Development of a Continuous 3D-Monitoring System for Unstable Slopes using TDR

By John Singer, Kurosch Thuro and Ulrich Sambeth

Although great advances in the recognition, prediction and mitigation of landslides have been made in the last few years, major events especially in alpine regions still claim a high social and economical tribute. Especially through extreme weather conditions, as e.g. the intense rainfall in August 2005, instable slopes can be activated and endanger people, settlements and goods in its surrounding. Currently an increase of this problem caused by the global climate change can be observed.

Recent landslides, which occurred in the alpine region, demonstrate the need for a deeper understanding of the geological and physical processes, which can lead to a spontaneous failure of a natural slope. Major rockslides as Vajont

Entwicklung eines kontinuierlichen 3D Monitoringsystems für instabile Hänge mittels Time Domain Reflectometry (TDR)

In den letzten Jahren ist die Zeitbereichsreflektometrie (engl. Time Domain Reflectometry, TDR) als ein neues System zur Überwachung von Hangbewegungen eingeführt worden. Bis heute sind jedoch keine Standards definiert worden, wie ein TDR-System am günstigsten installiert wird oder wie etwa die gewonnenen Daten zu verarbeiten sind – dies gilt vor allem, wenn die Daten mehrerer TDR-Messstellen zusammengefügt werden sollen, um ein 3D Modell der Deformationszone zu erstellen.

Ein TDR-System besteht grundsätzlich aus zwei Komponenten: einem Koaxialkabel und einem TDR-Messgerät („Kabeltester“). Das Koaxialkabel wird dabei in ein Bohrloch innerhalb der Hangbewegung eingebracht und mit einem Injektionsgut mit dem umgebenden Gebirge verbunden. Wenn das Kabel dann aufgrund der auftretenden Bewegungen deformiert wird, kann dies mit dem TDR-Kabeltester nachgewiesen werden. Dazu schickt der Kabeltester wiederholt elektrische Impulse durch das Koaxialkabel, die durch die Störungen in der Kabelgeometrie reflektiert werden. Diese Reflexionen werden analysiert und ausgewertet. Jede Veränderung der Kabelgeometrie führt zu einer charakteristischen Reflexion, die eine ungefähre Bestimmung der Art und des Betrags der Bewegungen ermöglicht. Die genaue Position der Deformation kann über die Laufzeit des Signals im Kabel (von der Aussendung bis zum Empfang der entsprechenden Reflexion) gewonnen werden, da die Ausbreitungsgeschwindigkeit des Signals im Kabel bekannt ist. TDR-Messungen werden jedoch von einer ganzen Reihe von verschiedenen Faktoren beeinflusst. Neben der Deformation selbst ist der Typ des verwendeten Koaxialkabels und die Festigkeit des Injektionsgutes von entscheidender Bedeutung.

In einem aktuellen Forschungsprojekt sollen verschiedene, an bestimmte geologische Verhältnisse angepasste TDR-Messkonfigurationen definiert werden. Diese sollen dann in Scherversuchen kalibriert und anschließend im Feld in realen Hangbewegungen verifiziert werden. Dies erfolgt am besten durch den direkten Vergleich mit Inklinometermessdaten. Durch die Verbindung mehrerer, über einen instabilen Hang verteilter kalibrierter TDR-Messstellen kann bei verhältnismäßig niedrigen Kosten eine bessere Kenntnis der Lage, Breite und des Typs der Bewegungszone erreicht werden. Da die TDR-Messdaten kontinuierlich und auch per Fernabfrage gewonnen werden können, kann die Wirkung von äußeren Einflüssen auf die Deformationszone, zum Beispiel starke Regenfälle, nahezu in Echtzeit bestimmt werden.

In recent years Time Domain Reflectometry (TDR) has been introduced as a new system for landslide monitoring. Until now no standards have been defined, how to install a TDR system 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 into a borehole and coupled to the surrounding rock mass with grout. The cable tester sends an electric pulse through the coaxial cable and receives and analyses its reflection. Changes in the geometry of the coaxial cable due to movements in the surrounding rock mass produce characteristic TDR signatures, which allow an approximate determination of type and amount of movement. The exact location of the deformation can be acquired by measuring the time span between the initiation of the electric pulse and the detection of its reflection, since the propagation velocity of the electric pulse within the coaxial cable is constant. TDR measurements are influenced by a great variety of parameters. Beside the deformation itself, the used cable and grout types are surely the most significant factors which have to be taken into account.

In ongoing research attempts are made to define a couple of different TDR measuring-system configurations, 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 at comparably low cost. Since the TDR data can be acquired continuously as well as remotely, the effect of outside influences (e.g. rainfall) on the landslide can be determined nearly in real time.

(1963, Italy) or Randa (1991, Switzerland) and recent minor events as Sibratsgfäll (1999, Austria) prove the destructive potential of these mass movements and the need to investigate the mechanics of such processes more deeply. Progress in the assessment of the land slide risk will only be achieved if the triggering processes and the kinematics of the movements are better understood.

To accomplish this task an assumedly instable slope has to be examined for its engineering geological properties and then has to be observed continuously with a suitable monitoring system. Exclusive instruments and methods to achieve this are available, but for economical reasons they are rarely used. At the same time the number of localities with need for monitoring is rising noticeably. The objective of the research, which is currently being carried out at the Technical University Munich, is therefore to develop and test a relatively economic and widely applicable monitoring and early warning system.

The monitoring system is based on the integration of innovative and economical measuring technologies to a Geo-Sensor Network. One of these is the measurement of subsurface movements by using a newly developed Time-Domain-Reflectometry (TDR) System.

Time Domain Reflectometry (TDR) is widely known as a system for the measurement of soil moisture (1). 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 Charles H. Dowding and Kevin M. O'Connor, who have without doubt proved the usability of TDR in landslide monitoring (2).

Especially the comparably easy and low-cost installation as well as the possibility to perform continuous and remotely accessed measurements make TDR an interesting alternative to classic inclinometers. Momentarily 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) (3).

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 are to be developed, 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 first results.

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 obstacle (such as e.g. an airplane) 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 obstacle can be determined by measuring the time span between the emission of the signal and the reception of its reflection. Furthermore by analysing the received signals certain information about the obstacle as e.g. its size and shape can be won.

TDR can be described as "cable-based radar": The TDR cable tester emits electric pulses which are sent through a coaxial cable (Figure 1). When these pulses approach a deformed portion of the coaxial cable a signal is reflected to the cable tester. As with radar, by measuring the

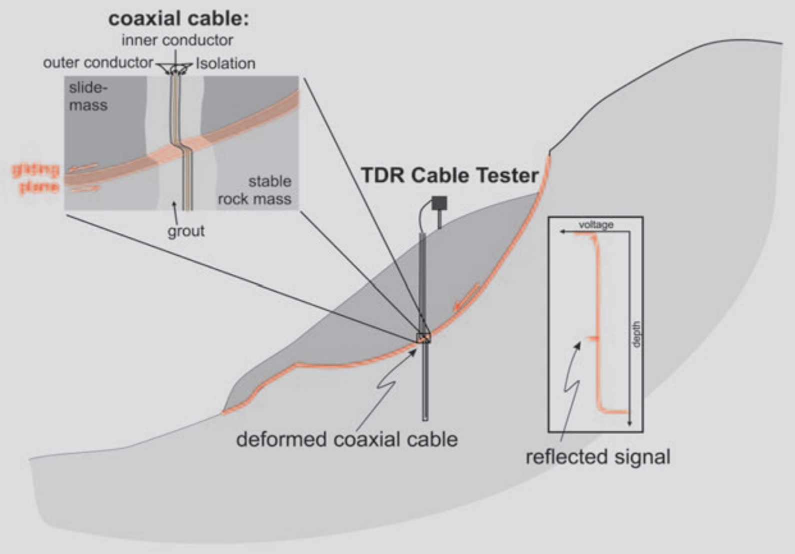

Fig. 1 Basic setup of a TDR landslide monitoring site. The coaxial cable is installed into an instable slope and connected to the TDR cable tester. As soon as the coaxial cable is deformed by the mass movement a peak can be seen in the reflected signal. Its amplitude is directly dependant to the amount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

Bild 1 *Skizze eines TDR-Monitoring Systems für Hangbewegungen. Das Koaxialkabel wird in den instabilen Hang installiert und mit dem TDR-Kabeltester verbunden. Sobald das Koaxialkabel durch die im Hang auftretenden Bewegungen deformiert wird, wird eine Reflexion im TDR-Messgerät sichtbar, deren Amplitude direkt von dem Deformationsbetrag abhängt.*

time span between emission and reception of the electric pulse the distance to the deformation can be determined. Furthermore the analysis of the reflected signal (amplitude, width, form) can reveal information about the type and amount of deformation.

For landslide monitoring the coaxial cable is installed into a borehole and connected to the rock mass with grout. When the rock mass starts to move, the coaxial cable is deformed (e.g. altering the distance between inner and outer conductor of the cable). This results in a change of the electric properties (impedance) of the cable, which can be measured with TDR.

The monitoring of deformations in rock/soil using TDR is therefore an indirect measuring method. Not the deformation itself is measured (as e.g. when using inclinometers) but a dependant value: the change in impedance of a coaxial cable due to deformation. A detailed description of the underlying physics is given in (2).

Installation

As already mentioned, a TDR system for deformation measurements consists of two main components: A TDR cable tester and a coaxial cable. A coaxial cable consists of an inner conductor which is surrounded by a pipe-shaped outer conductor. Both are separated by an isolation material, as e.g. PE foam.

For landslide monitoring the coaxial cable is installed into a borehole and connected to the rock mass with grout. Three different ways of doing so are conceivable (Figure 2):

- The TDR cable is installed parallel to an inclinometer into the same borehole,
- The coaxial cable is installed into a sheared inclinometer casing, therefore extending the lifespan of an inclinometer borehole,
- The coaxial cable is installed into a borehole of its own.

The installation parallel to an inclinometer in the same borehole is surely interesting primarily for research reasons, 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, whenever possible, be used during the field tests in this research, as it has already been done by various authors (4, 5,

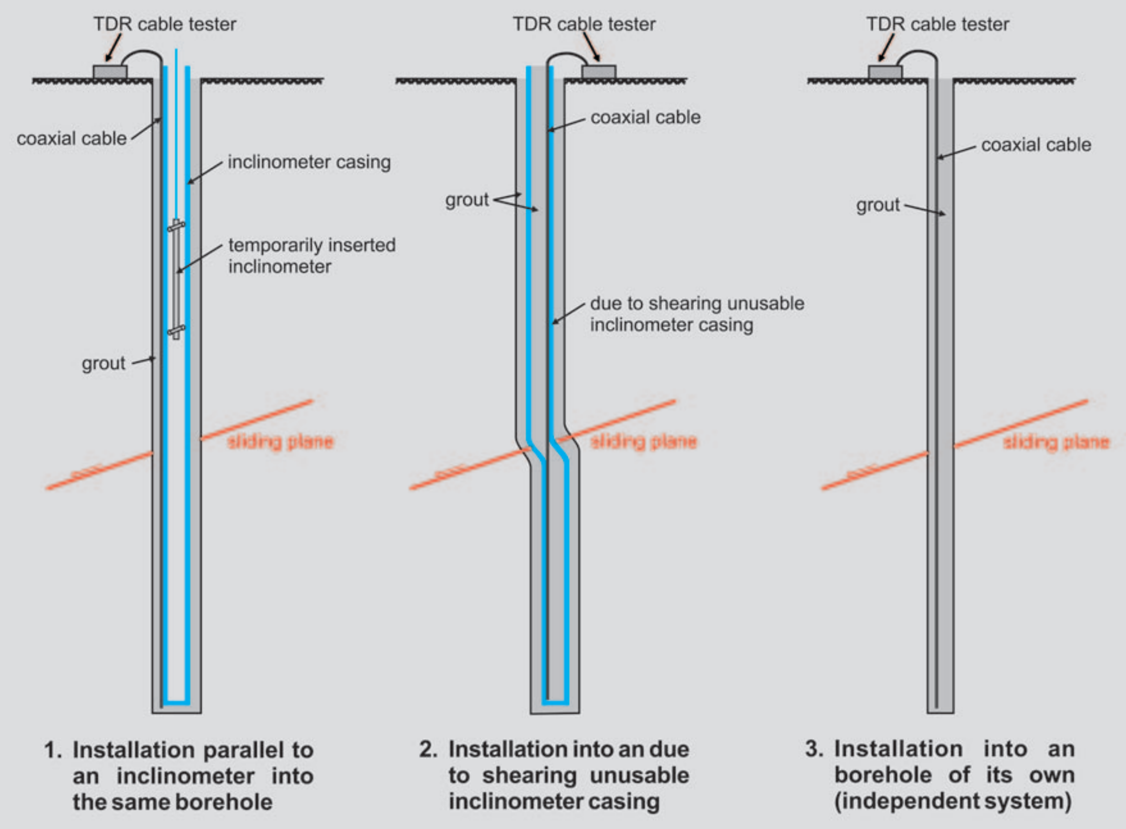

Fig. 2 Possible installation setups for a TDR coaxial cable into a borehole with and without an inclinometer.

Bild 2 *Mögliche Installationsanordnungen eines Koaxialkabels in ein Bohrloch mit und ohne Inklinometer.*

6). The other installation options are surely more interesting for commercial use, the second option because it makes the extension of the lifespan of an inclinometer borehole possible and the third option because a sole TDR installation can be established at comparably low costs. This is due to the fact that only relative small boring diameters are required and the costs for the coaxial cable are comparably low. Further savings are made possible when using remote data acquisition techniques. Thereby manpower costs are reduced significantly and at the same time continuous measurements are made possible (2).

A premise for receiving as much and accurate information (especially deformation type and amount) through the indirect measurement of deformation with a TDR system is the exact calibration of the entire system.

Influencing factors

Many different factors influence the measurement of deformation with TDR (2). These can be divided into three groups:

- The deformation of the cable itself,
- Installation parameters,
- Outside influences on the TDR system.

Deformation

Obviously, the deformation of the coaxial cable has an influence on the received signals, as this is the basis of landslide monitoring with TDR. The shape and size of the resulting TDR signal mainly depends on the type of deformation (e.g. shearing, extension, compression), the amount of deformation and the width of the deformation zone (length of cable section affected by deformation). The amplitude of the signal generally is directly dependant to the amount of cable-deformation (within certain boundaries), which makes a quantitative assessment possible (7). By the analysis of the waveform some statements can be made of the type of deformation (differentiation of shearing, extension and compression). The width of the deformation zone has a direct influence on the width of the received signal. Also with increasing width of the deformation zone the overall sensibility of the measurement is reduced. In extreme, when the coaxial cable is bent slowly over a larger distance, the deformation can not be determined at all. This limits the application of TDR to landslides with a relatively localized deformation. The development of installation procedures to at least minimize this problem are also a part of the ongoing research project (see below).

Also the distance between the TDR cable tester and the deformation zone has great impact on the measurement. For example with increasing distance the amplitude of the signal is reduced. This is a result of the attenuation of the signal along the cable (8).

Installation parameters

Naturally the components used in a TDR system and the way it is installed into a landslide have an effect on the measurement. Especially two parameters stand out in their importance: the type of coaxial cable used and the physical properties of the grout which connects the cable to the surrounding rock mass. Not only the material, the cable is made of, has an influence, but also the diameter and the length of the used cable. Generally, when using thicker cables, larger total amounts of deformation can be monitored before the cable is severed. At the same time, however, the sensibility of the system for small movements is reduced. Accordingly, thinner cables generally should used for landslides with low deformation rates, thicker cables for “faster” landslides.

The grout is the interface between the cable and the rock mass. It is therefore very important to adjust the physical properties of the grout to be fitting for the surrounding geology, especially when working in soil. If, for example, the grout is too strong, a “pillar-effect” might occur: the soil moves around a pillar of too strong grout, resulting in reduced or no deformation of the TDR cable.

By changing the used cables and grout mixtures depending on the surrounding geology and the expected deformation rates the quality of the received TDR measurements can be enhanced greatly. This is the main task of the ongoing research: defining certain installation procedures for different geological settings and deformation types and rates.

Outside influences

As the TDR measurements are based on electromagnetic pulses, which run through the coaxial cable, the electric properties of the surrounding soil/rock mass might have an influence on the measurement. Especially in soil, where the dielectric constant is influenced strongly by its water content, this has to be taken into account.

Luckily the electromagnetic pulses used for deformation measurements are mostly confined to the area within the coaxial cable (in difference to the measurement of soil water content with TDR), which has constant and defined electric properties. Thus, the named outside influences seem to be negligible. Nevertheless the influence will be quantified through appropriate tests.

Approach of research

The application of TDR for the monitoring of landslides has already been proved functional in various laboratory and field tests (3, 4, 9). However, to date only few systematic tests have been carried out, to find the optimal installation parameters for varying geological and geomechanical surroundings. Especially the used coaxial cable types and grout strength is of great importance. Furthermore, installation procedures for the enhancement of TDR deformation measurements in soil e.g. through the implementation of predetermined breaking points are tested.

To achieve this, in a first step, different cable and grout combinations are tested in an extensive series of simple shear tests with the objective of finding first basic setups for different conceivable landslide scenarios. As an example, setups with high sensitivity to initial movement need to be found, which can be used in slowly moving landslides, thereby differing landslides in soft soil (wide deformation zone) from those in a rock mass (discrete deformation zone).

When the first basic standards have been defined, these have to be calibrated by the execution of a series varying deformation tests (eg. different deformation types, angles and rates), thereby learning the characteristic TDR signatures of each setup.

After this, the calibrated installation setups are to be tested in field, preferably in combina-

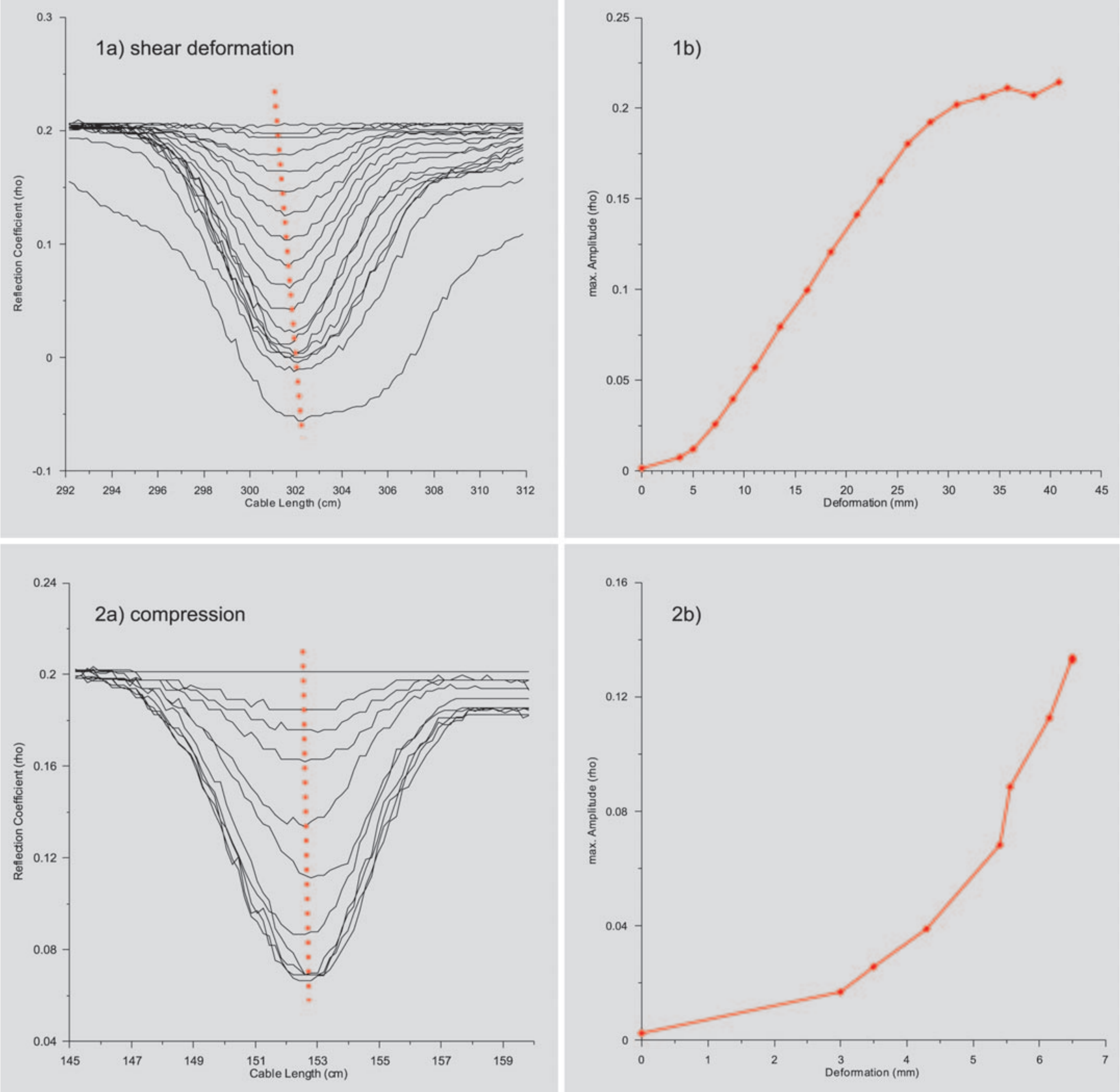

Fig. 3 Comparison of TDR measurement results when shearing (1) and compressing (2) the coaxial cable. Note the wandering of the peak maximum with proceeding deformation when the cable is sheared (1a), while it stays nearly at the same place when the coaxial cable is compressed (2a).
This can be used to distinguish the deformation mechanism. The rise of maximum amplitude with proceeding deformation is shown in the diagrams 1b and 2b for shear deformation and compression respectively. Measurements made with Campbell Scientific TDR 100 Time Domain Reflectometer and a CommScope P3 500 CA coaxial cable with 12 mm diameter.

Bild 3 *Ergebnisse von TDR-Messungen bei einer Scherung (1) und einer Quetschung des Koaxialkabels. Bei der Scherung ist mit zunehmender Deformation ein langsames Abwandern der Höchstwerte nach hinten zu beobachten (1a). Bei der Quetschung ist dieses Verhalten nicht zu beobachten – die Maxima bleiben an der selben Stelle (2a).*
Dieses Verhalten kann möglicherweise zur Unterscheidung von Deformationstypen herangezogen werden. Der Anstieg der maximalen Amplitude der Reflexe mit zunehmender Deformation ist in den Diagrammen 1b und 2b zu sehen. Die Messungen wurden mit einem Campbell Scientific TDR 100 Time Domain Reflectometer und einem CommScope P3 500 CA Koaxialkabel mit 12 mm Durchmesser durchgeführt.

tion with an inclinometer, which enables the direct verification and enhancement of the measured TDR data. If necessary the previously defined installation setups then have to be adjusted and optimized before sole TDR measurements can be carried out.

First results

First simple shear tests have confirmed the dependency between the amount of deformation and the amplitude of the received TDR signal, as it was already presented by various authors (7). This relationship is not linear (Figure 3, 1b). Especially in the beginning and at the end of a shear test the amplitude/deformation ratio is strongly reduced and the TDR system therefore less sensible.

This dependency varies for different deformation types (Figure 3): While a shear deformation of 5 mm produced a TDR signal with an amplitude of approximately 0.01 rho (reflexion coefficient), a compression of the cable to the same amount will produce a significantly stronger signal of approximately 0.06 rho. Therefore a determination of the deformation type is essential for the quantitative analysis of TDR measurements.

This is, however, not always possible. But mostly, especially with proceeding deformation, the deformation type can at least be estimated by the analysis of the received signals (see Figure 3). Anyway, when monitoring landslides, surely shear displacements will be the dominating deformation type, so that this assumption can be made in most cases.

Furthermore the distance of the deformation to the cable tester has to be taken into account when analysing the TDR signals. The larger the distance is, the lower the amplitude and the larger the width of the received signals will be, leading to a reduction in the resolution (smallest distance of two cable deformities that can be measured) of the TDR system. This attenuation of the signal with distance can be accounted for with relatively easy correction charts, which have to be determined during the calibration of the installation setups. This procedure has already been carried out by (10).

With TDR basically multiple deformations within a single coaxial cable can be determined. However the preceding unconformities influence the measurement of the succeeding (Figure 4). Opposing to the observations made by (8), who only found a minimal aberration in the measurements due to multiple deformations, the recently conducted tests have shown a decrease in amplitude of up to 30 % due to only three preceding unconformities. This deviation can not be easily corrected, since it is highly dependent of the position, size and amount of the preceding deformations. Thus, the quality of the quantitative analysis of downstream deformations is drastically reduced. The application of crimps to enhance the position accuracy of TDR measurements, as it is proposed by various authors (2), therefore must be rejected.

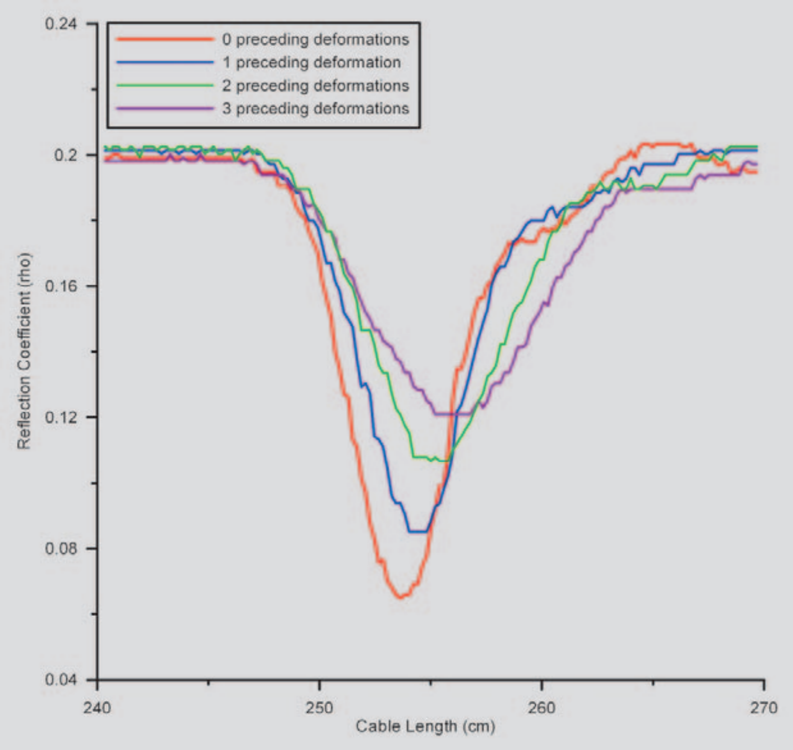

Fig. 4 Influence of multiple deformations on TDR measurements. First the crimp at approximately 250 cm length was made and measured with a TDR Cable Tester (red line) Then, consequently three additional crimps preceding the first one were added at 50, 100 and 150 cm distance to the Cable Tester and tested again via TDR. The reduction of the amplitude due to the existence of the preceding crimps reached as much as 30 % (purple line).

Bild 4 *Einfluss von multiplen Deformationen auf die TDR-Messungen. Zunächst wurde ein „crimp“ (Quetschung des Kabels) bei einer Kabellänge von 250 cm gesetzt und mit dem TDR-Kabeltester gemessen (rote Linie). Dann wurden nach und nach drei weitere crimps vor den bereits bestehenden an den Positionen 50, 100 und 150 cm gesetzt und wiederum mit dem TDR-Messgerät vermessen. Die Erniedrigung der Amplitude des reflektierten Signals durch die im Kabel weiter vorne liegenden crimps kann bis zu 30 % erreichen (lila Graf).*

Prospects

The overall goal of the research project is the development of a continuous 3D-monitoring system based on TDR. This is achieved by installing several TDR measuring points into a landslide according to Figure 5 with the objective to continuously observe subsurface movements. Additionally the surface movements should be monitored by geodetic surveying (tacheometry or GPS).

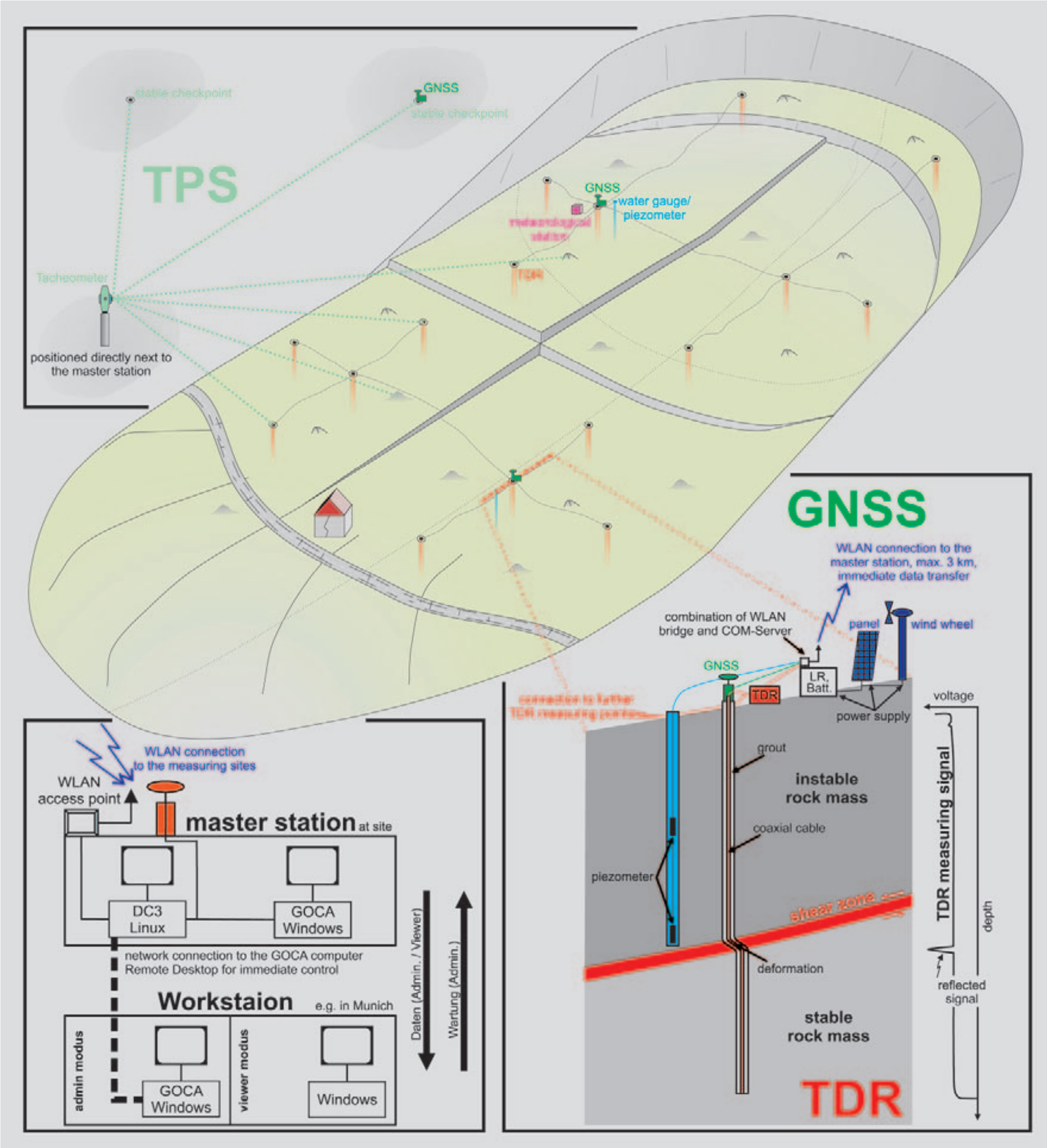

Fig. 5 Schematic illustration of an integrative 3D early warning system for instable slopes. GNSS (Global Navigation Satellite System) and TDR continuously gather highly precise punctiform information about the movements on the surface and underground, respectively. The TPS (Terrestric Positioning System) e.g. in form of a reflectorless tacheometer can gain displacement information covering the complete landslide area. When combining the different measurements, a 3D model of the slope and its movements can be derived. The measured data is transmitted to the master station via WLAN and stored in a central computer. The data can be accessed and downloaded from a remote computer for further analysis and interpretation.

Bild 5 *Schematische Zeichnung eines integrativen 3D-Frühwarnsystems für instabile Hänge. GNSS (Global Navigation Satellite System) und TDR generieren punktuell laufend hochgenaue Informationen zu den ablaufenden Bewegungen über und unter der Erde. Das TPS (Terrestric Positioning System), zum Beispiel in Form der reflektorlosen Tachymetrie, kann Oberflächenbewegungen über die ganze Oberfläche der Hangbewegung detektieren. Die verschiedenen Messdaten können dann zu einem 3D-Model des Hangs und dessen Bewegungen zusammengeführt werden. Die gewonnenen Messdaten werden dazu via WLAN zu einer Zentralstation übermittelt und dort im Computer gespeichert. Von dort können diese dann via Modem von einem externen Computer für die weitere Auswertung und Interpretation abgerufen werden.*

Parallel to these measurements the registration of the hydrostatic pore pressure or the groundwater table, respectively, as well as the climatic conditions at the site (precipitation, temperature, snow depth) should be carried out. In this way the 3D movements of the slope, which are determined nearly in real time, can be compared with the surrounding conditions (precipitation, hydrostatic pore pressure) and can be analysed for trigger mechanisms. Through the large amount of data collected by the system (in time and space) it should be possible to determine causal and temporal coherences between the most important influencing factors and the movement of the instable slope within a relatively short period of time (six to nine months), allowing the definition of critical threshold values. By using an automated alarm function, which informs the responsible authorities when the threshold is exceeded, an early warning system can be implemented.

Additional to this empiric approach, the data won through the monitoring system, together with the data won during obligatory geological field mapping, can flow into a numerical model of the landslide. This will lead to an even better understanding of the mechanics of the landslide and subsequently to a better hazard and risk analysis.

Besides the relatively low installation costs, a further significant cost advantage of the readily developed monitoring system is achieved by making remote maintenance and inquiry possible. All important functions can be queried and controlled from the project office via modem, reducing the costs for personnel in comparison to conventional measurements by eliminating the need for repeated manual measurements. Furthermore the installation costs are – when compared to the amount of data which is gathered in space and time – relatively low due to the used measuring technologies. The linking of the different measuring units with the local control centre will as far as possible be accomplished using WLAN, which makes the usage of an expensive mobile telephone system or beam radio unnecessary.

References

1. Topp, G.C. ; Davis, J.L. ; Annan, A.P: *Electromagnetic Determination of Soil Water Content: Measurement in Coaxial Transmission Lines*. Water Resources Research 16 (1980), No. 3, pp. 574-582.
2. O'Connor, K.M. ; Dowding, CH.H.: *Geo-Measurements by Pulsing TDR Cables and Probes*. Boca Raton: CRC Press, 1999.
3. Kane, W.F. ; Beck, T.J. ; Hughes, J.J.: *Application of Time Domain Reflectometry to Landslide and Slope Monitoring*. TDR 2001 – Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications, Infrastructure Technology Institute, Northwestern University, Evanston, Illinois, U.S.A.
4. Kane, W.F. ; Beck, T.J.: *An Alternative Monitoring System for Unstable Slopes*. Geotechnical News 14 (1996), No. 3, pp. 29-31.
5. Kane, W.F. ; Perez, H. ; Anderson, N.O.: *Development of Time Domain Reflectometry System to Monitor Landslide Activity*. Final Report, June 1996, FHWA/CA/TL-96/09.
6. Freeman, E.L.: *Time Domain Reflectometry at Cloverdale Landslide, U.S. Highway 101, Sonoma County, California*. Technical Research Report CE-96-03, Department of Civil Engineering, University of the Pacific, April 1996.
7. Su, M.B.: *Quantification of Cable Deformation with Time Domain Reflectometry*. Ph.D. Thesis, Northwestern University, Evanston, Illinois, 1987.
8. Pierce, C.E. ; Bilaine, C. ; Huang, F.C. ; Dowding, C.H.: *Effects of Multiple Crimps and Cable Length on Reflection Signatures from Long Cables*. Proceedings of the Symposium on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications, Northwestern University, Evanston, Illinois (1994), S. 540-554.
9. Dussud, M.L.: *TDR Monitoring of Soil Deformation: Case Histories and Field Techniques*. Master Thesis, Northwestern University, Evanston, Illinois, 2002.
10. Kim, M.H.: *Quantification of Rock Mass Movements with Grouted Coaxial Cables*. Master Thesis, Northwestern University, Evanston, Illinois, 1989.

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