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New landslide monitoring techniques – developments and experiences of the alpEWAS project

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Abstract. Mainly in the context of global climate change the awareness of landslide hazards has risen considerably in most mountainous regions worldwide in the last years. National and regional hazard mapping programs were set up in many countries and most of the potentially endangered sites have been identified. Although exclusive geodetic and geotechnical instrumentation is available today, due to some economical reasons only few of the identified potentially risky landslides are monitored permanently. The intention of the alpEWAS research project is to develop and to test new techniques suitable for efficient and cost-effective landslide monitoring. These techniques are combined in a geo sensor network with an enclosed geo data base and a developed software package to use the whole system for stakeholder information and early warning purposes. The core of the project is the development and testing of the three innovative measurement systems time domain reflectometry (TDR) for the detection of subsurface displacements in boreholes and reflectorless video tacheometry (VTPS) and a low cost GNSS sensor component for the determination of 3D surface movements. Essential experiences obtained during the project will be described.

Keywords. Landslide monitoring techniques, geo sensor networks, time domain reflectometry, reflector-less video-tacheometric positioning system, low cost GNSS sensors.

1. Scope and project outline

Recognizing the worldwide exponential growth of natural disasters caused by earth quakes, flooding, volcano eruptions and landslides in the past years the German Federal Ministry of Education and Research (BMBF) launched the widespread geoscientific research and development program "Geotechnologien" (www.geotechnologien.de) inter alia with a focus on early warning systems (EWS) for earth management. Supported by a grant of this course the alpEWAS project "Development and testing of an integrative 3D early warning system for alpine instable slopes" started in spring 2007. Superior aim of the project is the integration of different innovative measuring methods to an economically working geo sensor network (GSN) for instable slopes. The Aggenalm Landslide in the Bavarian Alps was chosen as a field laboratory. In the process, on the one hand the individual measuring techniques are enhanced and on the other hand methods for the data combination and analysis using modern communication and computing facilities are developed.

The alpEWAS project consists of the following three sub-items:

– TDR: Development and testing of time domain reflectometry for the detection of subsurface movements in boreholes (responsibility of Chair of Engineering Geology, TUM);
– VTPS: Displacement monitoring of natural targets by prism-less video robot tacheometry (responsibility of Chair of Geodesy, TUM);
– GNSS: Development and testing of a low cost GNSS monitoring component (responsibility of Institute of Geodesy, UniBw M).

Common objective is the integrative data management and analysis. Here a new flexible and easily extendible control, management and data analysis software package for landslide early warning is evolved. The still ongoing work can be consulted under www.alpewas.de.

2. Monitoring of landslides – some general remarks

Due to the main factors climate change, tourism in mountainous areas and the build-up of new infrastructure objects (settlements, roads, railways) there is a rise of potentially endangered sites prone to be activated in future. Statistics show that the amount of damage caused by landslides worldwide is ranking behind earthquakes and flooding and cannot be seen isolated from other natural disasters (Krauter 1990). Beside identification and mapping of potentially risky areas – for instance with the ,,Gefahrenhinweiskarte Bayerische Alpen" [hazard map of

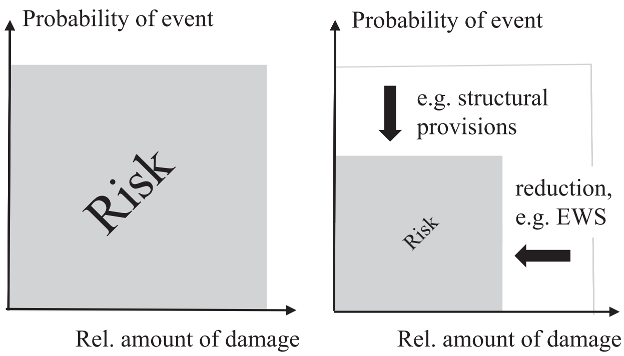

Figure 1: Possibilities of risk interference (compare Glabsch et al. 2010b).

Bavarian Alps] (BLfU 2008) – and applicable structural provisions like timbering and drainage to reduce the probability of an event a better understanding of the mechanisms and slope stabilities is essential. Furthermore risk management is considerably enhanced using powerful monitoring systems.

If a landslide risk is defined as an eventually occurring undesirable event which induces damages, the contribution of permanent monitoring aims at reducing or even minimize any resulting damage by early warning, see Figure 1. Ultimate aim of every risk management of endangered regions is to reduce vulnerability by a combination of efforts in such a way that the remaining risk is controllable. Early warning requisites a permanently operable measuring system on site. Exclusive geodetic and geotechnical instrumentation is available today (e.g. Thut 2008, Stempfhuber 2009) but a serious problem for widespread application are the resulting costs for hard- and software as well as maintenance. Therefore the development of efficient and cost-effective landslide monitoring techniques was a challenge when the alpEWAS research project started in spring 2007. Today such monitoring techniques should be designed as GSN with an option of remote access at any time. For stakeholders this offers to keep the overview especially in situations where several sites are affected at the same time, e.g. due to heavy rainfall in the whole region. However, in order to evaluate slope stability, continuous observations of the ongoing surface and subsurface deformations as well as of the triggering influences (e.g. precipitation and ground water levels) are essential, which – together with a geo-mechanical model of the slope – may make a quantitative assessment of the causal and temporal relation between movements and its triggers hopefully possible.

3. Geological situation of the Aggenalm, Bavarian Alps

The Aggenalm Landslide is situated in the Bavarian Alps in the Sudelfeld region near Bayrischzell. Assumedly triggered by heavy rainfall the slide was activated in 1935 and destroyed three bridges and a road. After extreme precipitation some damages were caused by the slide in 1997 again. Since then the Aggenalm has been surveyed periodically twice a year by the Bavarian Environment Agency (Bayerisches Landesamt für Umwelt, BLfU). Momentarily there are about 1 cm movements per year. The slide is not appraised to be precarious which makes it ideal for research activities to prove new monitoring techniques under field conditions.

Geologically this area is part of the Northern Calcareous Alps and is mainly built up of various triassic and jurassic limestones, dolomites and marls. The so-called Kössen formation, an alternating sequence of dark colored limestones and marls, and the Oberrhät limestone, a massive partly dolomitic limestone, crop out to surface, see Figure 2. During the alpine orogeny the rock mass was heavily faulted and in the last ice age the area got its typical glacial morphology. The marls of the Kössen formation which underlie many Alpine slopes are very sensitive to weathering with a distinctive reduction of the rock mass strength and involving instabilities. The shear zone has a depth of approx. 25 m. While the upper part of the Aggenalm can be classified as a rock spread, further downhill the mechanism of the landslide changes into a very slow debris flow (Cruden and Varnes 1996). As the events of 1935 and 1997 have shown, the Aggenalm Landslide is sensitive to heavy precipitation and the accompanying rise in ground water levels. Some more details on the geological situation are depicted in Singer et al. (2009a) and Thuro et al. (2009b).

4. The Aggenalm geo sensor network

4.1. *Instrumentation*

According to the geological expertise and the general conditions and possibilities of a research project the instrumentation of the Aggenalm Landslide was planned to be able to monitor the different mechanisms – each with presumably different deformation behaviour through time. The actual instrumentation setup with the positions of the different measuring devices is shown in Figure 3. The red boundary line

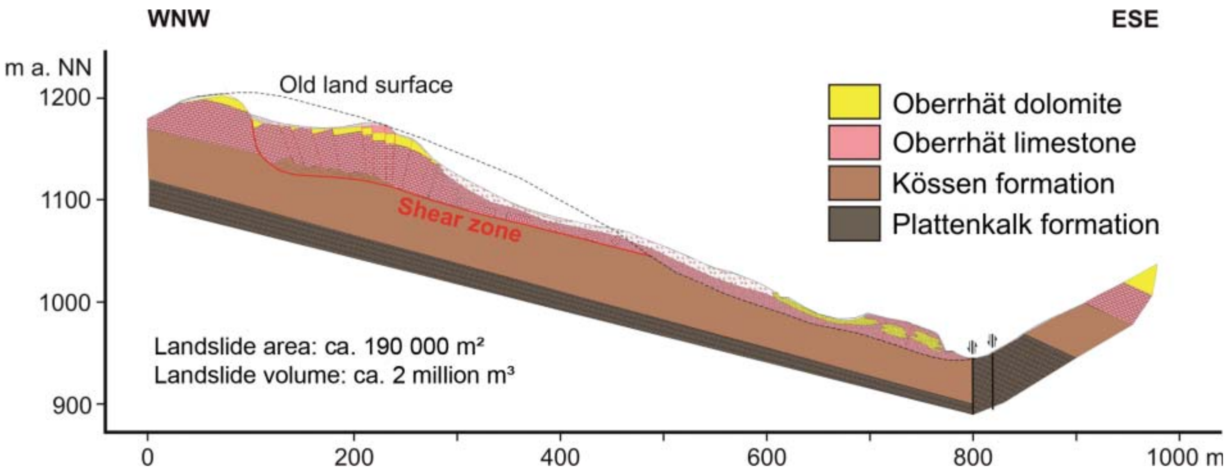

Figure 2: Geological cross section (WNW-ESE) through the Aggenalm Landslide (Singer et al. 2009a, Thuro et al. 2009b).

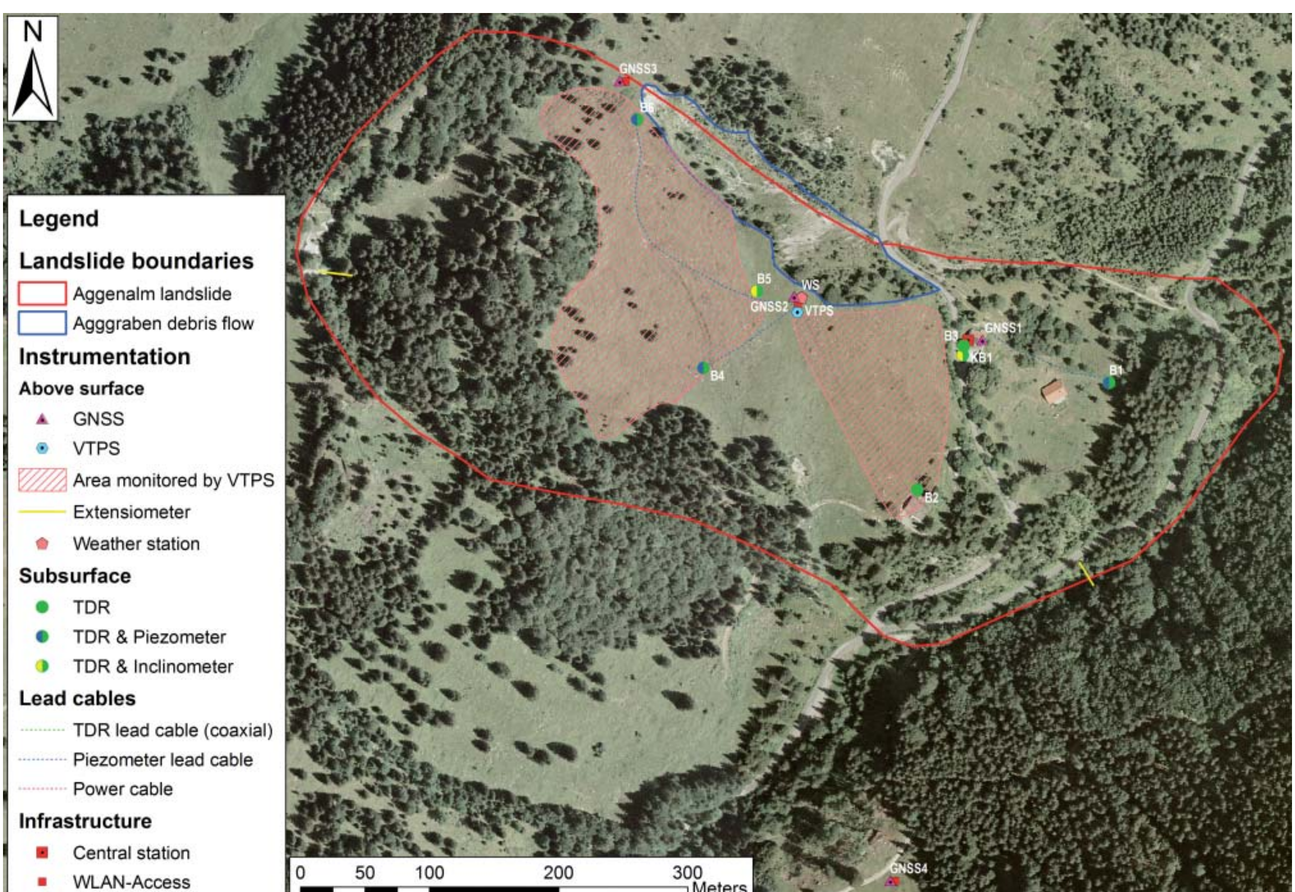

Figure 3: Actual instrumentation setup depicted in an orthophoto (Singer et al. 2009a).

indicates the landslide complex while the blue line shows the debris flow of the 1997 event.

With the above mentioned general conditions it was possible to drill seven boreholes for TDR measurements, to establish four low cost GNSS points and to erect a central pillar for the investigated VTPS instrument. The central position of the VTPS instrument provides extensive measurements of the surface deformation of natural targets; see hatched red area in Figure 3. At the moment the VTPS instrument is used only temporarily. There is also a meteorological station close to the pillar and two additional piezometers devices for pore water pressure determination installed in the boreholes close to the assumed shear zone. By combining the data of these measuring systems, 3D deformation information can be gained with high spatial and temporal resolution, as well as the setup of causal relationships (trigger mechanisms) is possible. The TDR measurements provide information about the location and activity of the subsurface deformation zones, the GNSS sensors were installed at locations of particular geological interest while one point is on stable ground. The VTPS measurement should give a laminar evidence of the slope. Some of the measurements can be compared directly for reliability reasons. However, in the following the more technical aspects are concerned.

4.2. GSN approach

Technically speaking all different measuring devices are integrated in a GSN. Organizationally a GSN is subdivided into several so called sensor nodes or motes which – in general – operate fully autarkic. A central computer centre manages all system operations on site, e.g. data collection and logging and also controlling of the sensor nodes. Finally an infrastructure comprised of measuring, computing, and communication elements is established. For some general aspects of sensor networks see e.g. Sohraby et al. (2007). All development of the project is commercial off-the-shelf, however. A design for harsh environmental conditions is essential for landslide monitoring in the Alps. The schematic layout of the Aggenalm GSN is presented by Figure 4.

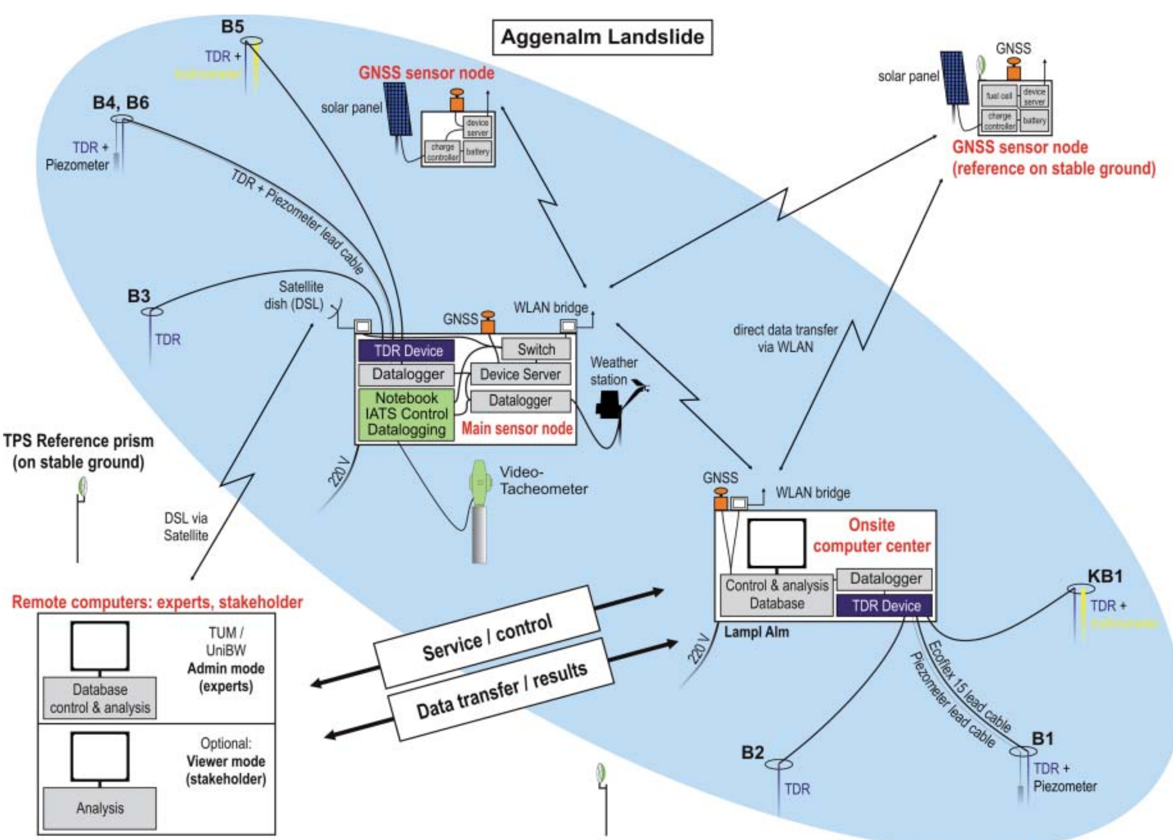

Figure 4: Schematic configuration of the GSN at the Aggenalm Landslide (Thuro et al. 2009b).

In total there are four sensor nodes which are located within and outside the slope:

– two completely autarkic GNSS sensor nodes, while one is on stable ground nearby,
– the so called main sensor node with a high diversity of different sensors (including VTPS, weather station and a webcam and
– the onsite computer station that also contains a separate multifunctional sensor node.

Cable connections were established from the main sensor node and the computer centre to all distributed boreholes containing the TDR and piezometer setup. This basically results from economic reasons, as the installation of a separate autarkic sensor node at each location with an own set of measuring devices, power supply and network access point – although of course technically realizable – would drastically increase costs. The transfer of data from all sensor nodes to the computer centre is handled by an infrastructural Wireless Local Area Network (WLAN). Customary hardware components (e.g. bridges, wireless device servers) using the IEEE 802.11g standard are exploited. In order to achieve comparable transfer rates over distances of about 500 m and more, specific high quality WLAN-antennas have to be used. For remote maintenance and supervising a DSL internet connection via satellite is set up at the base station.

5. TDR, VTPS and low cost GNSS – new measuring techniques at landslides

5.1. TDR monitoring of subsurface deformation

In order to evaluate a deep seated landslide, an observation of the surface deformation is not sufficient. Detailed information about the depth of the movement and its changes through time are needed. To date, if continuous monitoring is required, usually inclinometer chains installed in boreholes are used. These techniques allow determining subsurface deformations with high precision, but the associated costs are quite high. So often continuous monitoring is rejected in favour of cheaper sporadic measurements.

With a TDR measuring system continuous monitoring of subsurface deformation can be performed at approx. 25% and less of the costs compared to inclinometer chains (Singer et al. 2009a, Sargand et al. 2004). However, the landslide mechanism has to meet some premises in order to be able to use this measuring system, as it is mainly limited to the detection of localized shear zones (Dowding and O'Connor 2000).

5.1.1. Basic principle

A TDR measuring system consists of three major elements: 1. the measuring device (TDR cable tester including data logger for continuous measurements), 2. the measuring cable (usually semi rigid coaxial cable) and 3. the lead cable (rugged low loss coaxial cable) which connects the measuring cable to the measuring device (see Figure 5). For landslide monitoring the measuring cable is installed into a borehole and connected to the rock mass with grout.

TDR can simplified be described as "cable-based radar" (O'Connor & 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 can reveal information about the type and amount of displacements. The orientation of the movement, however, cannot be determined.

When using TDR for subsurface deformation monitoring, it should be kept in mind, that TDR detects changes in the coaxial cables impedance, which among others is controlled by the cables geometry, namely the distance between inner and outer conductor. When the cable is subject to localized shear (e.g. deformation along joints, bedding planes or fractures) this change in geometry is easily achieved, while a gradual deformation over several decimetres (general shear, gradual bending of the cable) fails to fulfil this criteria (Kane 2000). Therefore TDR measurements generally are limited to discrete deformation zones with a width of centimetres to decimetres. In this context the mechanical properties of the grout used to connect the measuring cable to the surrounding rock mass is of utmost importance.

5.1.2. Installation guidelines

5.1.2.1. Grout

When designing a TDR measuring site, the interaction of rock mass, grout and cable as well as the expected deformation rate has to be taken into account. Only after the grout surrounding the coaxial

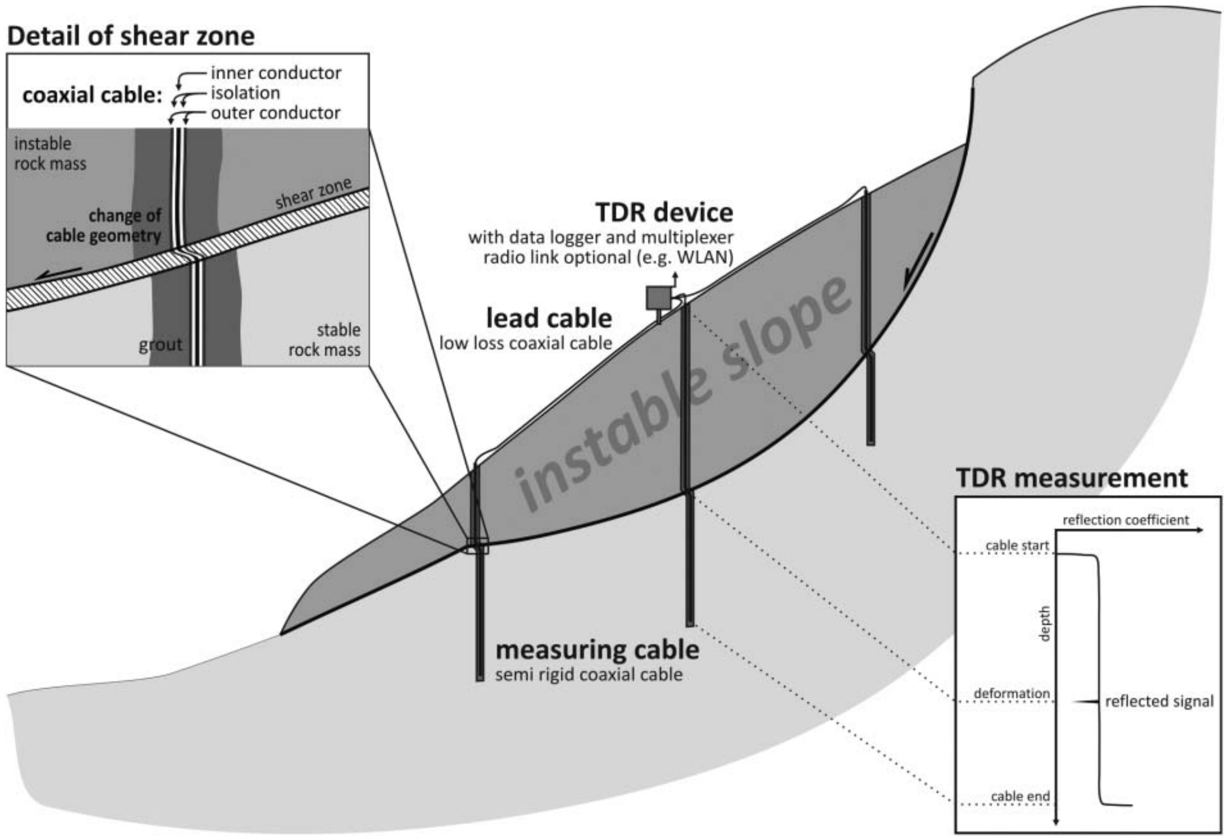

Figure 5: Illustration showing the basic setup of a TDR subsurface deformation monitoring system (Singer et al. 2006, edited). The deformation of the rock mass is transferred to the coaxial cable by the grout, thereby locally changing the cables geometry (inset top left). This produces a characteristic signal in the TDR measurements (inset bottom right; the reflection coefficient is the ratio of reflected to emitted voltage), which can be used to determine the magnitude and type of deformation.

cable has fractured and starts to indent the measurement cable, the TDR will begin to produce a signal. Therefore the grout on the one hand has to be weak enough to be fractured by the surrounding rock mass and on the other hand has to be stiff enough to deform the coaxial cable. An expression of the ability of the grout to deform the coaxial cable is the sensitivity – the amount of deformation needed to produce a detectable TDR signal for a certain cable-grout assembly and mode of deformation. Festl (2008) and Singer (2010) performed a large series of laboratory shear tests with different cable grout assemblies. For the Commscope P3-500 JCA – an often used semi rigid coaxial cable for TDR deformation measurements in hard rock – they showed, that the grout needs to possess a minimum strength of about 10 MPa (uniaxial compressive strength according to DIN EN 196-1, 2005; Figure 6) in order to effectively transfer the rock mass deformation to the coaxial cable.

According to Blackburn and Dowding (2004), who performed finite element analyses on cable-grout-soil interaction during localized shearing, the shear strength of the grout can be one to maximum five times the soil strength in order to ensure the fracturing of the grout, which often can easily be achieved. This is supported by Lin et al. (2009), who based on several soil-grout-cable shear tests conclude, that having a stronger grout around the coaxial cable facilitates cable deformity in response to the shear displacement and therefore the compliance of the grout to soil stiffness should not be a major concern. However, more weight should be put on the cable grout interaction (see above).

5.1.2.2. Coaxial cables

Generally any coaxial cable can be used as lead or measuring cable. O'Connor and Dowding (1999) suggest using semi rigid coaxial cables as measuring

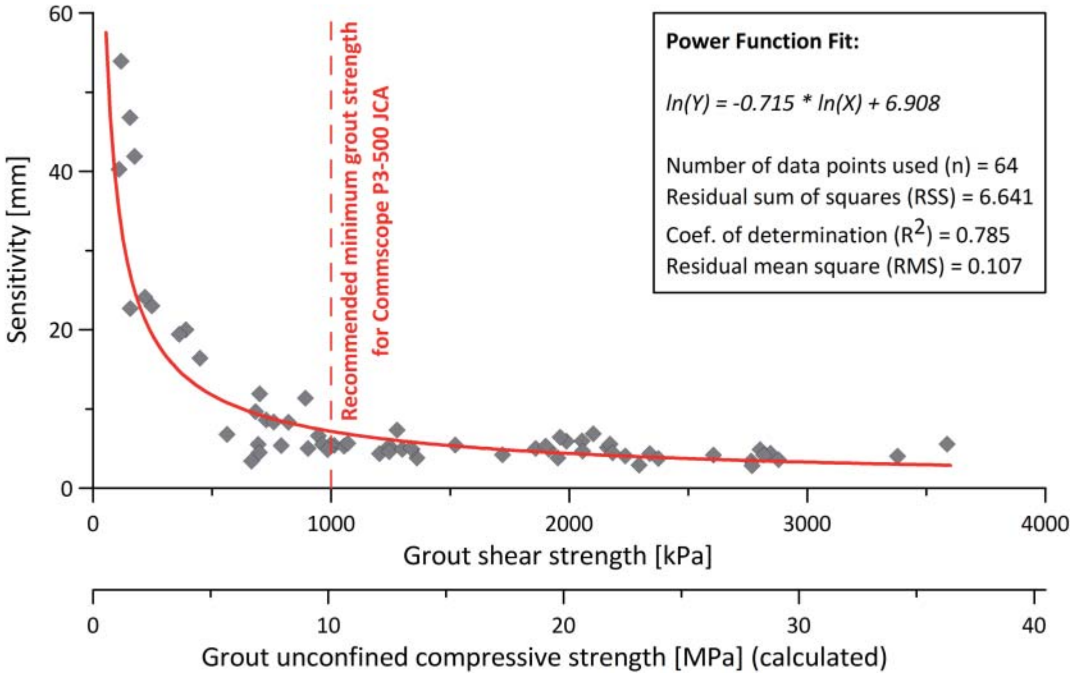

Figure 6: Sensitivity of TDR measurements in dependency of grout strength in laboratory shear tests (shear width 15 mm) using grout-cable-assemblies with the Commscope P3-500 JCA coaxial cable and various different grout compositions (grout column diameter 70 mm). Below about 1000 kPa shear strength the sensitivity of the grout-cable assembly drastically increases. The shear strength is determined during the shear test; the approximate according unconfined compressive strength is calculated using a linear relation determined by Singer (2010) for TDR shear tests.

cables in rock, since these on the one hand are easy to install into a borehole, and on the other hand – as laboratory shear tests have shown – achieve a relatively high reproducibility (and thus accuracy) in the TDR measurements. For installations in soft soil the use of less rigid coaxial cables with a braided copper outer conductor may be preferable in order to be able to use weaker grout compositions, although the TDR signal quality may be degraded.

Cable length has a dramatic effect on the TDR signals produced by a deformed coaxial cable (see Figure 7). The signal amplitude is reduced and at the same time the spatial resolution at which two separate deformation zones can be distinguished decreases. This frequency dependant attenuation is mainly caused by the electrical series resistance of the coaxial cable (Lin et al. 2009) and needs to be considered during signal analysis even at short cable lengths. In addition each disturbance of impedance within the transmission line (e.g. cable connections, multiplexers and multiple deformation zones) influences the recorded signal. Therefore great care should be taken to introduce as little disturbance to the transmission line as possible. Attenuation limits the maximum useable transmission line lengths drastically; e.g. for the Campbell Scientific TDR100 device and the Commscope P3-500 JCA coaxial cable the maximum useable cable length is about 150 metres (see Figure 3).

5.1.3. Signal analysis

TDR signals can be analyzed using calibration curves gained through empiric observations in laboratory shear tests (see also Singer et al. 2009a). Lin et al. (2009) have developed a complex electromagnetic wave propagation model for TDR measurements to account for the effects of cable resistance and conclude that the TDR reflection spike (amplitude) – when corrected for signal attenuation – can be correlated with cable shear deformation. This however is only valid if the shearing mode (shear bandwidth) is fixed and the installation setup is considered. This behaviour is supported by observations from TDR shear tests performed by Festl (2008), which show that the TDR signal amplitude strongly depends on the used grout and shear zone width (see Figure 8 and 10).

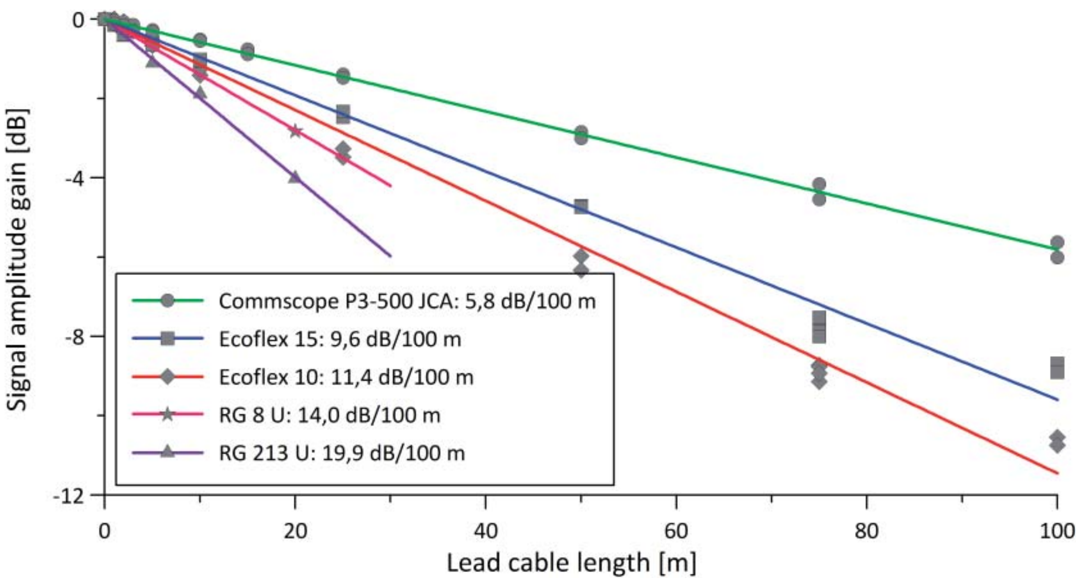

Figure 7: Signal amplitude attenuation with increasing lead cable length for five different commonly used coaxial cables. Frequency dependant signal attenuations stated in cable specifications are determined for sinusoidal waves and thus differ from the attenuations determined here for the TDR step function (rise time of 300 picoseconds, pulse length 14 microseconds for the Campbell Scientific TDR100).

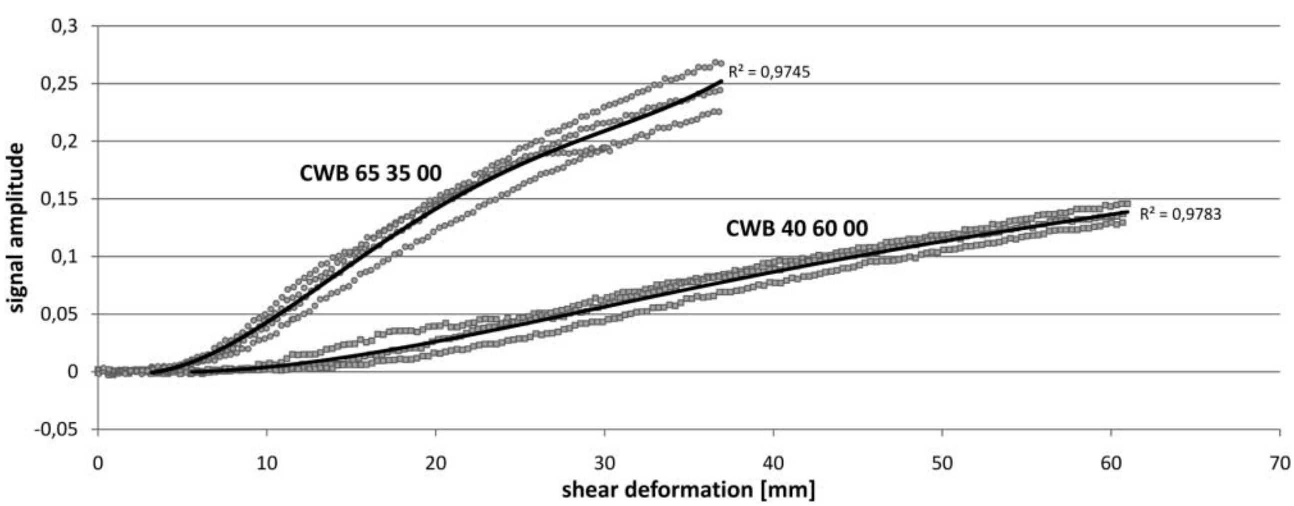

Figure 8: The correlation between signal amplitude and shear deformation determined in laboratory shear tests differs strongly for two different grout compositions (from Singer et al. 2009a) and therefore has to be determined for each TDR installation setup (cable-grout assembly) individually.

In order to make TDR a flexible and easy to use deformation measuring technique, without the need to perform a large number of laboratory shear tests for each assignment, Singer et al. (2010) suggest to define several standardized installation setups (cable-grout combinations), each of which is optimized for a different typical geological surrounding/measurement target. For each of these setups the correlation between signal amplitude and shear deformation is determined for different modes of deformation. In general various different modes of deformation are conceivable in landslides – especially in soil. Mainly tension, kinking and shear deformation at different bandwidths is to be expected. As the TDR signal

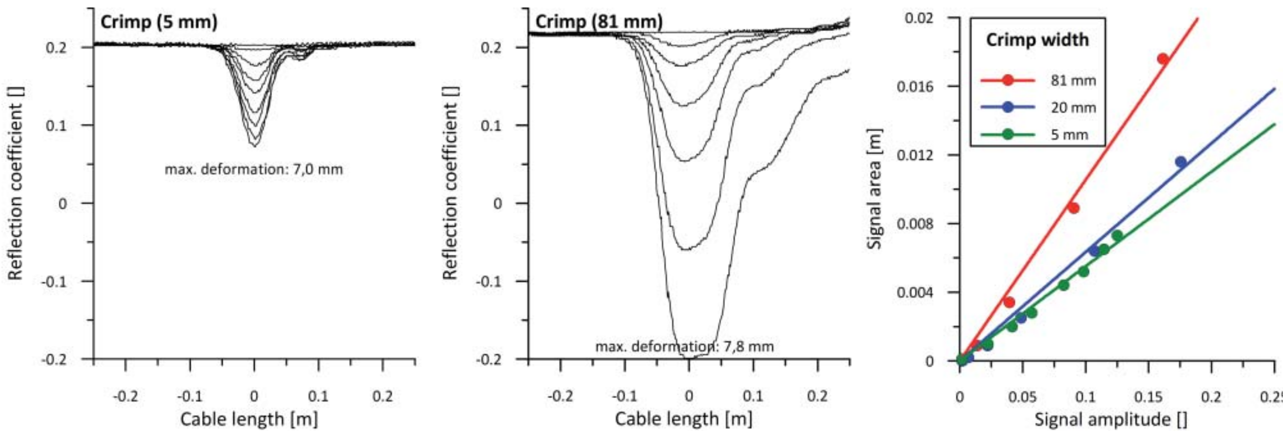

Figure 9: TDR signals produced during cable crimping with 5 and 81 mm width (left and middle). The maximum deformation amount is about the same in both cases, the resulting signal amplitudes however differ greatly. By additionally taking e.g. the signal width or area into account (right), the different crimp widths can be discerned.

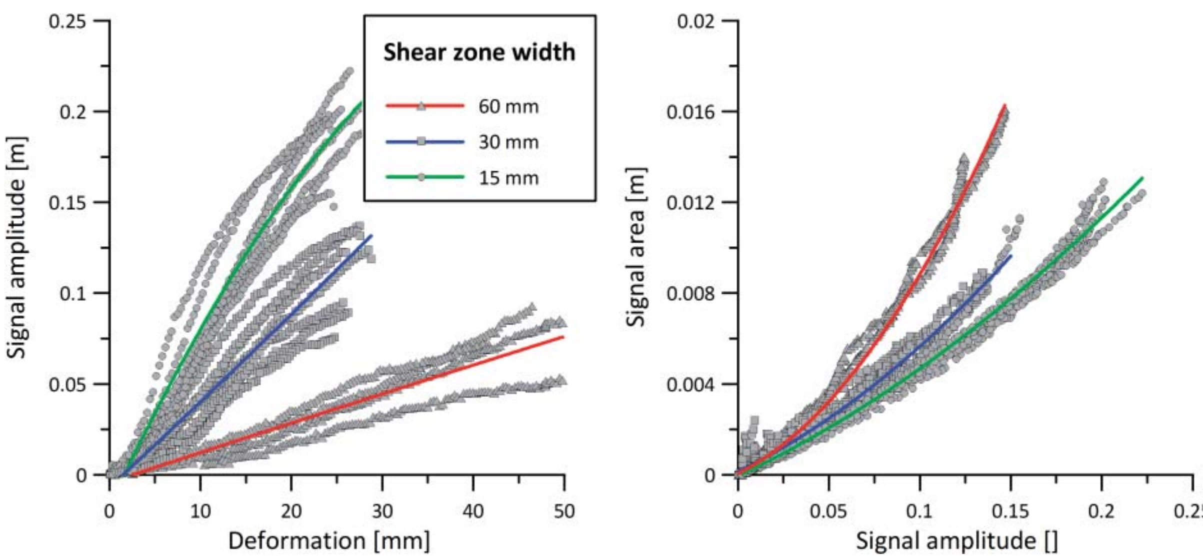

Figure 10: Left: Correlation between signal amplitude and deformation determined in laboratory shear tests with the same grout but different shear zone widths. Right: The comparison of the signal area in dependency of the signal amplitude can be used to determine the shear zone width.

amplitude is ambiguous for different modes of deformation, a determination of the deformation amount is impossible, if the mode of deformation is not known.

This on the one hand can partially be overcome by restraining the possible modes of deformation through measures taken during installation (e.g. introduction of predetermined breaking points into the grout column) and on the other hand by analyzing not only the signal amplitude, but also other characteristics of the TDR signal (e.g. area, width, symmetry and form), which allow to draw conclusions about the mode of deformation and ideally lead to a better quantification of the deformation (see Figure 9 and 10).

In first tests using advanced data mining techniques as e.g. artificial neural networks for pattern recognition (Bishop 2008) on all the TDR signal parameters up to 90% of the measurements from multiple laboratory tests were assigned to the correct mode of deformation. Difficulties however persist especially in the initial phase of deformation, when the TDR signal is very weak.

5.1.4. First field experiences at the Aggenalm Landslide

The TDR measuring system at the Aggenalm Landslide is in continuous operation since October 2008, performing hourly measurements. The TDR system has been very reliable; in the last 12 months the data loss caused by some short power outages and memory overflows due to late data retrieval sums up to less than 5% of the planned measurements. Still, through the installation of the automated data acquisition and status monitoring software it is probable that in future an even higher reliability will be achieved. Most transmission lines (lead- and measuring cables, connectors; mostly buried) have also proven stable to outside influences even throughout the winter. To date no significant deformation signals could be found in the TDR measurements, prohibiting to perform deformation analyses. As no meaningful deformation was measured in the inclinometer measurements either, it seems the Aggenalm Landslide has shown only very little subsurface movement in the monitored boreholes throughout the past 12 months. So far the deformation obviously was not large enough to fracture the grout columns of the TDR measuring sites – a prerequisite for the detection of deformation with TDR.

5.2. VTPS approach

5.2.1. Tacheometric monitoring

At various sites, tacheometric systems are used for permanent or time-discrete monitoring tasks of absolute deformations (ClimChAlp 2008). Typically, the tacheometer and one or more reference targets are located in an area proven or at least assumed to be stable, while an arbitrary number of target points can be chosen in the deformation zone. An indispensable precondition for reliable time series and displacement calculation consists in long-lasting, permanent setup monuments as well as target signalisations in the moving area. Modern tacheometers are motorized, computer-controlled and capable of automatically detecting retro reflecting target prisms by evaluating reflected infrared radiation using simple integrated CCD or CMOS sensor chips as additional sensors. Pre-defined observation cycles can be executed periodically; the results are sent to office directly via internet without human interaction. Application programmes can be developed individually or commercial ones can be used. Instruments in monitoring tasks mostly are top-level due to the high accuracy demands.

5.2.2. VTPS prototype

For the VTPS video tacheometer prototype, the principle of the ATR approach becomes consequently enhanced: A camera not only is used as an additional built-in sensor just to detect binary reflection images in infrared spectrum, but to display any object scene as a human operator would see it. For that purpose, a high resolution camera device is used while either the field of view and telescope magnification of the basic instrument remain unchanged (fully replacing the eyepiece) or the camera optics is mainly used for overview images (additional to the eyepiece). Actual commercial solutions on the market more and more include imagery into their instruments and workflow (e.g. Trimble 2007, Topcon 2008). Those systems, however, are only intended for overlaying measured data in the images, documentation purposes and detecting possible points of interest by using simple corner evaluation routines performed as on-board routines; the straight-forward assignment of image information for proprietary applications is not yet supported. While algorithms and processing operators are well-known from close range and industrial photogrammetry and image analysis, it is still the hardware available which is the limiting factor in video tacheometry. To overcome that, in cooperation with Leica Geosystems a short run prototype based on a TCRA1201+ R1000 tacheometer equipped with a 5 megapixel coloured CMOS eyepiece-camera was acquired within the alpEWAS project. It offers full remote access to all controls and data via USB and/or serial data connections and guarantees most flexible operation and calibration possibilities especially for academic research purposes.

A video tacheometric setup provides a photogrammetric system in combination with the very precise determination of its exterior orientation (e.g. by the angular readings of the tacheometer the spatial direction the camera points to is known very exactly) and with a reflectorless distance measurement unit to overcome the 2D limitation of imagery. Pixel size is 2.2 μm, leading to an angular resolution of 0.9 mgon if the worst comes to the worst. In standard applications, sub-pixel evaluation is possible and the medium angular resolution rises to 0.1 mgon and even better, limited more by the angular reading of the tacheometer's pitch circle than by the camera dimensions.

The camera's interior orientation changes with any focussing operation as well as the image scale and

Figure 11: VTPS prototype in its housing at the Aggenalm Landslide test site (Singer et al. 2009a).

the pixel-angle-relationship. Therefore a calibration parameter set for a sufficient number of focus positions needs to be determined. This is done using a combination of the well-known collinearity equations and an affine chip geometry approach regarding a tacheometer axis error model using a virtual 3D point field (Huang and Harley 1989). By this way, for any pixel of the tacheometer image its corresponding spatial direction (horizontal and vertical angle) can be obtained with respect to the focussing and the actual angular readings of an arbitrary or calibrated centre pixel. This does not only allow the measurement of single target points, but also of linear and laminar structures, which not necessarily have to appear simultaneously in the same image. A combination of object parts due to image mosaiking is even possible without overlapping regions.

5.2.3. Target detection strategies and drawbacks

Detection of targets is mostly done using a wide variation of edge or gray value operators (see a compacted flowchart in Figure 12). When the target representation in the image is adequately large, sub-pixel algorithms can be used with high reliability. To retrieve the necessary complement of the two-dimensional image information for spatial coordinates, reflectorless laser distance measurement on the detected points is used. Video tacheometry, considered as a moveable, always absolutely oriented and calibrated measurement camera, offers completely new possibilities for geodetic targets to be observed. Artificial structures can be found and measured automatically while natural structures can be taught and relocated by matching algorithms (see Figure 13).

In a controlled environment, i.e. with indoor applications and distances not longer than 100 m, video tacheometry showed very high accuracy exhausting the possible sub-pixel angular resolution. When being used under outdoor conditions, however, refraction issues have to be considered. In a pure geometric way, especially high frequent, turbulent air density variations due to thermal and stochastic convection (air flickering over hot surfaces, scintillation of objects in larger distances) lead to aggravations in target detection: even in consecutive images apparent target positions vary by a few pixels, target structures show fluctuating shape structure deformations and blurring increases. In practical use, these problems may be restricted by integrating over a whole series of images. Outdoors the expected accuracy therefore is reduced to approx. 1 mgon, advancing with the number of images to evaluate (Wasmeier 2009a).

Additionally, illumination variations at different measurement times alter the looks of the mapped object scene. Global changes may be counteracted with an adoption of exposure time, but when image brightness does not change linearly, some over- or underexposed areas may remain in which also geometric information is askew. This is problematic especially when there are bright blooming image domains on the one hand, while on the other hand still too little texture information can be seen in the dark areas (sun & shadow-effects). This circumstance also leads to blurring effects of object edges and is a severe limiting factor.

Furthermore, sufficient visibility is essential of course. Scheduled measurements during darkness or heavy weather (snow, rain, fog) are impossible or only possible with restrictions. When using outdoors, the system therefore is only qualified for long-term monitoring tasks without impending of sudden catastrophes. At the Aggenalm landslide this precondition is given.

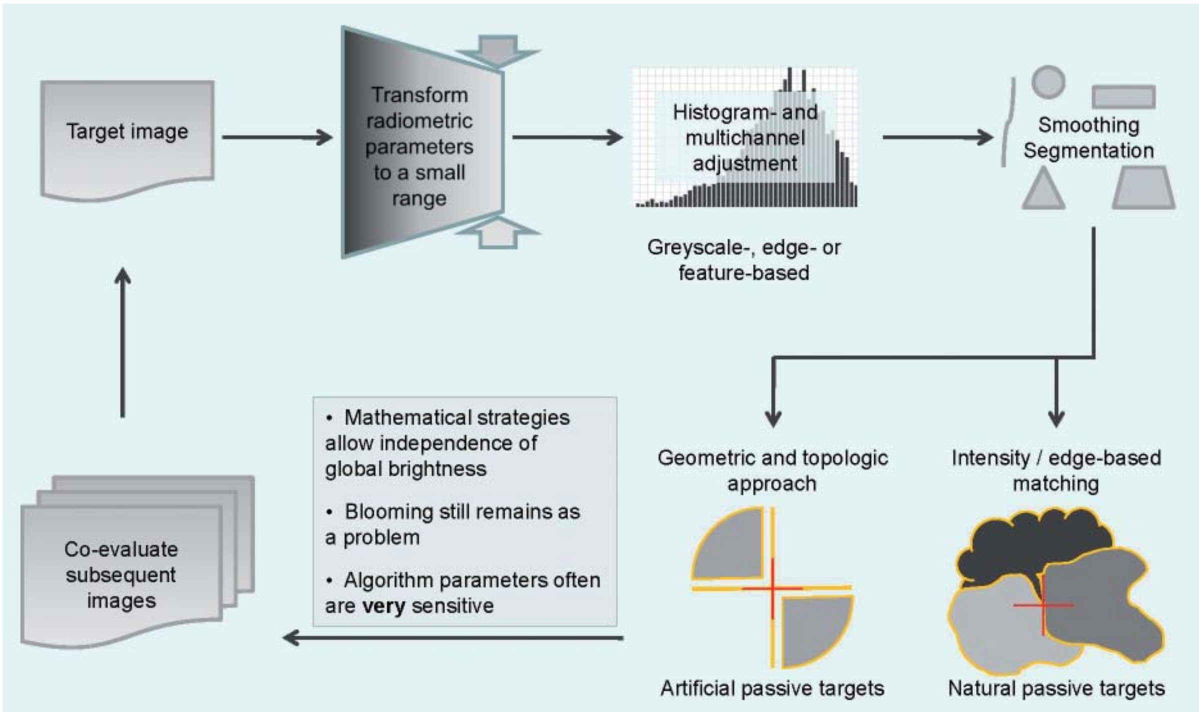

Figure 12: Image evaluation and target detection flowchart. Pre-processing tools like radiometric and segmentation operators are used to normalize the input images for the later detection algorithms. To increase reliability and precision, a subsequent set of images becomes evaluated and averaged.

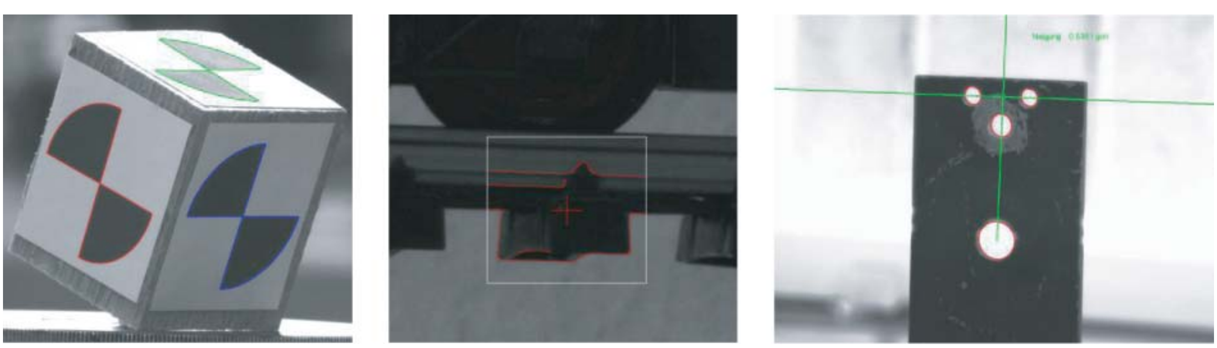

Figure 13: Possibilities of target detection with VTPS: geometrically defined artificial structures under different viewing angles (left), natural structure defined by edges (middle), target "which does not exist", i.e. a hole centre only defined by its shape (right) (Wasmeier 2009b).

5.2.4. The alpEWAS setup

As stated above, video tacheometer systems like the VTPS prototype, which exclusively use the camera image for precise targeting, are primarily suited for a diversity of indoor applications in close or medium range. One innovative goal of the alpEWAS project is to extend this scope of application also to the monitoring of buildings and landslides.

Within the project, reflecting targets are only used at some reference points in the stable area off the slope to calculate the tacheometer position right in the middle of the test site. All other targets in the project are non-signalled natural ones, predominantly surface rocks which are meant to move with the slope. By this setup, targeting density and distribution can be adapted to actual preconditions and upcoming cognitions at any time during the monitoring pro-

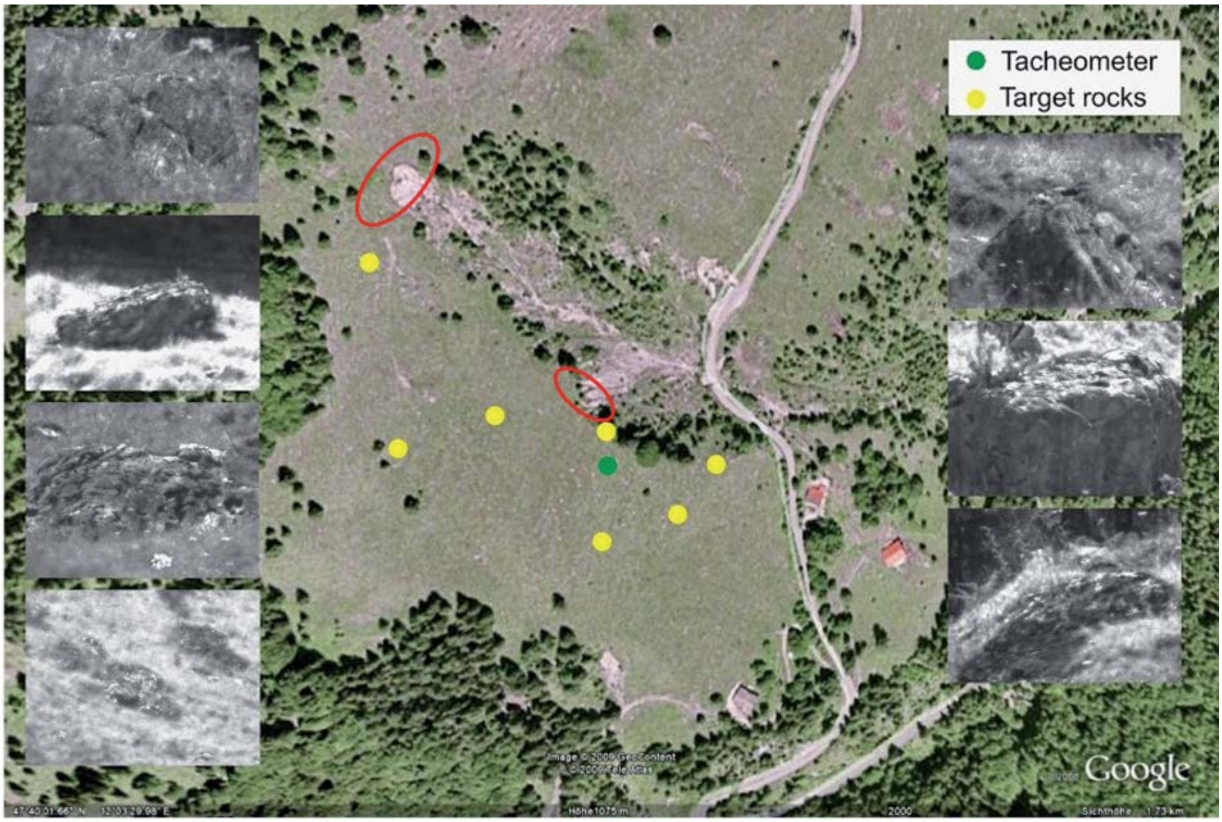

Figure 14: The alpEWAS test site "Aggenalm", the location of the VTPS and some surface rocks which are used as natural targets. The very different illumination situation can be seen in the target images. The red marks show some tear-off edges which could also be monitored with VTPS.

cess, as long as there are enough potential elements to monitor. The system is flexible to target changes (appearance, perspective, alteration), so target losses are minimized and targets can easily be replaced by other close objects. Accessing some instable and potentially dangerous area would not be necessary any more (although on the test site this is not the case).

One more advantage of video tacheometry is the possibility to perform simultaneous and continuous surveys of linear and laminar natural features as e.g. tear-off edges or debris flows, which cannot be equipped with reflectors at all. Using the calibrated spatial direction measurements directly from the image and reflectorless distance measurement, 3D-localisation of surface objects is actually in progress. Currently, selected points at the slope are observed semi-automatically and periodically (see Figure 14), as outdoor applications do not yet show the unsupervised detection stability one must expect of a fully autonomic monitoring system. The monitoring of surface rocks gives promising results indeed, but not all of the rocks could be detected in every epoch, especially when there is only little contrast to the background due to the actual light conditions.

The results of the first year of experience are shown in Figure 15, compared to the GNSS-detected slope movements. Assuming all the reference points on opposing slopes (including the GNSS reference station) remained stable, the VTPS pillar and the GNSS stations show downhill displacements of approx. 1–1.5 cm, while the VTPS-measured target rocks show 3–8 mm. The displacements are not significant yet, but qualitatively point at the expected direction and represent the expected movement rate deduced from alternative measurements of the past years.

5.3. *Low cost GNSS component*

5.3.1. *PDGNSS NRTP approach*

For the detection of movements on the surface at selected points low cost GNSS sensors were installed

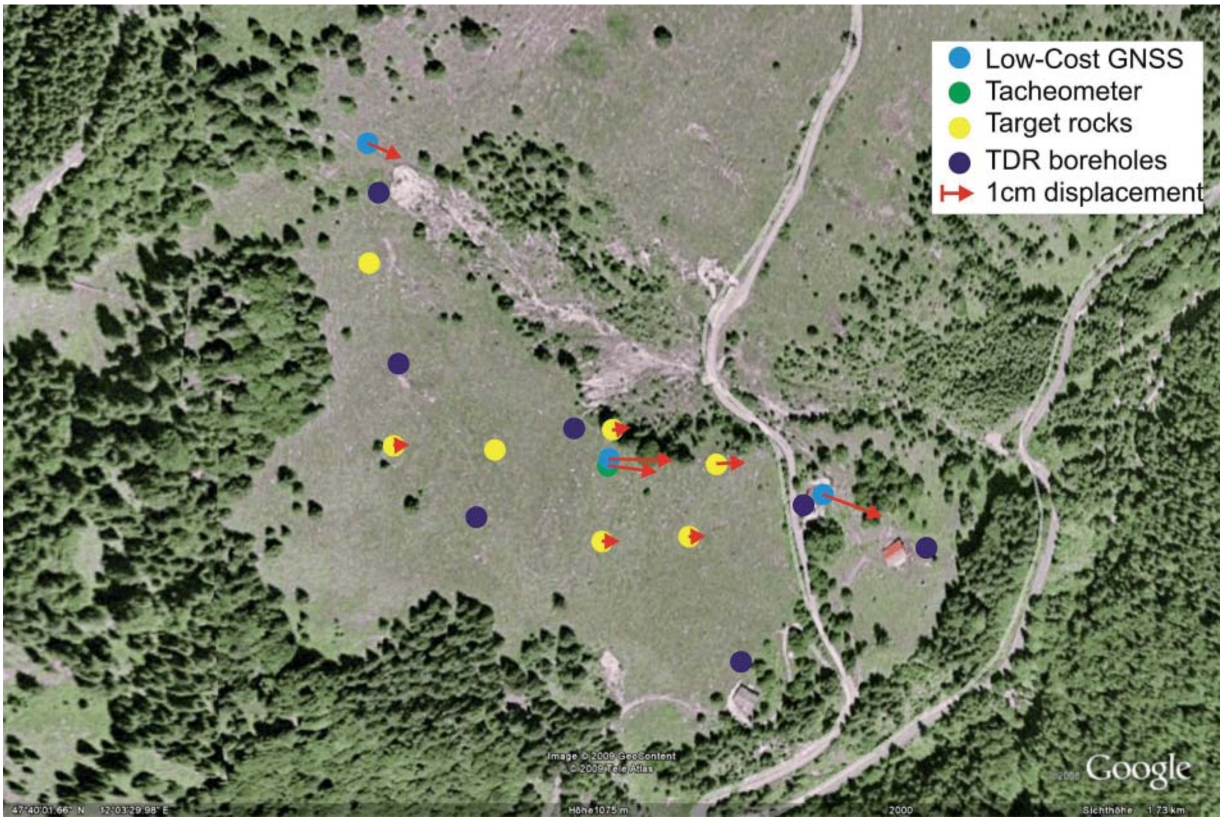

Figure 15: First results from autumn 2008 until late summer 2009. Until then, GNSS and the VTPS pillar show displacements of ~1 cm while the target rocks show slightly less. Regarding the achievable accuracy, the displacements are not significant yet, but qualitatively point downhill and with the expected rate per year. Two target rocks could not be reliably detected in all the epochs and therefore were omitted at that time.

at the Aggenalm. To achieve accuracies in the range of a few mm only carrier phase (CP) based GNSS methods come into consideration, namely precise differential positioning (PDGNSS). Using PDGNSS techniques to observe discrete points permanently in a monitoring network the results should be available only with a short delay. Processing data in near real time (NRTP) is very close to this association. CP measurements are recorded over certain, in principle freely and individually selectable time span at the involved different locations. Depending on the receivers, the satellite visibility and the expected velocities of the points usually a time interval of about 15 min with a recording frequency of 1 Hz or similar can be considered for the CP raw data acquisition at landslide monitoring tasks, however. Once the raw data from several locations – at least one should be on stable ground and the others are spread on the slope – is available at a central computing station the baseline processing can start immediately. More details of the NRTP PDGNSS approach and the technical realization is described in Glabsch et al. (2009b). As to be seen the chosen concept opens all the well-known options of high sophisticated post processing in a geodetic monitoring network adjustment.

For economic reasons, only simple low cost navigation receivers are investigated in the project but nevertheless the NRTP approach is not restricted to such kind of receivers solely. The essential requirement of the involved receivers is that they must have the possibility of read-out the CP raw data. Most of the simple navigation receivers make use of these data for some internal smoothing operations but do not have the ability of an autonomous phase-based positioning like the customary rovers. A relative simple "loose coupling" of the sensors into a GSN can be realized if raw data is disposed via a serial RS232 interface. Examples of in the proj-

Table 1: GNSS hardware components.

Model	Novatel Smart Antenna	Novatel Smart-V1G Antenna
GNSS	GPS	GPS & Glonass
Receiver type	Superstar II	OEMV-1G
No. of channels	12 L1 GPS	14 L1 GPS 12 L1 Glonass
Accuracy carrier phase	1 cm rms	0.15 cm rms
Power	9–24 V; 1.4 W	9–24 V; 1.2 W
Price incl. VAT	~800 €	~1200 €

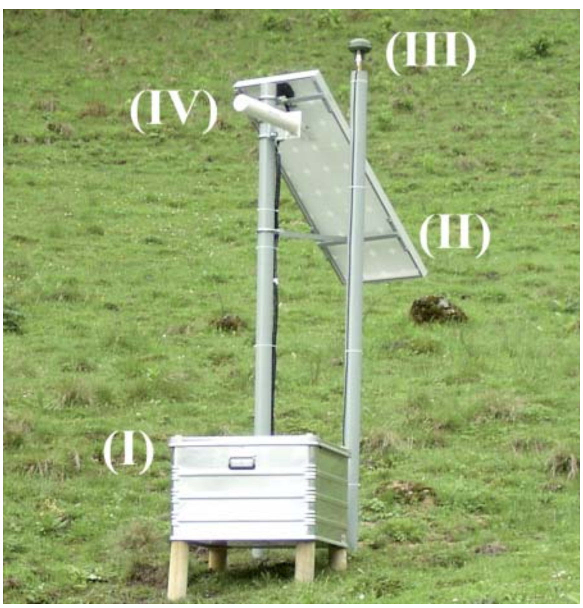

Figure 16: Autarkic GNSS sensor node.

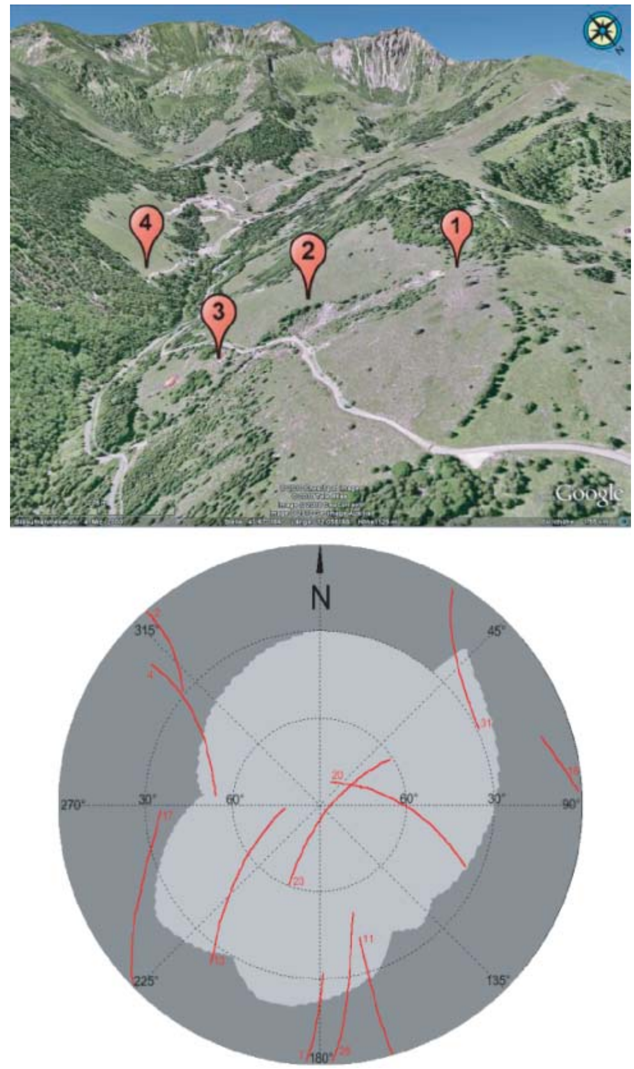

Figure 17: Topographic situation at Aggenalm, beneath shadowing mask for baseline $\boldsymbol{b}_4^1$ with satellite availability during a 2 hour time span on June 15th, 2009 (04:00–06:00 o'clock CET).

ect deployed receivers with some technical specifications are shown in Table 1. Figure 16 depicts their implementation in an autarkic sensor node. Housed in the metal case (I) is the backup battery, the charge controller and the wireless device server. On the left pole the solar panel (II) and the WLAN antenna (IV) is fixed, on the right pole the GNSS sensor (III) is mounted.

5.3.2. *Environmental constraints*

The geographic location of the project area at about 1050 metres above sea level leads to some adverse effects. Shadowing effects have to be regarded which have negative impact on GNSS capability. The surrounding mountains in the south and the topographic situation restrict the open sky strongly. A temporarily small number of satellites in view can lead to an inaccurate position solution or in extremely adverse cases even to no reasonable solution for the chosen 15 minutes time interval. An example of the situation for baseline $\boldsymbol{b}_4^1$ (reference station – sensor node 1) is shown in Figure 17. In the depicted time slot of 2 hours temporarily less than 5 satellites are available.

Furthermore weather related malfunctions can occur which may have implications in the form of individual small signal disturbances up to the failure of an entire sensor node. In particular, sustained heavy snowfall may increase the probability of a failure although the stations are designed for harsh environ-

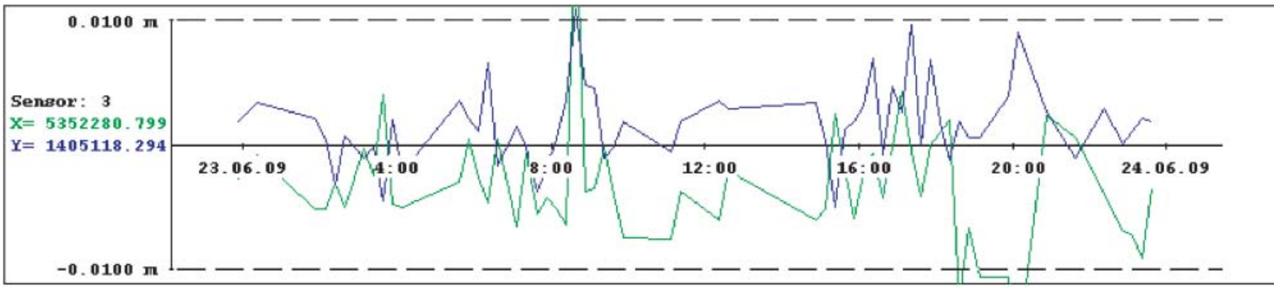

Figure 18: Variations of the horizontal position during a representative day. Depicted are the 15 min. solutions of sensor #3 where all outliers are eliminated and the gaps are closed.

mental conditions. The worst case scenario – which already occurred – are a completely snow covered GNSS and WLAN antennas for days. However, the main knock-out factor is power supply. Although the autarkic sensor nodes can operate several days without any recharge, the point in time where the charge controller unlinks the consumer load to protect the battery from deep discharge would come – the sensor node is taken out of service until sufficient recharge via the solar panel has taken place. Such operational disorders generally become apparent some days in advance which normally gives the administrator the time to dispose a remedial action. For GNSS sensor nodes with less solar radiation in winter months like #4 (maximal hours of sunshine per day < 2) an additional fuel cell stabilizes the power supply considerably. At the Aggenalm the low cost GNSS system works reliable however some loss of data due to the rough environmental conditions has to be accepted.

5.3.3. Selected GNSS results

Since the beginning of permanent data recording in February 2009 about a year of data is available at the moment. First data assessment and calculation of movement patterns are possible. However, before the results of the baseline processing can be used for further analysis all data must be filtered to eliminate outliers which are primarily caused by an insufficient satellite visibility or other faulty calculations. This first step is called raw data filtering. The pre-filtered epoch solutions then can be used e.g. to derive movement trends or just visualize GNSS-time series by enclosed additional filter steps.

The results of the pre-filtered raw data (horizontal position -Northing X, Easting Y-, height is worse with the factor of 3) of sensor #3 (Lampl Alm) for a selected day is shown exemplarily in Figure 18. After the elimination of incorrect measurements the total variation of the horizontal position spreads in an area of quite clear less than ± 1 cm.

The above mentioned problems by temporarily unavailable or inadequate quality of computational results are particularly evident in the period between 10:00 o'clock and 15:00 o'clock. For further analysis – especially in order to make predictions of long term trends of the deformation process – a moving average (MA) filter based on the L1-norm estimator can be used preferably. The length of the filter can be chosen individually, an appropriate adaption in relation to data quality and time-series length has to be considered. In the following figures the filter extends over 24 epochs which corresponds to a 6 h mean value. As depicted in Figure 19 even small movements become visual, e.g. in springtime the accelerating influence of snow melt (April–May) or periods of heavy rainfall (occurred end of June 2009 in the Alps).

6. Integrative data management and analysis

6.1. Data management

Figure 20 shows the flowchart of the main steps from the sensors respectively measurements to an automatically generated permanently actualized result or status report. A flexible data storage is achieved with an open source MySQL database. All sensor data – results and raw data as far as there is no extensive preprocessing essential and some additional quality parameters and meta data – are stored in the database. The sensors in the field are addressed by so called sensor plug-ins. Preprocessed so-called 1st level results are maintained in a structured format for further analyses or for a standardized data exchange. Various monitoring tools permanently check the current status of critical system

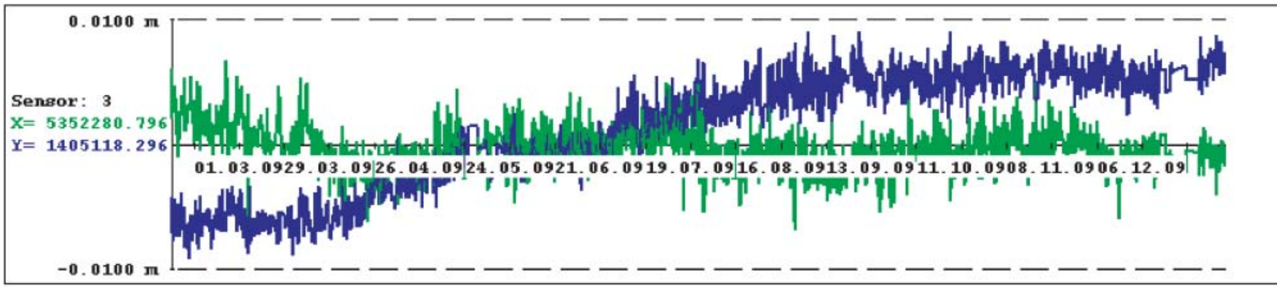

Figure 19a: Medium-term trend of sensor #3 (moving average filter of 6 hours between February and December 2009). The estimated movement rates of the slide from former sporadic measurements are at the order of 1 cm per year which already can be confirmed by the developed system. However, small gaps due to system breakdown and other failures in March and December are to be seen.

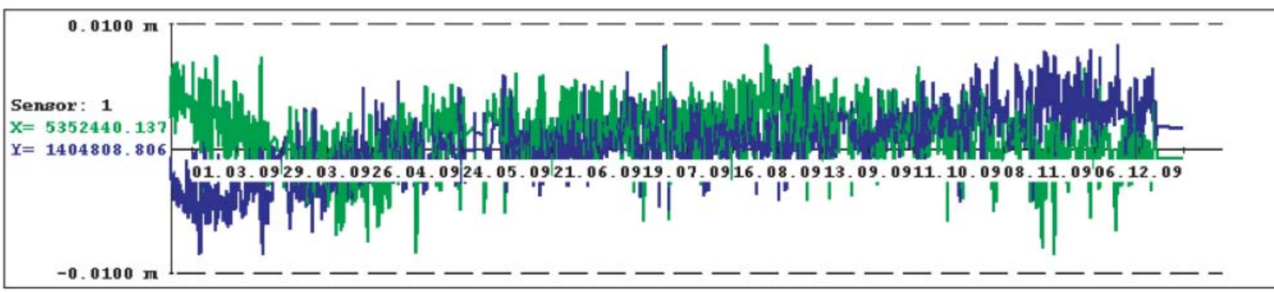

Figure 19b: Medium-term trend of sensor #1 (moving average filter of 6 hours between February and December 2009).

parameters in order to detect failures of individual sensors or subprograms as quickly as possible, thus long-time data loss can be avoided. In the course of further considerations e.g. by the implemented integrative analysis data from all different measurement systems can be merged in a joint evaluation to get information of the current state of the monitored object. If preset thresholds or critical states are detected it is possible to activate a predetermined warning plan.

An important interface is the link between the onsite computer centre and the system operator(s) or possible end users. Since it is not necessarily required to run complex and computationally intensive analysis on the onsite computer, a trouble free data exchange and access is provided – computational power can be split to several machines this way. The chosen and realized approach is as follows: To ensure fast data access the database is constantly reflected to a second data server at the project office. With only a short time delay all new datasets are available on a server that possesses a broadband connection. Querying large amounts of data is not affected by the limited internet link via satellite from the office to the project site.

In time of worldwide network-link by the internet, interoperability is one of the main criterions for a standardized trouble-free data exchange between heterogeneous systems. The Sensor Web Enablement (SWE) initiative of the Open Geospatial Consortium (OGC®) aims to develop and introduce a worldwide standard of handling space-orientated data for an interoperable benefit. More details see e.g. Walter et al. (2008). Finally, every monitoring system has to be regarded as a part of the Spatial geo Data Infrastructure (SDI). According to Botts et al. (2007) the intention of the initiative is that

- all sensors (sensor nodes) of monitoring systems reporting preservative position (and position changes, occasionally restricted to single components like changes in inclination);
- all connected to the Web (whereby an differentiated access of administrators, stakeholders and other parties is to recommend);
- all with metadata registered (for further data handling like corrections or the assessment of the system's status);
- all readable and – as an option – controllable remotely.

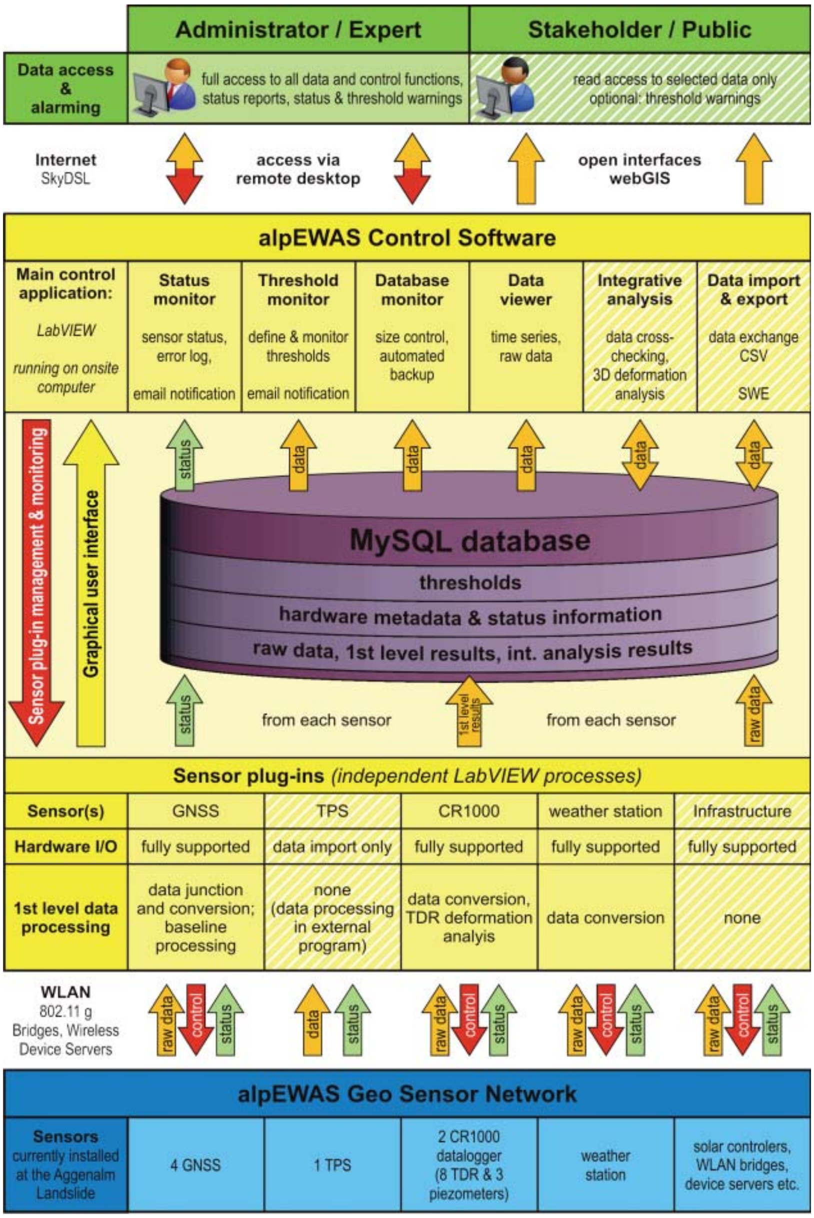

Figure 20: alpEWAS control, management and data analysis software (Thuro et al. 2009a).

Therefore in the alpEWAS data management open, standardized interfaces play an important role to face the requests for an interoperable data exchange. According to requirements of data security and the restriction of access rights to selected users data exchange can be handled in two different ways: Directly forwarding of sensor measurements for example with a Sensor Observation Service (SOS), which coincidentally needs a detailed technical description of the connected sensor. This can be realized via Sensor Modelling Language (SML). If only prepared results should be transferred in order to reduce the possibility of misinterpretation or for data protection reasons other interfaces have to be provided like data access via Web Map Services (WMS) or Web Feature Services (WFS).

6.2. *Integrative data analysis*

Since February 2009 a continuous recording of all sensors with the possibility of remote access and control has been realized, thus permitting to perform first time series analysis on the collected data. From prior landslide events at the Aggenalm and first re-

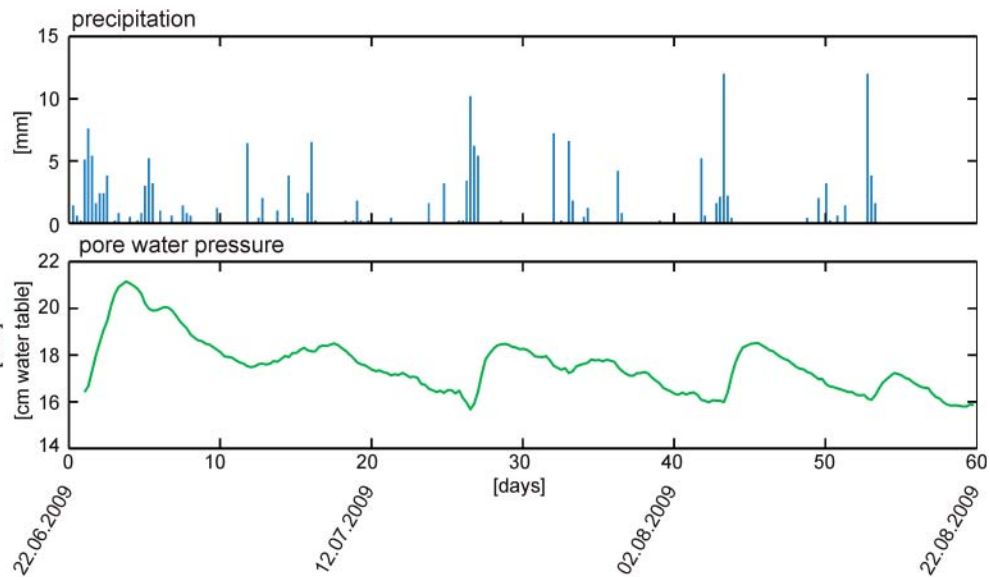

Figure 21: Filtered and resampled time series of the precipitation and pore water pressure from June 22nd to August 22nd 2009.

sults of the geomechanical model it is fancied that one of the major influencing factors on the movements of the slide is the precipitation. Aim of the time series analysis is to proof dependencies between precipitation, pore water pressure and deformation. Up to now only about 1 cm of displacements could be detected by the VTPS and the GNSS system. With the TDR component no subsurface deformation could be detected yet, since the clamping process of the TDR cable is still in progress. Therefore for the moment mainly the GNSS results and the environmental data can be used.

The data analysis described in the following is reduced to a 60 day section from June 22nd to August 22nd 2009, where only rare losses of data occurred. These short data gaps can be interpolated with linear methods or can be solved by resampling with lower frequencies.

6.2.1. *Filtering and resampling*

For the preparation of the precipitation data 6 and 12 hour cumulatives have been calculated, respectively. This provides a better comparability with the piezometer and GNSS data. The piezometric data set shows a smooth gradient and had to be corrected by the influences of the barometric pressure. To improve GNSS data a low-pass filter can be applied, see Figure 19. Due to different sampling intervals in the data acquisition – the pore water pressure and precipitation are acquired in a one hour interval whereas the GNSS positions are processed for every 15 minutes – all data has been resampled with the same time interval. Finally, because of minor data losses a 6 hour resampling was chosen.

Figure 21 depicts the filtered and resampled time series of precipitation and pore water pressure for a chosen 60 day interval. Examining the time series, it is obvious that there is a cause-and-effect chain between the amount of precipitation and the pore water pressure. One can see that a few days after a major rainfall event the pore water pressure begins to rise (see Figures 21, 22). Because of the relatively short time span of identical time series and only few days of precipitation, the system (rainfall, increase in pore water pressure, change in GNSS coordinates) can yet not be described by more sophisticated models. In this first attempt the time response between rainfall and pore water pressure was the major objective. Even though GNSS observations showed about 1 cm down slope displacement time correlation with the precipitation and/or pore water pressure showed no significant results up to date. Beside the analysis of the 60 day span, also shorter time series of only about ten days were examined by cross correlations.

6.2.2. *Cross correlation*

To show the temporal dependency, cross correlations were calculated using the time series toolbox integrated in MATLAB. The analysis of the

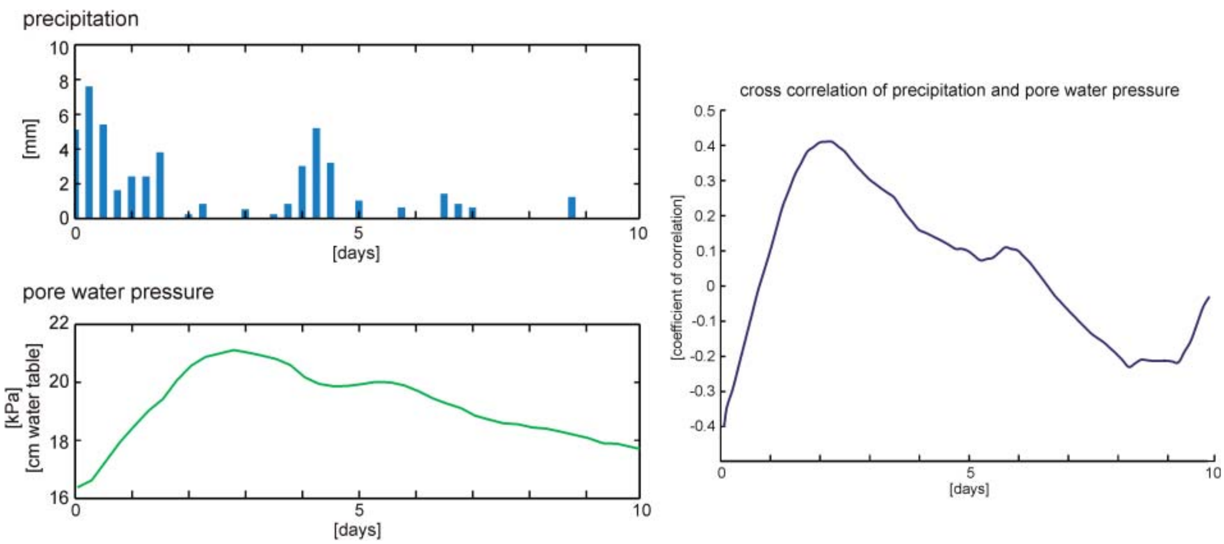

Figure 22: Time series of precipitation and pore water pressure for a time span of 10 days (June 23rd to July 3rd 2009) and the cross correlation of these two time series.

complete time span (60 days) shows a correlation between the precipitation and the pore water pressure with a delay of 2 to 3 days, but cross correlation of the piezometric time series with the GNSS results did not approve significant temporal dependency.

Figure 22 shows the two time series for a shorter span of only 10 days, starting June 23rd 2009. The first two days a strong continuous rainfall (~20 mm) can be observed. Comparing the time series, a peak in the pore water pressure is reached about 3 days after the beginning of the rainfall. The cross correlation of the same time span illustrates a fairly good correlation coefficient showing a time delay between the precipitation event and the pore water pressure of about 2.5 days. This behaviour with a slightly varying time delay of 2 to 3 days can also be detected in other sequences of the acquired data set following a strong rainfall event.

The correlation of the time series presented gives one a first view on a possible analysis method. Longer time series with less data gaps as well as a greater number of significant precipitation events should allow a further and more detailed interpretation of the cause-and-effect chain. In particular greater point movements in the GNSS data should make it possible to integrate these in the analysis and also detect dependencies between trigger events and deformations.

7. Conclusion

The alpEWAS project should be continued in the future under the common responsibility of the research team of this article. A main focus is the development of cost-effective monitoring techniques like TDR, VTPS and low cost GNSS and their individual as well as combined analysis. However, in comparison with high-end devices like dual-frequency GNSS receivers with a choke ring antenna etc. a certain diminishment with respect to accuracy and reliability has to be accepted. Thus, small movements as they occur recently at the Aggenalm are hard to describe but nevertheless the early warning option in case of larger events is possible with the already available devices.

TDR is a method easily to automate and capable to localize subsurface deformations. The quantification of the deformation, however, remains a challenging task, as many parameters affect the signals received from a deformed coaxial cable. While the influence of the installation setup and the signal attenuation can be accounted for using empirically determined calibration and correction curves, the identification of the mode of deformation has to be performed based on parameters derived only from the observed TDR signal. However, especially in the initial phase of deformation this is not always possible as the experience from the Aggenalm showed.

VTPS for monitoring tasks including autonomous target detection and recognition is at its beginnings in Geodesy. Current research is performed at various places with the different available prototypes. Its usage in the scope of the alpEWAS project is an academic feasibility study, which tries to determine the potential, but also the limitations in continuous service. The above depicted results of the low cost GNSS monitoring system already allow first geological assessments and interpretations of the landslide. However, further effort has to be made to increase reliability and accuracy. Here current work concentrates on a comprehensive quality management and on developing additional processing and estimation procedures.

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References

A) Project publications

Festl, J. (2008), Eignungsprüfung von Zement-Bentonit-Suspensionen als Injektionsgut bei TDR Deformationsmessungen. Master thesis. Supervised by Kurosch Thuro and John Singer. Munich. Technical University Munich, Chair of Engineering Geology.

Glabsch, J., Heunecke, O. and Schuhbäck, S. (2010a), Development and testing of a low cost sensor PDGNSS landslide monitoring system using the example of the Aggenalm Landslide in the Bavarian Alps. Joint Board of Geospatial Information Societies (JB GIS), Best Practices Booklet on Geo-information for Risk and Disaster Management (reviewed paper, in preparation).

Glabsch, J., Heunecke, O. and Schuhbäck, S. (2010b), Überwachung von Rutschhängen mittels Low-Cost GNSS Empfängern im Near Real Time Processing. In Wunderlich (ed.), Int. Kurs für Ingenieurvermessung, Munich (reviewed paper).

Glabsch, J., Heunecke, O. and Schuhbäck, S. (2009a), Hangüberwachung mittels Low Cost GNSS im alpinen Raum – Ansätze und Erfahrungen. AHORN 2009, Zürich. 5./6. November 2009; see: www.igp.ethz.ch/AHORN/downloads/OttoHeunecke_AHORN2009_Publication.pdf.

Glabsch, J., Heunecke, O. and Schuhbäck, S. (2009b), Monitoring the Hornbergl landslide using a recently developed low cost GNSS sensor network. Journal of Applied Geodesy (JAG), Issue 4, pp. 179–192 (reviewed paper).

Günther, J., Heunecke, O., Pink, S. and Schuhbäck, S. (2008), Developments Towards a Low-Cost GNSS Based Sensor Network for the Monitoring of Landslides. 13th FIG International Symposium on Deformation Measurements and Analysis, Lisbon, May 12–15.

Singer, J., Thuro, K. and Sambeth, U. (2006), Development of a Continuous 3D-Monitoring System for Unstable Slopes using TDR. Charaterisation and Monitoring. In: Felsbau, Jg. 24, H. 3, pp. 16–23, last accessed 30.06.2009.

Singer, J., Thuro, K. and Festl, J. (2010), Development and testing of a time domain reflectometry (TDR) monitoring system for subsurface deformations. (Paper accepted). In: N. N. (Hg.), Proceedings of the European Rock Mechanics Symposium (EUROCK 2010). Lausanne, Switzerland, 15.–18. June 2010: CPC/Balkema (Taylor & Francis).

Singer, J. (2010), Development of a continuous monitoring system for instable slopes using Time Domain Reflectometry (TDR). Dissertation in preperation. Supervised by Kurosch Thuro. Munich. Technical University Munich, Chair of Engineering Geology.

Singer, J., Schuhbäck, S., Wasmeier, P., Thuro, K., Heunecke, O., Wunderlich, Th., Glabsch, J. and Festl, J. (2009a), Monitoring the Aggenalm landslide using economic deformation measurement techniques. Austrian Journal of Earth Sciences (AJES), Vol. 102, No. 2, pp. 20–34 (reviewed paper); see: http://www.univie.ac.at/ajes/download/volume_102_2/singer_et_al_ajes_v102_2.pdf.

Singer, J., Festl, J. and Thuro, K. (2009b), Computergestützte Auswertung von Time Domain Reflectometry Messdaten zur Überwachung von Hangbewegungen. In Marschallinger, R., Wanker, W. (eds.), Geomonitoring, FE-Modellierung, Sturzprozesse und Massenbewegungen, Beiträge zur COG-Fachtagung Salzburg 2008, Wichmann publishing house, Heidelberg, pp. 19–34.

Thuro, K., Wunderlich, Th., Heunecke, O., Singer, J., Wasmeier, P., Schuhbäck, S., Festl, J. and Glabsch, J. (2009a), alpEWAS – The Aggenalm Landslide – a testing site for an integrative 3D early warning system. In: Geotechnologien Science Report, Statusseminar 12.–13. October 2009, Technical University Munich, pp. 33–48.

Thuro, K., Wunderlich, Th., Heunecke, O., Singer, J., Schuhbäck, St., Wasmeier, P., Glabsch, J. and Festl, J. (2009b), Low cost 3D early warning system for alpine instable slopes – the Aggenalm Landslide monitoring system. Geomechanics & Tunnelling 3: pp. 221–237 (reviewed paper).

Wasmeier, P. (2009a), Videotachymetrie – Sensorfusion mit Potenzial. AVN 7/2009, Wichmann publishing house, Heidelberg, pp. 261–267.

Wasmeier, P. (2009b), Grundlagen der Deformationsbestimmung mit Messdaten bildgebender Tachymeter. PhD thesis, DGK Reihe C 638, Munich 2009.

B) Other publications

Bayerisches Landesamt für Umwelt (BLfU) [ed.] (2008), Bayerns Klima im Wandel – erkennen und handeln. Informal brochure. Munich. ISBN 978-3-940009-73-9.

Bishop, C. M. (2008), Neural networks for pattern recognition. Reprinted. Oxford: Oxford Univ. Press.

Blackburn, J. T. and Dowding, Charles H. (2004), Finite-Element Analysis of Time Domain Reflectometry Cable-Grout-Soil Interaction. In: Journal of Geotechnical and Geoenvironmental Engineering, Jg. 130, H. 3, pp. 231–239. Online available under doi:10.1061/(ASCE)1090-0241(2004)130:3(231), last accessed 28.07.2009.

Botts, M., Percivall, G., Reed, C. and Davidson, J. (2007), OGC® Sensor Web Enablement: Overview And High Level Architecture. OGC White Paper, February 27, 2007.

ClimChAlp (2008), ClimChAlp Interreg IIIB Alpine Space WP6:

Slope Monitoring Methods – A State of the Art Report. Munich, February 28th.

Cruden, D. M. and Varnes, D. J. (1996), Landslide types and processes. In: Turner, A. K., Schuster, R. L. (ed.), Landslides: Investigation and Mitigation. Transportation Research Board – National Research Council. Special Report 247, pp. 36–75. Washington, D.C., USA: National Academy Press, 1996.

Dowding, C. H. and O'Connor, K. M. (2000), Comparison of TDR and Inclinometers for Slope Monitoring. In: Marr, W. A. (Hg.), Geotechnical measurements. Lab and field; proceedings of sessions of Geo-Denver 2000. August 5–8, 2000, Denver, Colorado. Reston, Va.: American Society of Civil Engineers (Geotechnical special publication, 106), pp. 80–90.

Foppe, K. (2009), Zeitabhängige Messgrößen: Verborgene Schätze in unseren Daten. DVW-Schriftenreihe, Vol. 59, Wißner publishing house, ISBN 978-3-89639-732-4.

Huang a. H. (1989), Calibration of Close-Range Photogrammetric Stations Using a Free Network Bundle Adjustment. Grün/Kahmen (Eds.), Proceedings of the Conference on Optical 3-D Measurement Techniques in Wien, p. 49ff, 18.–20. September 1989.

Kane, W. F. (2000), Monitoring Slope Movement with Time Domain Reflectometry. In: "Geotechnical Field Instrumentation: Applications for Engineers and Geologists". Seattle. Online see www.kanegeotech.com.

Krauter, E. (1990), Hangrutschungen – ein Umweltproblem. XI. Int. Kurs für Ingenieurvermessung, Zurich 1990, Contribution V4/1, Dümmler book 7816, Bonn.

Lin, C. P., Tang, S. H., Lin, W. C. and Chung, C. C. (2009), Quantification of Cable Deformation with Time Domain Reflectometry – Implications to Landslide Monitoring. In: Journal of Geotechnical and Geoenvironmental Engineering, Jg. 135, H. 1, pp. 143–152. Online see doi:10.1061/(ASCE)1090-0241(2009)135:1(143).

O'Connor, K. M. and Dowding, Charles H. (1999), GeoMeasurements by Pulsing TDR Cables and Probes. Boca Raton: CRC Press.

Sargand, S. M., Sargent, L. and Farrington, S. P. (2004), Inclinometer – time domain reflectometry comparative study. final report. Report No. FHWA/OH-2004/010. Athens, Ohio, USA.

Sohraby, K., Minoli, D. and Znati, T. (2007), Wireless Sensor Networks – Technology, Protocols and Applications. New York: John Wiley and Sons, ISBN 978-0-471-74300-2.

Stempfhuber, W. (2009), Geodätische Monitoringsysteme – Stand der Technik und Abgrenzung der gegenwärtigen Systeme. DVW-Schriftenreihe, Vol. 59, pp. 181–191. Wißner publishing house, ISBN 978-3-89639-732-4.

Thut, A. (2008), Geotechnische Messverfahren. In Witt (ed.), Grundbau-Taschenbuch, Teil 1: Geotechnische Grundlagen. Contribution 11, Ernst & Sohn, ISBN 978-3-433-01843-9.

Topcon 2008, Topcon Imaging Station – Long Range Scanning, Imaging and Robotic Total Station, Brochure, 2008.

Trimble 2007, Trimble Spatial Station VX Data Sheet, 2007.

Walter, K., Niemeyer, F. and Bill, R. (2008), Geosensor Web Enablement in Early Warning Systems for Landslides. EuroSDR & ISPRS Workshop on Geosensor Networks, Hannover, February 20–22, 2008 (published on CD).

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