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GEOPHYSICAL RECONNAISSANCE METHODS FOR LANDSLIDES IN SOFTROCKS

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ABSTRACT

Geophysical ground-based surveys can be applied to obtain many parameters required for assessing landslide potential and activity. These methods and are not only effective in the early reconnaissance stage, but may also be applied for detailed mapping purposes and for time dependent observations. If the landslide is not directly accessible, helicopter-mounted systems had been successfully used. By applying the most appropriate method it is possible to contribute to the investigation of the water regime, to monitor active landslide zones differentiating between displaced material and solid bedrock. Only a proper combination of different geophysical methods will yield most likely sufficient information for the civil engineer to proceed with the layout of drilling patterns or to locate trial pits. Within this paper focus is set only onto geoelectric and electromagnetic methods – both techniques are based on measurements of the electric bulk resistivity of the in-situ strata. Furthermore, it is shown that only the combination of a electromagnetic survey, providing the lateral resistivity information, with 2-dimensional DC-surveys, providing the resisitivity distribution with depth, yields reasonable results for the civil engineer.

To observe the dynamic properties of landslides, evaluation and research is done on a total new approach – e.g. the registration of natural electromagnetic pulses. In order to test and observe such new methods under long-time conditions, a test site had been established and used in central Styria since 1997. The particularity of the site is the possibility of man-made triggered slope movements. A clear correlation between the actual ground movement and accompanying geophysical effects had been proofed and results obtained at this experimental site are promising.

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INTRODUCTION

Three geotechnical aspects are necessary for the civil engineer to evaluate the stability of landslides in unconsolidated sediments, *(i)* the 3-D shape of the sliding masses with emphasis given to existing shear- and slip surfaces, *(ii)* the hydrogeological regime and its network within the slip mass, and *(iii)* the detection of movements and their directional tracking. In the past, ground geophysics, (McGUEFFEY *et al.* 1996) and helicopter-borne systems, (SEIBERL *et al.* 1995), had developments of successfully been applied for reconnaissance work over landslides.

The usefulness of geophysical surveys accompanying investigation processes of landslides has been demonstrated in many casestudies in throughout Europe (e.g. CAMPAGNOLI & SANTARATO 1995, CARIS & VAN ASCH 1991; MUELLER 1977) and, with special emphasis to the venue, in Austria (ARNDT *et al.* 1997; FIGDOR *et al.* 1990; BRÜCKL 1977).

But, geophysical surveys are not only effective in the reconnaissance stage of an mass movement investigation, they provide also useful information in a latter stages *e.g.* mapping of details of the main body of a landslide or even for time dependent observations. By combining appropriate methods (e.g. refraction seismics, electromagnetics, geoelectrics) it is possible to contribute to (*i*) the investigation of the water regime, (*ii*) to monitor the activity of landslide zones and to (*iii*) differentiate between loose material and more consolidated rock. Thus, by conducting geophysical surveys using typical near surface methods, - e.g. electromagnetics, DC multi-electrode soundings, induced polarisation, GEORADAR, shallow seismics - sufficient information may be provided to optimise the layout of drilling patterns, to locate trial pits and to design or redesign drainage systems.

Unfortunately, the field of engineering geophysics developed slowly until the last decade, (ANNAN 1998). The traditional application of geophysics for engineering and landslide hazards was typically limited to refraction seismics for depth of bedrock. As technology evolved, more different applications have been applied for measurements on hillslope in a steady manner. In return, the geophysical community, especially in German speaking countries, has been slow in learning the real requirements of the engineering community dealing with torrent and avalanche control in the Alpine area. One drawback is, that geophysical information is difficult to convey in a format which is understandable by the civil engineer, for engineering geologist, for hydrologist or for decission.making lay person, e.g. the mayor of a village badly hit by a hillslope problem. All those professionals must decide upon *or* use this information even while not well versed with the distinctiveness of geophysical methodology, data presentation or the natural ambiguity of geological models derived from geophysics.

Notwithstanding that the reconnaissance character of geophysical methods in landslide investigations had been discussed in depth by (McCANN & FORSTER 1990), the pace of geophysical hardware developments and introduction of state-of-art software interpretations schemes sustain the necessity to revise this topic for electrical and electromagnetical surveys.

To support these developments, the Austrian Ministery of Science and Transport started a medium term R&D project. An initial step of this research program was the installation of a permanent pilot-site. There, research had been focussed on hillslope materials and processes to interrelate repeated geophysical standard surveys and other time-depended observations such as the registration of specific natural electric fields, changes in pseudo-impedance, irregularities in soil temperature and self-potential.

SOILFALL ST.MAREIN (STYRIA)

Soilfalls are one of the most common phenomena in the Alpine piedmont and thus, not only in the light of the Austrian economy, need special attention. Especially movements triggered by weakening of slope toes are common in area of soft rocks, e.g. shales, mudstones and over-consolidated clays. The weakening of a slope toe may have several causes, e.g. (*i*) flowing water may undercut the toe of a slope, (*ii*) the toe of a slope moves downward through the action of water streaming in the subsoil, (*iii*) present-day designs of motorways and railway tracks aim at a smooth line which frequently makes it necessary to cut through such softrock slopes or, sometimes, (*iv*) mining operation geared to the exploitation of building materials and normally undertaken as benching work is driven through slopes that are almost at limit equilibrium.

Based on above mentioned observations, a characteristically testsite for investigations of landslides in softrock had to be selected. Such a place, situated approx. 40 km W of Leoben, had been found and set up in early 1997 and is used since for repetitive geophysical surveys, for field investigations and for the *in-situ* verifications of research in theory and laboratory. This test site, established in a maiden field of an operating clay pit, allows mass movements to be evidently triggered by the still on-going mining operations.

The regional geology is characterised by a structural depressions formed during the Neogen, and filled with thick Tertiary sediments during post-tectonic processes. These tertiary sediments, situated in the north of the *Seckauer Through,* superimposed on top the of crystalline basement with slight south dip. In latter geological stages the Pliocene and quartenary layers of gravel, sand and clay had been deposited on top. The detailed geology is derived from eight boreholes drilled in and around the vicinity of the investigation area. A geological interpretation of the boreholes presents a few meters thick morainic layer consisting of sand and gravel, followed by interbeddings of silt and clay, sometimes even intersected by sandy layers. From a geotechnical point of view this mass movement shall be described as "*stiff clay overlain by porous caprocks which form water reservoir*".

In Fig. 1 a wireline log (*here:* borehole No. 4) and the resulting geological interpretation is shown. It has be noted, that a minute distinction between clay and silt is often difficult if only geophysical data are used for interpretation.

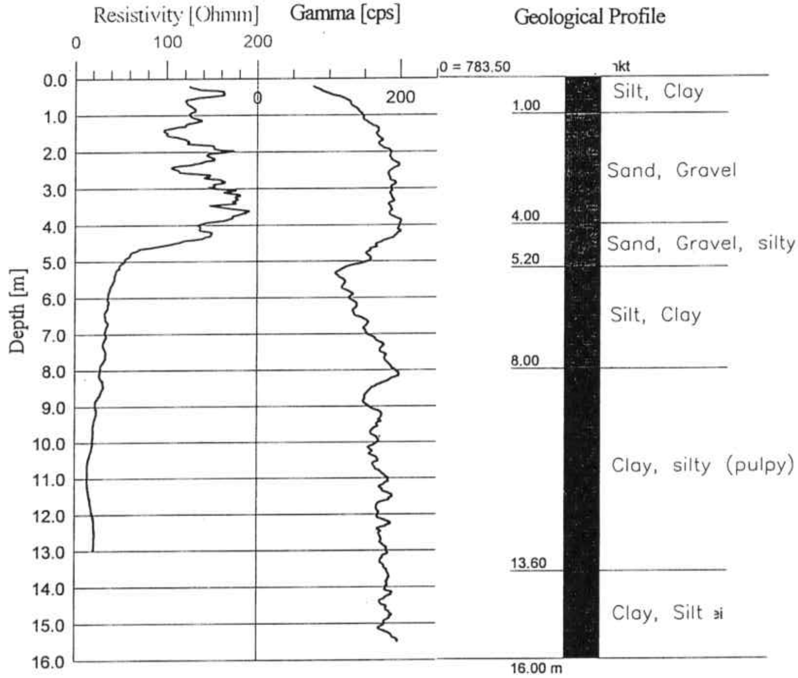

Fig. 1: Geological profile and geophysical well logging, Borehole No. 4

The good distinction between the moraine and the silt/clay layer in a depth of approx. 5 m is obvious. The decrease of the resistivities and the increase of the gamma values at the same time from a depth of approx. 5 m to 8 m could be interpreted as an increase of the fine grain components respectively clay content. From a depth of approx. 8 m a more clayey layer occurs. The geophysical characteristics of the geological formations could be summarised as follows:

• Moraine(sand and gravel)	Resistivity	> 80 – 180 Ωm
(sand and gravel)	Gamma	170 – 200 cps
• Silt	Resistivity	> 20 – 60 Ωm
	Gamma:	100 – 200 cps
• Clay	Resistivity	≤ 20 Ωm
	Gamma	~ 200 cps

THE APPLICATION OF GEOELECTRICS TO LANDSLIDES

All geoelectrical methods, such vertical- and horizontal profiling methods and electromagnetic conductivity profiling, have been successfully used to differentiate between displaced material and the original ground surface. Landslides in softrocks results in the derangement of soil and earth material and the development of an irregular slip-plane, and thus, rather large electrical contrasts are associated with these phenomena. But also the pattern of hillside seepage may change and subsurface water may accumulate at the toe or drain from the top the landslide.

Today, **geoelectric measurements** (DC) are carried out quite often with a multi-electrode system, mostly run in WENNER configuration. Entirely controlled by a laptop, the system measures automatically every possible electrode array, thus providing a high data-density. Fig. 2 shows the some results of the such a resistivity survey, conducted along the line of slope at the soilfall of St. Marein. Fig. 2A depicts the distribution of the resistivities whereas Fig. 2B is a geological interpretation calibrated using the results of the geological profile and the logging of Borehole No. 4, *cf.* Fig 1.

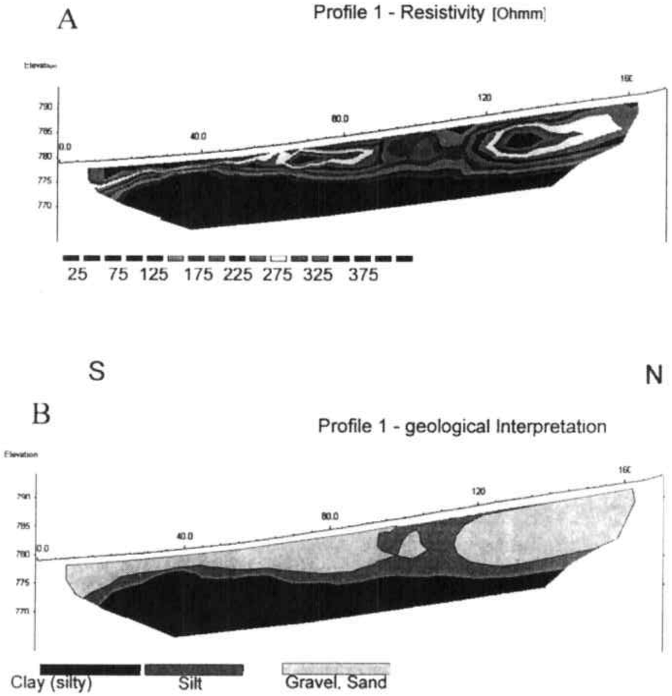

Fig 2: St. Marein: Geoelectric Profile 2: 2A: Resistivity distribution, 2B: Geological Interpretation

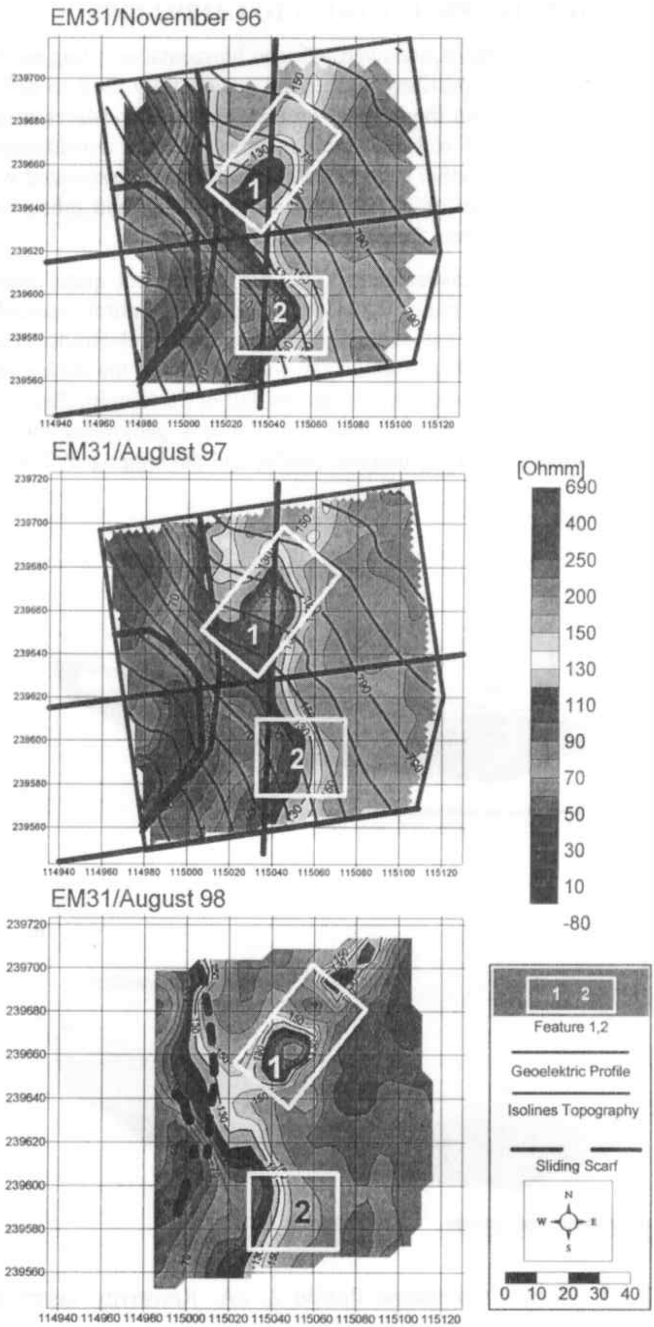

Fig. 3: Resistivity distribution from Electromagnetic EM31

It is obvious by the interpretation of the geoelectrics that the top of the clay layer has a distinctive topography, which is important for the subsurface water flow and thus for a cause of the landslide.

As with geoelectric profiling and soundings, the apparent resistivity of slope materials measured by **electromagnetic techniques** (EM), is for the most part a reflection of presence of bounded and unbounded groundwater. Hence, EM techniques are basically as applicable to landslide as the initial mentioned DC-surveys. An advantage of the inductive EM technique is the potential for a more areal reconnaissance of the investigated landslide. On the test-site of St. Marein electromagnetic measurements have been carried out in three campaigns (1996, 1997, 1998) with three different types of Geonics® EM instruments – (*i*) EM38 with a maximum investigation depth from approx. 1 – 2 m, (*ii*) EM31 with 5 – 6 m and (*iii*) a EM-34 XL with three different coil separations (10, 20, 40m), thus providing a maximum investigation depth of about 7.5 m, 15 m and 30 m respectively. All measurements were taken on a regular 10 m grid. However, only the EM 31 data shall be discussed herein.

A comparison of the EM31 data of three years is given in Fig. 3. There are two distinctive features (1, 2) which are marked in fig. 3. Feature 1 is a resistivity minimum striking NE. This is interpreted as an area with increased silt content. North and East more gravel and sand material occurs. Feature 2 also shows a resistivity minimum. This anomaly was interpreted as an uparching of the underlain clay layer. Between these two anomalies a zone of increased hydraulic routing is present. It is a NE-SW striking through shaped structure, confined to the north by a more silty formation (*Feature 1*) and to the south by the uplift of the clay layer (*Feature 2*).

MONITORING OF DYNAMIC LANDSLIDE PARAMETERS

For an overall evaluation of landslides the dynamic properties, e.g. change of rock porosity and water saturation, are also compulsory to be known. Thus, to understand dynamic processes research activities focussed onto new geophysical methods, *e.g.* the measurements of

- **Electric Emissions** (EE)
  Transport of water through fine capillaries is obviously influenced down by opposing forces such as *(i)* the viscosity of capillary moisture and *(ii)* by electrostatic attraction between the ions and the solid surface carrying an opposite charge,(HILBERT 1980). When the flow of liquid from the positive to the negative pole in a capillary tube is stationary, then the driving electrostatic force is compensated by the effect of internal friction of the liquid. The movements of ions outside the electrochemical double layer is described by the HELMHOLTZ-SMOLUCHOWSKI equation linking an electric potential with the flow velocity. Two assumptions are made for the validity of this equation, that is a stationary flow velocity within the capillary system and capillary radii significantly larger then the thickness of the electrochemical double-layer. A well-known effect of this equation is the **electroosmosis** – the flow of capillary water towards a negative pole. An example of natural electroosmosis is the rise of groundwater caused by electrical potential differences in the soil. But also an inversion of this effect is known – the **streaming potential**: if water is forced through a capillary system a electrical potential difference is measurable. This latter effect may be used for the observation of mass movements – before any displacement of soil occurs, the inner tension of the geological strata increases. An increase of inner tension reduces the radii of a capillary channels perpendicular to the effective direction of the stress, thus reducing the amount of water percolating through a capillary system. This change of the hydraulic properties is accompanied by a change of potential difference. As this process is not a stationary one, low varying electrical fields will occur. Thus, the variations of natural potentials can be understood as an attendant phenomenon to alterations in a pressure distribution pattern. With two cylindrical designed capacitor, one placed into the displaced material and another one as reference placed into undisturbed soil, this natural electrical field can be observed. In order to get a better understanding of this rather unusual application, several experiments with sample sizes ranging from a few cm^3 to several hundred m^3 *in situ* had been conducted during the course of the project. The laboratory results appeared very promising. However, electromagnetic emissions observed in higher frequency bands, *cf.* (BLÁHA & KNEJZLÍK 1993; HRICKO *et al* 1995; KHARKALIS 1995), have not been verified yet.

- **Secondary Acoustic Emissions** (AE)
  In general, the detection of reliable acoustic effects in landslide formed by softrocks, unconsolidated sediments or any other loose cohesionless materials is very difficult. Therefore, it is necessary to convert a slow deformation process into corresponding frequencies of acoustic emissions. One method introduced by (NAKAJIMA *et al.* 1991) and distributed by a Japanese supplier as "*acoustic emission monitoring rod*" consists of a steel-pipe moulded with acoustic emission material. This material is composed of glass-fibre and rosin and, due to a high degree of brittleness, breaks apart when the rod is slowly bended. During this fracturing process two dominant frequencies, with 3.62 kHz and 3.05 kHz respectively, are emitted into the mantle of the surrounding pipe and then propagated to the attached transducers. From there, the detected signals are transmitted via a normal copper cable to a recording unit. Various bandwidth filter (2-5 kHz) and amplifier (up to 40 dB) enhancing the raw signal before it is fed into an analysing software. The processed signals are converted into event pulses under a pre-selected envelope time (typical: 10 ms) and finally stored into a data logger at a constant time interval.

On the above mentioned testsite in St. Marein these novel methods are implemented for the very first time. In the course of the project, both methods had been equipped with permanent registration facilities to account for long-term observations.

CONCLUSION

Not only refraction seismics, but also geoelectrical methods can be used to estimate the thickness and extent of a landslide as well as to support the understanding of a local water regime. In addition to this, details in the displaced masses can be resolved.

As already pointed out by (EDDLESTON 1998) for the purposes of engineering geology, it is always useful, time and cost permitting, to use more than one array and more then one electrode spacing when conducting a **geoelectrical survey** over landslides. As the technique is relatively quick, it is possible to get lots of images of investigated complex earth slides / earth flows to assist the final modelling of the hillslope material and processes. With recent technological advances, this is now possible and cost effective.

The **electromagnetic** method has proved to be the most time efficient for an areal mapping and thus demonstrated also effectiveness for long-term studies of water regimes and/or for planning and controlling drainage systems.

However, geophysical methods must never been seen as isolated techniques – they are only additional sources for the general evaluation of mass movements. But because of speed and efficiency they are good tools for any site investigation. If electric methods is combined with refraction seismics, the heterogeneous nature of hillslope materials may give vertical and lateral deviations when used as singular source for a geological & geotechnical modelling. Therefore, a situation like this has to be avoided by combining appropriate geophysical methods and have geologist and geophysicists drawn a joint interpretation from it.

In the still on-going evaluation of the two new survey techniques, namely **Secondary Acoustic Emissions** and **Electric Emissions,** more research has to be conducted to improve the great potential of these methods for an application on landslides.

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