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Hydrogeophysical Monitoring of Landslide Processes Using Automated Time-Lapse Electrical Resistivity Tomography (ALERT)

J.E. Chambers* (British Geological Survey), P.I. Meldrum (British Geological Survey), D.A. Gunn (British Geological Survey), P.B. Wilkinson (British Geological Survey), O. Kuras (British Geological Survey), A.L. Weller (British Geological Survey) & R.D. Ogilvy (British Geological Survey)

SUMMARY

Geoelectrical techniques, such as resistivity and self-potential are being increasingly applied to study the hydraulics of landslide processes. The great strengths of these techniques are that they provide spatial or volumetric information at the site scale, and are sensitive to hydraulic changes in the subsurface. In this study we described the development and installation of an automated time-lapse electrical resistivity tomography (ALERT) system on an active landslide at a site near Malton, North Yorkshire, UK. The overarching objective of the research is to develop a 4D landslide monitoring system that can characterise the subsurface structure of the landslide, and reveal the hydraulic precursors to movement. In this paper we describe the installation of the ALERT system on an active landslide, and present initial results showing the 3D structure of the landslide and subsurface resistivity variations that occurred between static conditions and an active phase of slope failure.

INTRODUCTION

Landslides are often the result of complex, multi-phase process where gradual deterioration of shear strength within the sub-surface precedes the appearance of surface features and slope failure. Moisture content increases and the build-up of associated pore water pressures are invariably associated with a loss of strength, and thus are a precursor to failure. Consequently, hydraulic processes typically play a major role in the development of landslides.

Geoelectrical techniques, such as resistivity and self-potential are being increasingly applied to study the hydraulics of landslide processes (e.g. Jongmans and Garambois, 2007 and Jomard et al., 2007). The great strengths of these techniques are that they provide spatial or volumetric information at the site scale, and are sensitive to hydraulic changes in the subsurface. In this study we developed and installed an automated time-lapse electrical resistivity tomography (ALERT) system (Kuras et al., 2009; Ogilvy et al., 2009) on an active landslide at a site near Malton, North Yorkshire, UK. The overarching objective of the research is to develop a 4D landslide monitoring system that can characterise the subsurface structure of the landslide, and reveal the hydraulic precursors to movement. In this paper we describe the installation of the ALERT system on the active landslide, and present initial results showing the 3D structure of the landslide and subsurface resistivity variations that occurred between static conditions and an active phase of slope failure.

SITE GEOLOGY AND HYDROGEOLOGY

The research site is located on a south facing valley side with a slope of approximately 12^{o} (Figure 1). The bedrock geology, from the base to top of slope, comprises the Lias Group Redcar Mudstone Formation (RMF), Staithes Sandstone and Cleveland Ironstone Formation (SSF), and Whitby Mudstone Formation (WMF), which are overlain at the top of the hill by the Dogger Sandstone Formation (DF). The bedrock is relatively flat lying with a gentle dip to the north. Slope failure at the site is occurring in the weathered WMF, which is highly prone to landsliding. The landslide is characterized by shallow rotational failures at the top of the slope that feed into larger-scale slowly moving lobes of slumped material; the rotational features and active lobes extend approximately 150 m down the slope from the top of the hill, and extend laterally more than 1 km along the valley side. In recent years, movement of the lobes has been in the order of tens of centimetres per annum. Movement typically occurs in the winter months (i.e. January and February) when the slope is at its wettest. During this period water can be observed accumulating in the basins caused by rotational slips towards the top of the slope, and can be seen emerging from the front of the lobes. Drainage from the site also occurs along a spring line at the base of the SSF, where groundwater appears to be running off the surface of the less permeable underlying RMF. Recently installed piezometers have revealed elevated pore pressures at the failure planes within the slipped WMF and at the interface between the slipped WMF material and the underlying SSF.

ALERT SYSTEM INSTALLATION

The ALERT system was installed during the spring of 2008. The ALERT instrument uses wireless telemetry (in this case GPRS) to communicate with an office based PC, which runs control software and a database management system. The control software is used to schedule data acquisition, whilst the database management system stores, processes and inverts the remotely streamed ERT data. Once installed and configured, the system operates autonomously without manual intervention. Modifications to the ALERT system at this site have included the addition of environmental and geotechnical sensors to monitor rainfall, ground movement and pore pressure changes within the landslide. The system is housed in a weatherproof enclosure and is powered by batteries charged by a wind turbine & solar panels.

ERT electrode arrays were permanently installed within a grid with dimensions of x = 38 m and y = 147.25 m (Figure 1). Electrodes were separated by 4.75 m in the y-direction and by

9.5 m in the x-direction, and were installed in segments, each comprising 16 electrodes. This segmented design was used so that individual sections of the array are relatively easy to replace when breakage occurs due to ground movement. Each of the 16-way array segments and additional geotechnical and environmental sensors has been connected to the ALERT instrument located in the centre of the imaging area.

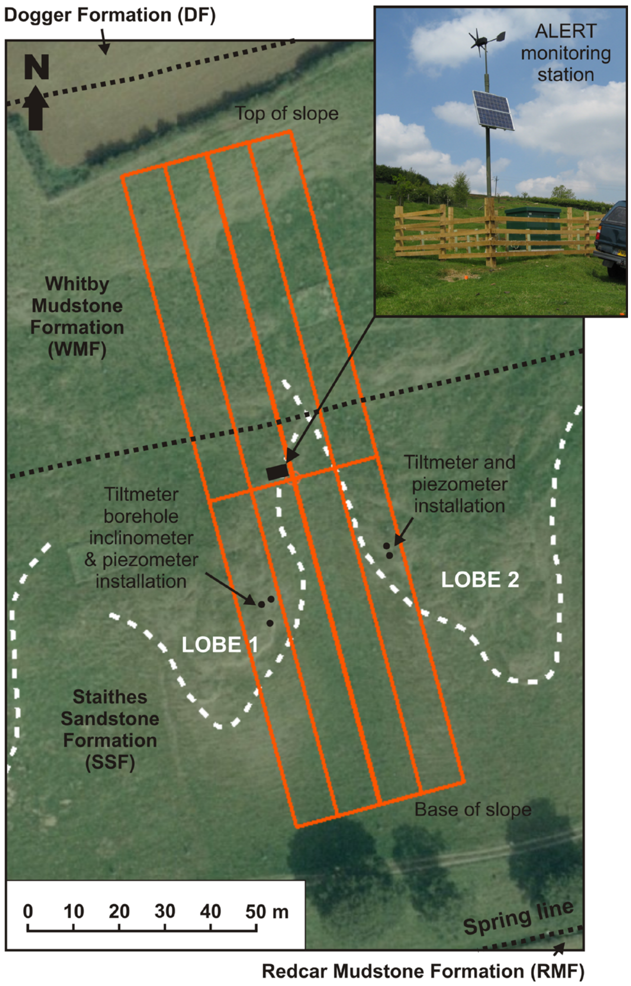

Figure 1. Site plan showing the location of the ALERT station, ERT monitoring arrays (red lines), major geomorphologic features (white-dashed lines) and bedrock geology (black dashed lines). (© UKP/Getmapping Licence No. UKP2008/01)

PRELIMINARY RESULTS AND DISCUSSION

Static 3D ERT Model

A 3D ERT model generated from dipole-dipole data (a = 4.75, 9.5, 14.25 & 19 m, and n = 1 to 8) collected shortly after ALERT system installation is shown in Figure 2. This model serves to both reveal the 3D structure of the landslide, and provides a reference model for subsequent ERT monitoring events.

The geology of the hillslope is clearly distinguished in the model: the WMF is a clay rich low resistivity formation (green-blue); the SSF has lower clay content and is more resistive (pink-white); the underlying RMF displays a similar resistivity range to that of the WMF (green-blue). The slipped WMF material of lobes 1 and 2 is clearly seen to override the SSF bedrock. Detailed analysis of the resistivity image has revealed variations in lobe thickness across the imaging area, which has subsequently been confirmed through intrusive investigations (i.e. drilling, augering, and cone penetration tests).

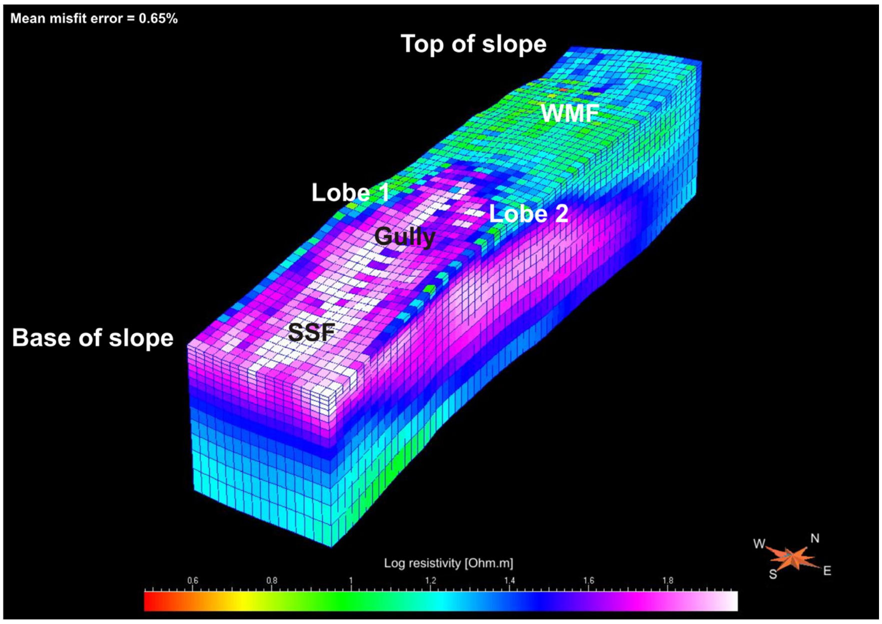

Figure 2. Baseline 3D ERT model of the landslide generated from ALERT data.

Time-lapse ERT

Preliminary time-lapse images generated from the electrodes on the western boundary of the imaging area are presented in Figure 3, and include resistivity sections from August 2008 (t_1) and February 2009 (t_2), along with a difference plot showing the change during this period. These two times were chosen as they represent a dry period (t_1) and a wet period during which movement was occurring (t_2). A broad resistivity increase of ~ 20 % occurred in the top few metres (Figure 3c) between t_1 and t_2. It is likely that this is due to seasonal temperature variations, which are masking the effects of increased moisture (which would normally decrease the resistivity) during the winter. Air temperatures in the two months leading up to t_1 and t_2 were on average 16 ^{o}C and 3.5 ^{o}C respectively. The magnitude and extent of these apparent temperature effects are broadly consistent with those observed by Hayley et al. (2007), assuming their empirical linear approximation of ~ 2 % change in resistivity per degree C, with seasonal air temperature influences extending to between 5 and 10 m below ground level. Monitoring using multi-level sensors is currently being undertaken within the imaging area to determine seasonal temperature changes in the subsurface; these data will be used to correct the time-lapse ERT image for temperature effects using the methodology described by Hayley et al. (2007).

Below depths of 5 m model resistivities decreased between t_1 and t_2, with the most pronounced decrease having occurred in the region of the model where SSF was overlain by slipped WMF. This was at a depth where temperature should be constant, and so the decrease was probably due to increased moisture content resulting from drainage of water through the disturbed WMF into the SSF during the winter months. Laboratory testing of borehole core recovered from the site is being undertaken to determine the resistivity-moisture content relationships for the WMF and SSF, which will then be used to calibrate the resistivity model.

Significant variability in model resistivity changes were seen across the top of the model between $y = 35$ & 75 m. Walkover surveys revealed very significant fissuring and movement in this area during the monitoring period. Very substantial increases in moisture content were also observed in this region at t_2. Variability in the both the resistivity (Figure 3b) and differential models (Figure 3c) is likely to be a function of the changed subsurface structure and moisture distribution. It is also probable that the movement of electrodes, which has not yet been accounted for in the modelling, has also caused distortions in the resistivity image. Geometric corrections to account for electrode movement will be applied to future datasets.

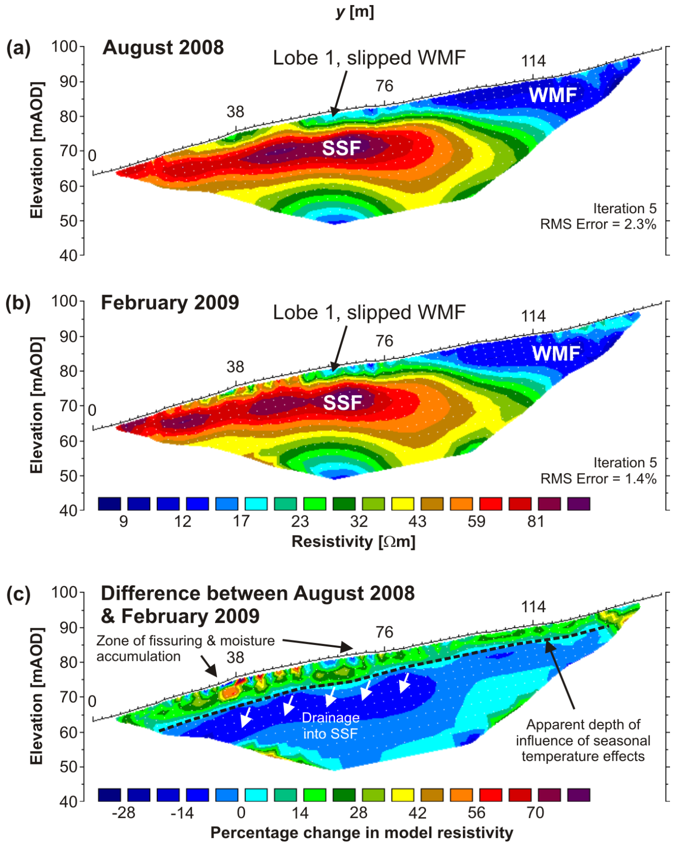

Figure 3. Time-lapse resistivity results from dipole-dipole data (a = 4.75, 9.5, 14.25 & 19 m, and n = 1 to 8) shown as 2D resistivity sections through Lobe 1. (a) August 2008 and (b) February 2009 ERT models, and (c) resulting differential resistivity image.

CONCLUSIONS

Time-lapse ERT imaging has shown changes associated seasonal temperature variation, moisture content and ground movement within the body of an active landslide. Near surface changes in resistivity caused by moisture content were masked by temperature effects. Only at depths (i.e. > 5 – 10m) where the influence of seasonal air temperature variations is minimal, could changes in resistivity be attributed to changes in moisture content. We conclude that for 4D ERT to be an effective means of investigating landslide hydraulics it is important to account for the influence of temperature and electrode displacement on time-lapse images.

ACKNOWLEDGEMENTS

We would like extend our sincerest gratitude to Steve and Josie Gibson (the landowners) for their involvement and cooperation in the research. This paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

REFERENCES

Hayley, K., Bentley, L. R., Gharibi, M. & Nightingale, M. [2007] Low temperature dependence of electrical resistivity: Implications for near surface geophysical monitoring. Geophysical Research Letters, **34**, L18402.

Jomard, H., Lebourg, T., Binet, S., Tric, E. & Hernandez, M. [2007] Characterization of an internal slope movement structure by hydrogeophysical surveying. *Terra Nova*, **19**, 48-57.

Jongmans, D. & Garambois, S. [2007] Geophysical investigation of landslides: a review. *Bulletin De La Societe Geologique De France*, **178**, 101-112.

Kuras, O., Pritchard, J., Meldrum, P.I., Chambers, J.E., Wilkinson, P.B., Ogilvy, R.D., Wealthall G.P. [2009] Monitoring hydraulic processes with Automated time-Lapse Electrical Resistivity Tomography (ALERT). *Comptes Rendus Geosciences - Special Issue on Hydrogeophysics* (in press).

Ogilvy, R. D., Kuras, O., Meldrum, P. I., Wilkinson, P. B., Chambers, J. E., Sen, M., Pulido-Bosch, A., Gisbert, J., Jorreto, S ., Frances, I. and Tsourlos, P. [2009] Automated Monitoring of Coastal Aquifers with Electrical Resistivity Tomography. *Near Surface Geophysics* (in press).