Geoelectrical imaging of slope deformations – towards repeated measurements, effective electrode array and limitations

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Abstract
Use of geophysical methods within the research of the slope deformation became a standard during last decades. Electrical resistivity tomography (ERT), as one of the advanced geoelectrical methods, experiences boom in its utilization in numerous scientific fields, such as archaeology, geomorphology, engineering geology or hydrogeology. The presented contribution deals with utilization of ERT on the various types of mass movements. Recognition of the processes that affect slope stability, predispose or trigger slope movements, is fundamental for both understanding of the slope development and effective rehabilitation of failing slopes or sliding mass. Contribution points out (dis)advantages of the method, its limitations and related electrode array selection that can be crucial considering the required results. The choice of the appropriate electrode configuration always depends on the demanded resolution, depth range, and sensitivity to vertical/horizontal structures and, of course, on the overall purpose of each measurement. Repeated measurements on landslides include range of difficulties that needs to be resolved. On the other hand, these practical experiences can help us to design a monitoring system based on repeated measurements.

Repeated ERT measurements on active landslide
Repeated ERT measurements were performed in the Ľubietová landslide (Central Slovakia), which is a large (320, 000 m^2) and relatively deep-seated (depth of the sliding plane is from 10 to 25 m) landslide body reactivated in 1977.
Four transversal ERT profiles were carried out repeatedly in different seasons of year with varying actual meteorological (humidity, precipitation) and hydrogeological (water saturation) conditions. As a whole, four sets of measurements were performed (Fig. 1) and figured as “1” (April 2008), “2” (November 2009), “3” (April 2010) and “4” (July 2010). Due to extremely slow movements (up to 1-2 cm per year) in the investigated landslide, observed changes in the resistivity pattern of the landslide substratum can be related rather to the slope saturation regime than deformation of the substratum.

Measured apparent resistivity (AppR) evaluated with respect to groundwater levels (measured in close monitoring wells, Fig. 1) and local precipitation data indicate that actual hydro-climatic conditions (actual weather, saturation of the near-surface layers) are affecting the extreme values of AppR (particularly the maximum), while the mean value of AppR (affected by actual weather) calculated from resistivity model probably responded to the combination of the long-term precipitation and actual rainfalls. The highest correlations among long-term hydrological condition (and ground water levels) are related to the lowest values of apparent resistivity (values close to minimal).

Repeatedly measured profiles thus gave us the opportunity to study relative changes in apparent resistivity distribution below the landslide body surface.

Simultaneously, we had an opportunity to test the method (ERT) and its various configurations (electrode arrays and spacing) in order to determine suitable (effective) parameters and limits for possible time-lapse ERT measurement. ERT proved a relative high potential as a method suitable for geoelectrical monitoring of active landslides (PROKEŠOVÁ et al., in review).

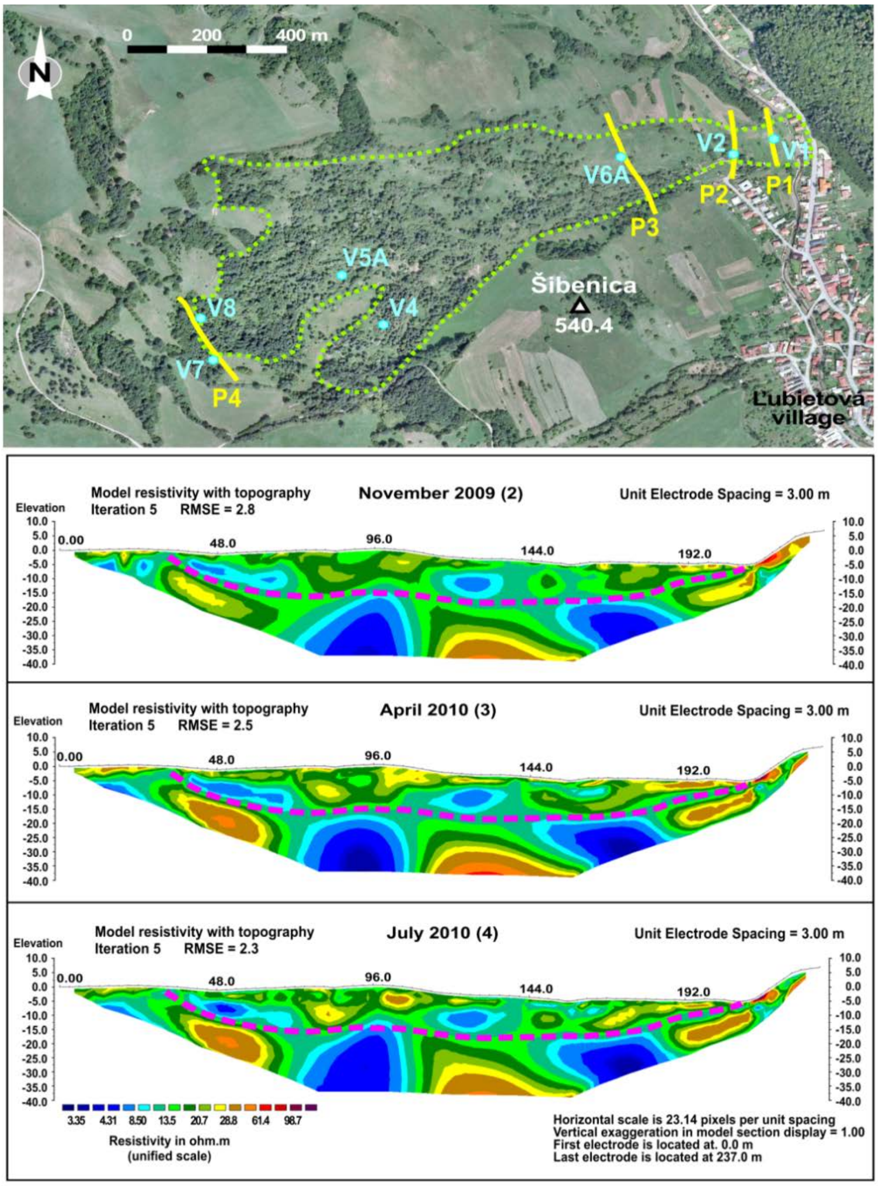

Fig.1: ERT monitoring on the Ľubietová active landslide.

Selection of effective electrode array and electrode spacing and its effect on final resistivity model

A detailed research of the Ondřejník Ridge collapse (Podbeskydská pahorkatina Hillyland, Czech Republic) revealed high intensity of flysch bedrock disruption caused by gravitational mass movements. Also tectonics (faults, crevices) and structure-geological conditions predispose this disintegration.

A number of 2D geoelectrical profiles were performed within subsurface survey. At the same time, different electrode arrangements (different arrays and variable electrode spacing) were tested. ERT survey also helped to extend valuable information - that we got from direct trenching - to deeper parts of the Ondřejník massif (Fig. 2, A).

The selection of the appropriate measuring method (electrode array) we consider as a crucial parameter of the measurements. We tested three most commonly used arrays that are Dipole-Dipole (D-D), Wenner-Schlumberger (W-S) and Wenner Alpha (W).

Our testing confirmed the presumption that W-S and W array offers similar results in depiction of horizontal and vertical structures. Nevertheless, W-S array has a deeper range and it is slightly more detailed as the W array. On the other hand, W array is less sensitive to geoelectric noise and also it offers lower RMS error.

Configuration of D-D differs in detection/depiction of horizontal and vertical structures. We use it particularly for vertical structure detection (widened crevices, tension cracks or vertical caves). Despite the best resolution (in comparison with the W-S and W arrays) based on higher number of the measured points, the D-D array is the most sensitive to geoelectric noise and higher near-surface resistivity and it is often affected by high RMS error. Higher depth range of the method can be very valuable. On the other hand, deeper range can cause a complication with higher electric noise. (PÁNEK et al., 2011)

Our evaluation of effective electrode array is in the case of the Ondřejník Ridge disintegration (flysch-type bedrock) slightly ambiguous. The W-S array seems to be a universal method with good resolution, very good depth range with slightly higher sensitivity to geoelectric noise. This method is a good compromise in detection of both vertical and horizontal structures. But, sometimes this compromise causes unclear imaging of some (sub-) vertical structures.

In this case, we consider the D-D electrode array as a more sufficient method - it is suitable rather for vertical structures and also it is more detailed (e.g. in case of narrow crevices). The disadvantage of high sensitivity to noise and higher near-surface resistivity was described above (PÁNEK et al., 2011).

If we have to deal with very high near surface resistivity (debris, block fields, etc) and, at the same time, we do not need a detailed survey or we are not focused primarily on vertical structures, we can employ the W method.

Similarly, we tested electrode configuration on an artificial embankment (Průhonice site, Praha, the Czech Republic). On the contrary to the Ondřejníks ridge, final resistivity model of the Průhonice embankment shows, that horizontal structures are better displayed with use of D-D configuration while the vertical ones are strongly depicted on model of W-S (or W) (Fig. 2, B).

This unexpected opposite depiction of subsurface structures could be a result of very steep slopes in combination with very narrow embankment body.

Higher resolution of the ERT results we can easily gain by variations of electrode spacing. Denser electrode configuration brings more detailed imaging, of course. On the other hand, technical equipment is often also limited (e.g. number of simultaneously connected electrodes) so with smaller electrode spacing we get shorter profile and then also shallower depth range.

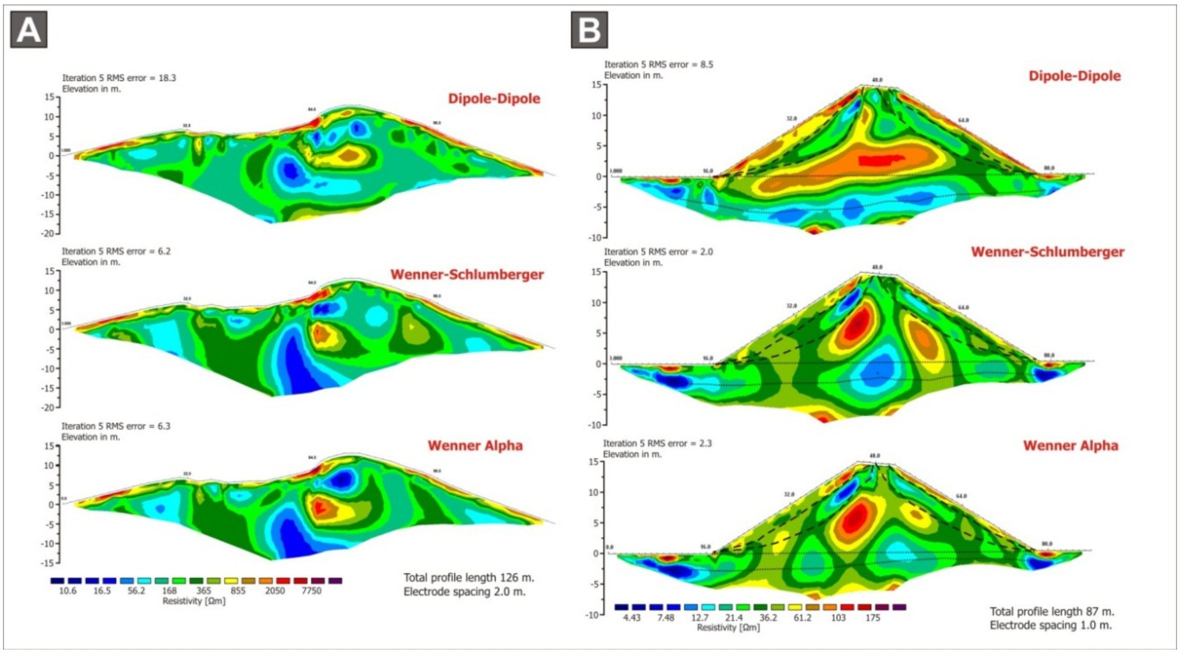

Fig.2: ERT electrode array testing: A. the Ondřejník ridge, B. the Průhonice artificial embankment (both localities are situated in the Czech Republic).

Geoelectrical modelling in electrode array selection

Selection of suitable electrode array is one of the most important things during the measurement. Besides the obvious problems with final resolution (depended mainly on electrode spacing), there are numerous measuring methods (arrays) which differs in the way of measurement, so, it can have an essential effect on final resistivity model. Each of the arrays is specific and brings different results in horizontal/vertical resolution and depiction of subsurface structures. Complex lithological structure of landslide bodies often requires information on both horizontal and vertical direction. Selection of the effective electrode array can be realized either by repeated measurement with application of various arrays or with use of geoelectrical modelling (LOKE, 2002).

Because we are not able to include all possible parameters of measured subsurface substratum, final result of forward modelling is only the simplified model. However, it has given to us valuable information on used arrays and it can help us to choose the most suitable method.

In case of mountain ridge disintegration (PÁNEK et al., 2010, 2011) we dealt with initial forms of deep seated slope deformations which are often represented by widening crevices and crevice-type (fissure) caves, open tension cracks and block subsidence, toppling, or lateral spreading of rock massifs. Rock disrupted by sets of crevices is, of course, more vulnerable to slope deformation, so detection of disintegrated zones is crucial for determination of possible subsequent development of the slope. Despite the complexity of the anisotropic flysch rock massif, forward geoelectrical modelling brings valuable information on suitability of the particular array, its resolution and depth range and also on distortion of depicted structures.

Forward modelling can be also used as an interpreting tool. For example, unclear boundaries in the final resistivity model of which strong expression were expected from direct survey (caving, trenching) can be specified by simplified model which is less affected by anisotropy of rock massive and upper laying colluvial sediments. Also the evidence of a very narrow crevice can be only indirect and we cannot distinguish the crevice in the model as a separate structure. But, the existence of it influences the final image (Fig. 3).

Nevertheless, the application of forward geoelectrical modelling requires deeper knowledge of the modelled structures and it needs as much additional information as possible (e.g. lithology, structural geology aspects, tectonics, ground water level, etc.) gained from direct survey – mapping, drilling, trenching or caving.

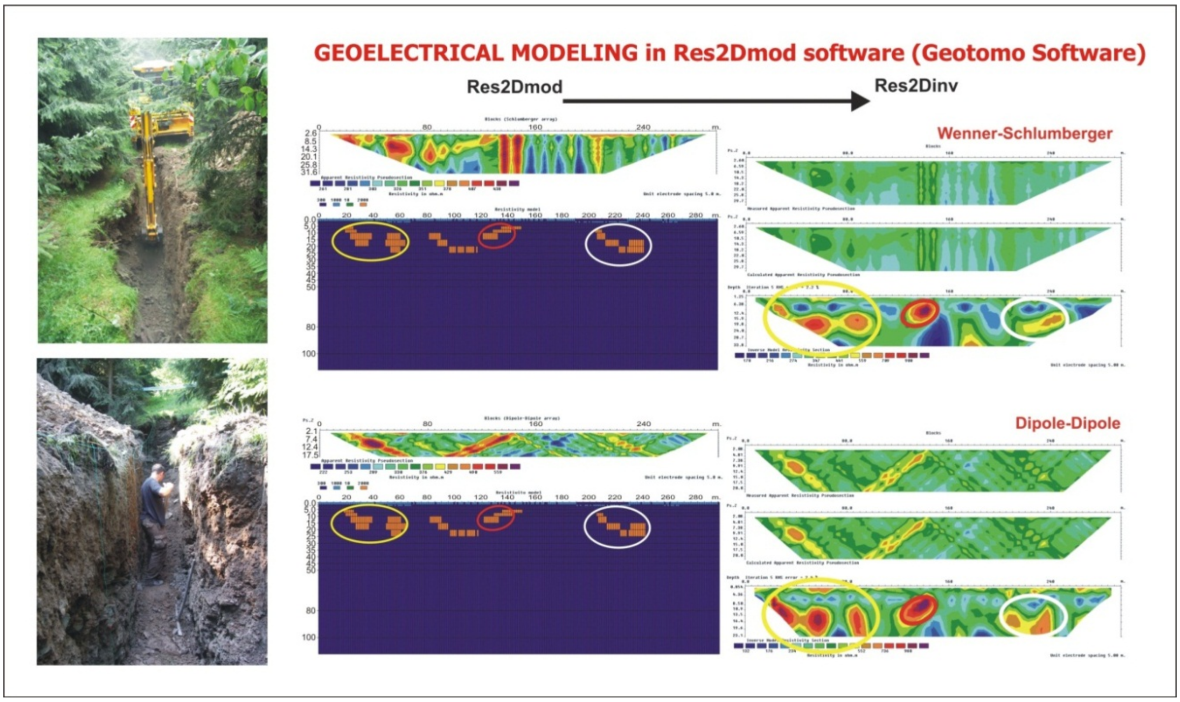

Fig.3: Directly investigated structures (e.g. from trenching) can be modelled and the model can help with selection of suitable method for further non-invasive ERT survey within wider area.

Conclusion

Suitability of resistivity methods (e.g. ERT) for geoelectrical imaging of slope deformation depends on various lithological, structural-geological and hydrogeological conditions. Slope stability is also affected by tectonics. Besides these natural conditions, we have to consider different result gained from different electrode array and spacing. So, for the optimisation of any geoelectrical monitoring, it is very valuable to test various electrode array with various electrode configuration. Repeated measurements bring knowledge on observational potential of each method and also help to set optimal interval of measurement (if it is not time-lapse).

In case, we are not able to test electrode configuration directly, we can use a forward resistivity modelling. This modelling tool is very effective, and even we are not able to include all possible parameters and conditions, final model is very useful in selection of the most effective electrode array. We can also create an approximate model of known situation below the surface (e.g. known cave system). Geophysical evidence of known structures can be used as an interpretation model for supposed similar structures (e.g. non-discovered cave chamber).

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