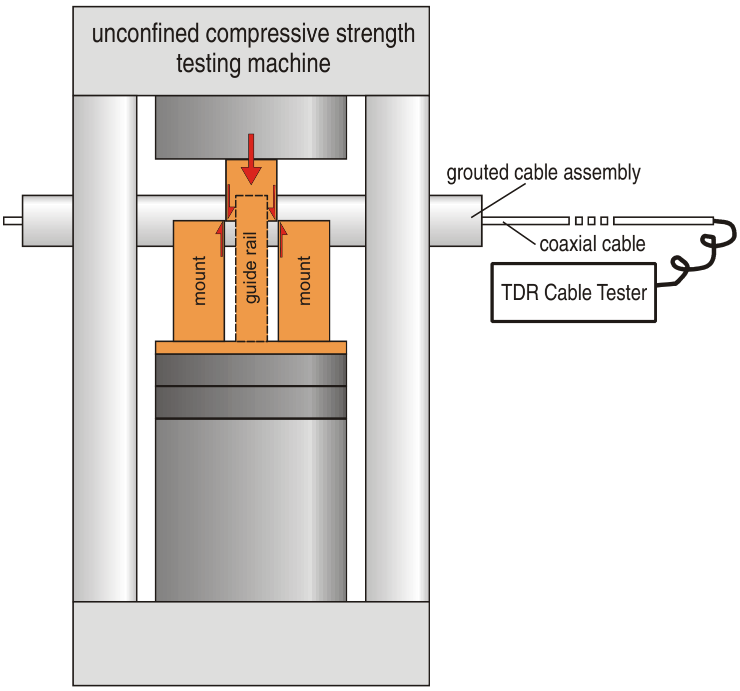

Figure 4. Test apparatus for laboratory shear tests with an unconfined compressive strength testing machine.

Field tests

After establishing initial installation protocols, a series of tests in the field are planned. Installation parallel to an inclinometer will be chosen whenever possible (type 1 in Figure 2), since this is the only method available to compare and verify the collected TDR data. Continuous data acquisition via a multiplexer and data logger, and the retrieving of the data via modem, will be tested also, being fundamental to the development of a continuous monitoring system.

Once these initial field trails have been completed successfully, the installation of TDR systems into an already well-studied landslide will be trialled, in order to verify TDR data in known, real-life conditions.

In a third phase, several TDR measuring points will be installed into a landslide according to Figure 5, with the objective to create a 3D model of the landslide based on TDR data as well as on geodetic surveying and geologic mapping. This information is the basis for numerical modelling and subsequent landslide risk assessment.

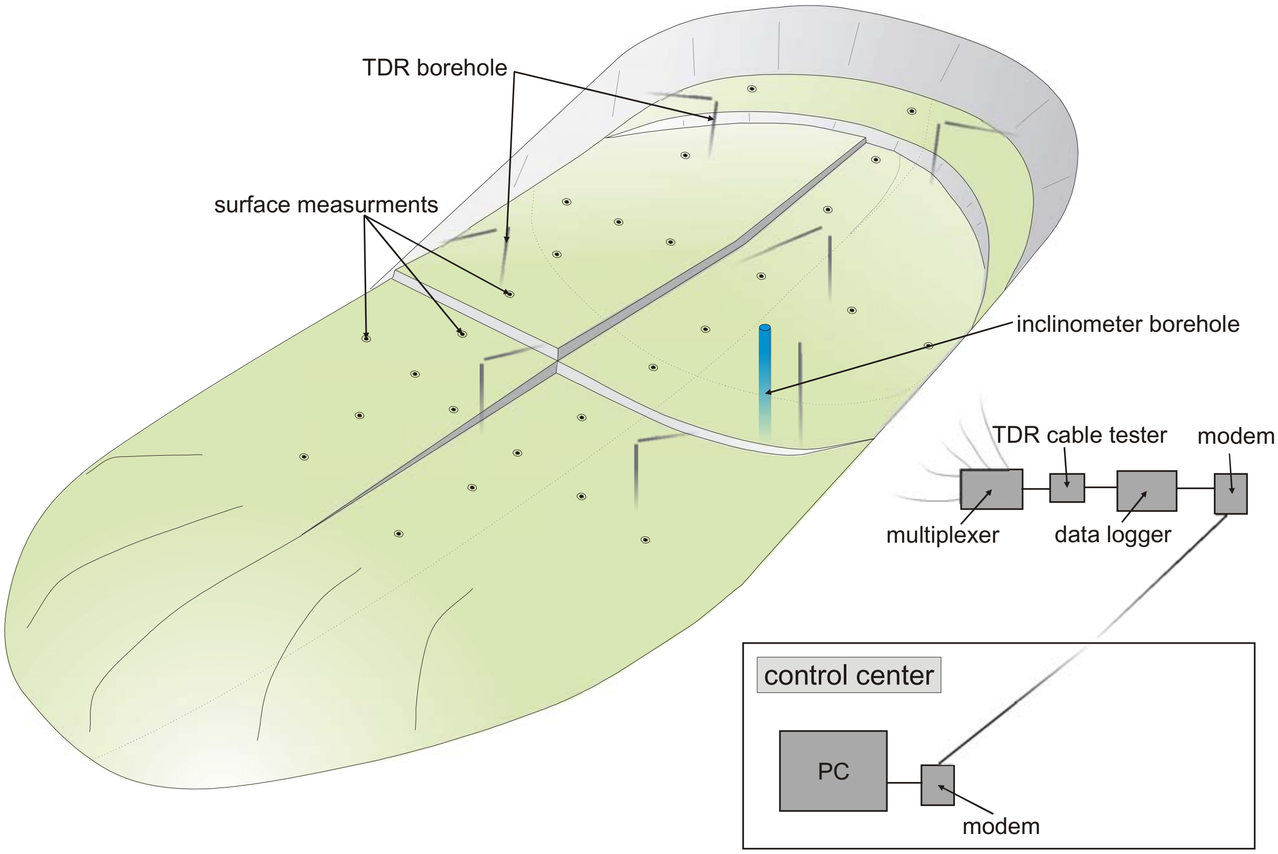

Figure 5. Possible layout of a continuous 3D-monitoring system for unstable slopes using Time Domain Reflectometry

CONCLUSIONS

Time Domain Reflectometry is a powerful system for the monitoring of unstable slopes, but some short-comings remain. One of the main drawbacks, compared to the use of an inclinometer, is the inability to determine the orientation of the movements. Furthermore, TDR works best when the deformation is focused on localized shear zones. To date, the amount of deformation can be determined only approximately.

It is envisaged that trialling a wide variety of installation configurations (including cable materials, sizes, thicknesses and grout mixes) will allow the establishment of a number of standard installation types for a range of geological settings. This should reduce some of the sources of error and result in an enhancement of measurement accuracy.

The most prominent advantages are the easy and comparably cheap installation of a TDR system and the ability to monitor the movements continuously by using remote data acquisition tools. This makes possible the real time monitoring of the influence of, for example, strong rainfall on slope stability, which could lead to a better prognosis of landslide behaviour.

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