LONG-TERM MONITORING OF SUB-SURFACE CHANGE IN EARTH EMBANKMENT DAMS

J.E. CHAMBERS, P. MELDRUM, P. WILKINSON AND D. GUNN
British Geological Survey, United Kingdom

C. GOFF
HR Wallingford Ltd, United Kingdom

N. SLATER
Socotec Monitoring UK Ltd, United Kingdom

ABSTRACT

Here we describe the development of a novel characterisation and monitoring approach for embankments such as earth dams. The system, called PRIME (Proactive Infrastructure Monitoring and Evaluation), is based on time-lapse electrical resistivity tomography (ERT), which is a geophysical technique used to non-invasively image subsurface resistivity to depths of tens of metres. Resistivity is a useful property because it is sensitive to compositional variations, changes in moisture content, and ground movement.

PRIME is a low-cost system designed for remote operation, allowing resistivity images to be captured automatically and streamed via a web interface. It comprises four key elements: (1) low-power field instrumentation; (2) data telemetry and storage; (3) automated data processing; (4) and web dashboard information delivery. These elements form the basis of an asset condition monitoring approach that provides near-real-time spatial information on both subsurface processes and surface responses

The use of this approach is illustrated with reference to a series of studies relating to earthwork condition monitoring. These studies demonstrate that PRIME provides a means of spatially tracking complex subsurface moisture driven processes (such as leakage or settlement) that would be very difficult to characterise using other approaches (e.g. surface observations or intrusive sampling).

1. INTRODUCTION

1.1 Context and Rationale

Assessment of the condition of earth dam structures is essential for cost effective maintenance and prevention of hazardous failure events. Early identification of deteriorating condition generally allows low cost preventative remediation to be undertaken and reduces the risk of catastrophic failures.

Conventional approaches to condition monitoring are often inadequate for predicting failure events. They are heavily dependent on walk-over surveys, intrusive investigations, or remotely sensed data such as aerial photography or LiDAR. However, surface observations (from walkover or remote sensing) cannot detect the subsurface precursors to failure; instead they identify failure once it is expressed at the ground surface, which is often at a late stage when there is insufficient time to implement low cost remedial solutions. Furthermore, they generally provide relatively low temporal resolution (e.g. weeks to years) due to the cost of manual site visits or flights. For intrusive sampling, even with significant numbers of boreholes, it is only ever possible to sample a tiny proportion of the overall volume of the earthwork – which means that in heterogeneous ground conditions small-scale processes (e.g. seepages or piping) can be extremely difficult to detect and characterise. Consequently, these conventional approaches are often inadequate for providing early warning of deteriorating condition or failure.

Here we describe the development and application of a low-cost low-power geophysical ground imaging system, for fully automated remote monitoring of earth structures, such as dams. The purpose of the system is to provide improved decision support and early warning of deteriorating condition. The system is called PRIME – 'Proactive Infrastructure Monitoring and Evaluation', and is designed to non-invasively visualise the interior of earthworks and unstable slopes. It has been applied to a range of moisture driven slope stability applications (e.g. Huntley et al., 2019), indicating its suitability for dam monitoring through enabling volumetric tracking of moisture content changes and ground movement to identify problems and implement remedial solutions at a much earlier stage.

2. METHODOLOGY

2.1 PRIME system overview

The PRIME system is based on time-lapse electrical resistivity tomography (ERT), which is a geophysical technique used to generate resistivity images of the subsurface. Resistivity data are useful measurements to make as they are sensitive to compositional variations, changes in moisture content, and also ground movement. PRIME is designed for remote operation using telemetry, so that ERT images can be captured automatically and streamed in near-real-time via a web interface – thereby providing a remote condition monitoring system to reveal subsurface changes within earth structures.

The system comprises four key elements (Figure 1): (1) Field measurement instrumentation comprising an array of electrode sensors, the PRIME instrument, and communications hardware; (2) Data telemetry (via wireless transfer to the office), storage and indexing; (3) Automated data processing, incorporating quality assessment, filtering, extraction of movement information, generation of resistivity images and translation to distributions of moisture content; and (4) Information delivery via a web dashboard for analysis, interpretation and early warning alerts.

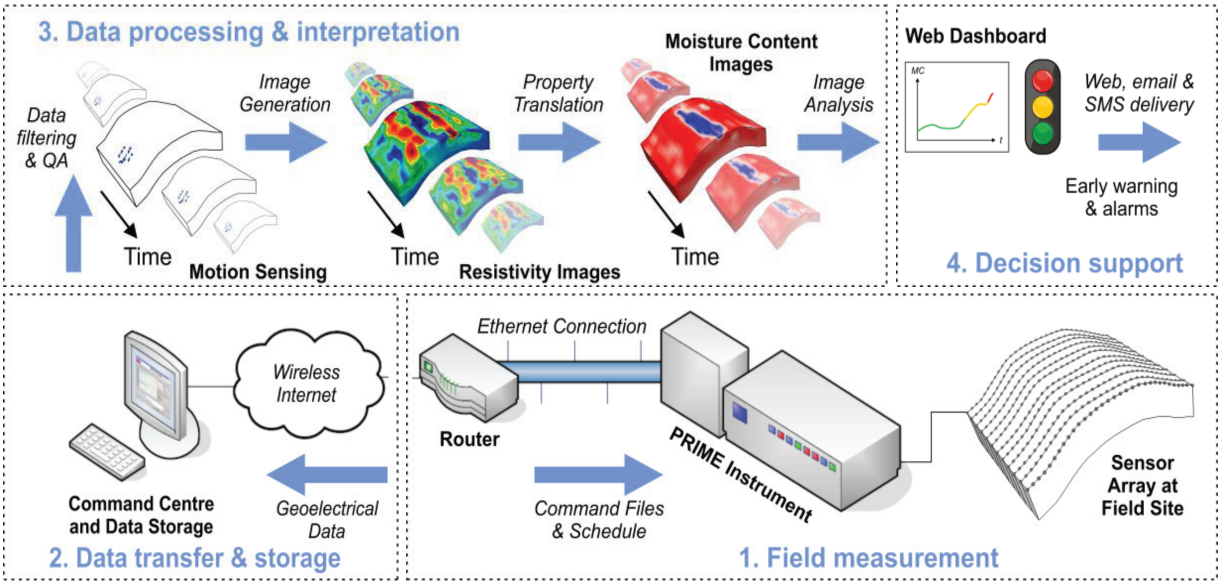

Figure 1 : PRIME system - geoelectrical monitoring and early warning workflow.

2.2 Measurement instrumentation

The PRIME system (Figure 2), comprised of the low power (10W) PRIME ERT instrument (standard 19-inch module) connected to the sensor array cables and communications hardware, is housed in a small equipment enclosure and powered from 12V batteries that are charged using a small solar array. The low power consumption of the instrument is essential to maintain operation in remote areas with no access to mains electricity.

Figure 2 : PRIME system field deployments showing key components and sensors array installation.

Measurement data is collected from sensors (metal electrodes) connected to the system by cables, which are typically deployed at the ground surface in lines (for 2D images) or grids (for 3D images). The depth of investigation of the technique is determined by the electrode spacing and spread, not by the length of the sensor (which is typically < 10 cm). Arrays of surface sensors can give information non-invasively to tens of metres below the surface. The system has 7 measurement channels and can address up to 256 electrodes (with the option to expand to >1000 electrodes). Tests have shown that the measurement quality is similar to existing resistivity imaging systems when using arrays covering 200 m with electrode spacings of 1 to 2 m. An SDI-12 interface has been incorporated into the system, meaning that a large range of geotechnical and environmental sensors (e.g. pore pressure, temperature, rainfall) can be attached to the system, and data from this interface is incorporated in the system telemetry.

2.3 Data Telemetry and control

The PRIME system has been designed to be fully automated / autonomous with measurements scheduled to run at given times during the day. Measurement data is stored locally then relayed using wireless telemetry, such as a GSM/Mobile network link. Along with the measurement data, health logs of system and sensor performance are also transmitted (Figure 3).

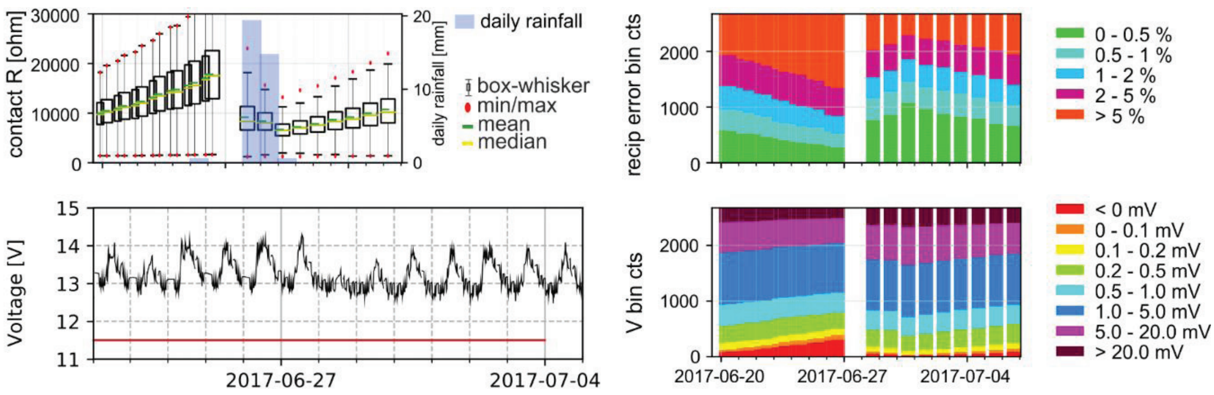

Figure 3 : PRIME system health logs (contact resistance; reciprocal error, battery voltage, measured voltages).

2.4 Automated data processing

For large ERT time-series data sets from multiple sites, manual processing and interpretation can be time-consuming and impractical. Consequently, an automated data processing workflow (Figure 1 – section 3) that comprises several stages is being implemented.

Stage 1 : electrode displacement information is extracted from the measured data using the method described by Wilkinson et al. (2016). This information is used as a means of detecting ground motion, and to provide updated electrode positions.

Stage 2 : the data are then inverted to produce 2D or 3D time-lapse images of subsurface resistivity distribution, to which a temperature correction is applied to normalise the resistivity images to mean air temperature (e.g. Chambers et al., 2014; Uhlemann et al., 2017).

Stage 3 : if suitable geotechnical – geophysical property relationship information is available (e.g. Gunn et al., 2015), the resistivity images will be converted into images of moisture content.

Stage 4 : for large ERT time-series data sets from multiple sites, manual interpretation can be time-consuming and impractical. Therefore we are developing automated approaches to image analysis drawing upon pattern recognition and change detection algorithms (e.g. Chambers et al., 2015).

2.5 Decision support

The timely and intelligible communication of monitoring results to stakeholders is essential for an effective decision support in the context of condition assessment and early warning. The PRIME system delivers near-real-time information in a number of ways. Firstly, the system has an autonomous monitoring capability, in that it can respond to environmental triggers (Figure 4); it uses environmental and geotechnical sensors (e.g. a rain gauge or pore pressure sensor) that are integrated into the system to trigger high intensity monitoring and SMS- and email-based alerts to stakeholders.

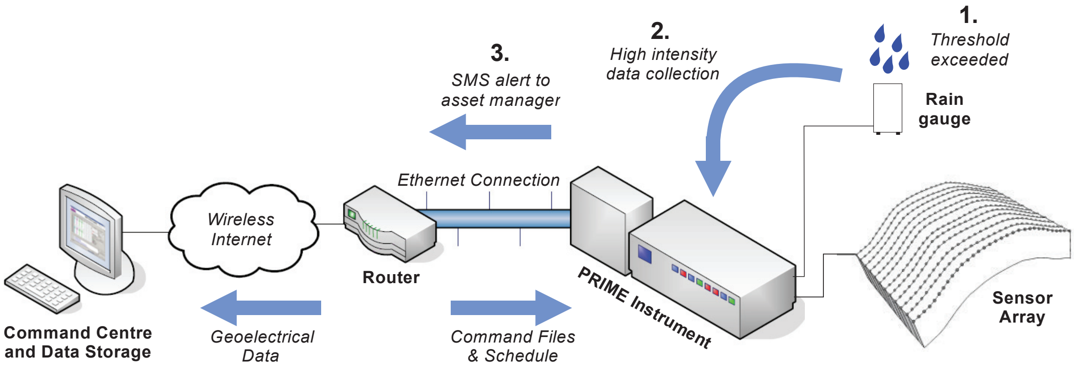

Figure 4 : Schematic describing PRIME operating in an autonomous [or responsive] monitoring mode, based on measurement and alert triggers using environmental point sensors (e.g. rain gauge).

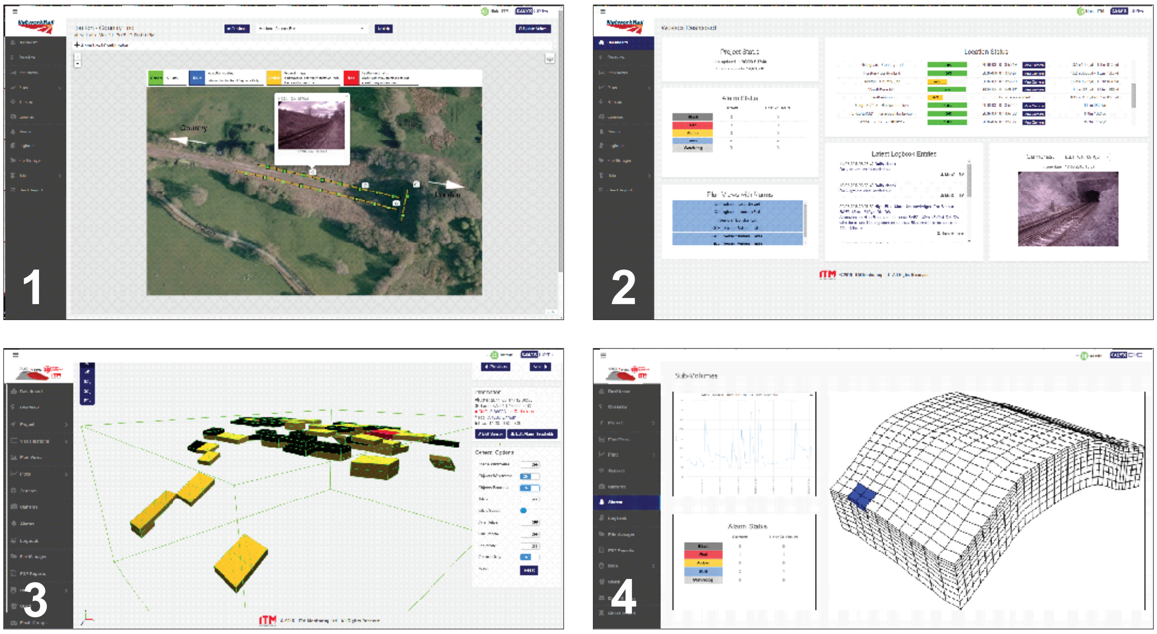

Figure 5 : PRIME-Calyx web-dashboard comprising: (1) GIS front end - showing site and sensor locations; (2) Site specific control dashboard - showing summary information and alarm states; (3) ERT data viewer - ena-bling alarm thresholds to be set for each voxel/pixel; (4) ERT data viewer - enabling time-lapse property changes to be assessed.

Also, information from the system can be delivered through a web-dashboard (Figure 5), where 4D monitoring results can be interrogated (Figure 5, top), alarm thresholds can be set, and the monitoring results can be analysed on a cell by cell basis (Figure 5, bottom) and compared with other environmental and geotechnical monitoring data to facilitate decision support.

3. CASE HISTORIES

3.1 Llangynidr canal embankment

A linear array of 100 sensors over a distance of 200 m, with spacings between electrodes of 1 – 2m, was installed on the toe of a canal embankment that was known to be leaking, with the PRIME instrument installed on the tow path (Figure 6). The canal was located in the village of Llangynidr, in south Wales, UK. During the monitoring period the leaks were remediated, allowing changing leak conditions and the success of the remediation to be assessed using PRIME technology.

Figure 6 : PRIME system enclosure at the Llangynidr canal embankment monitoring site.

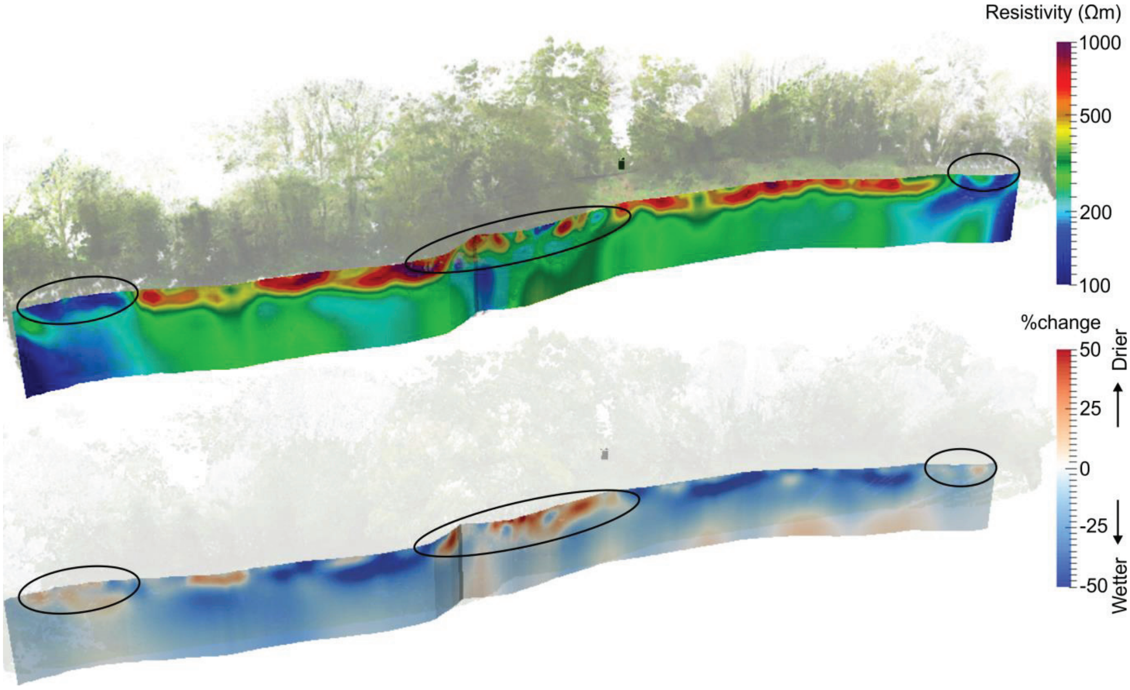

Figure 7 : Baseline resistivity image (top) from summer 2015 showing substantial subsurface heterogeneity in the toe of the earth embankment, and low resistivity zones linked to elevated moisture levels in the locations of ongoing leaks. Difference image (bottom) showing changes relative to the baseline image from winter 2015, after the canal had been remediated and the leaks stopped, showing relative drying in the leak locations.

The leak locations were highly saturated (very low resistivity regions, shown by ellipses in top section of Figure 7) before remediation. They become much drier (positive resistivity changes, red, in lower image) after remediation despite the embankment generally getting wetter (blue changes in lower image) due to heavy rainfall.

The deployment at Llangynidr demonstrated that PRIME could: (1) detect changing leak conditions in the canal embankment; (2) provide information on the location and size of the leaks; (3) provide daily spatial information on changing subsurface conditions; (4) operate remotely without mains power.

3.2 Old Dalby railway cutting

Moisture dynamics in a railway cutting near Nottingham, UK, were monitored to investigate

drainage pathways and the influence of vegetation - both of which influence stability. The site was selected as an example of a fully electrified operational environment, with the aim of assessing the operation of PRIME in an electrically noisy built environment, with variable vegetation cover (including heavily wooded and grassed sections). The cutting comprised weak mudstone materials, and was associated with a history of slope instability. The installation included a solar powered PRIME system connected to five 2D sensor arrays within a 100m section of the cutting, using a total of 256 electrodes with along-line sensor separations of between 1 and 1.5m.

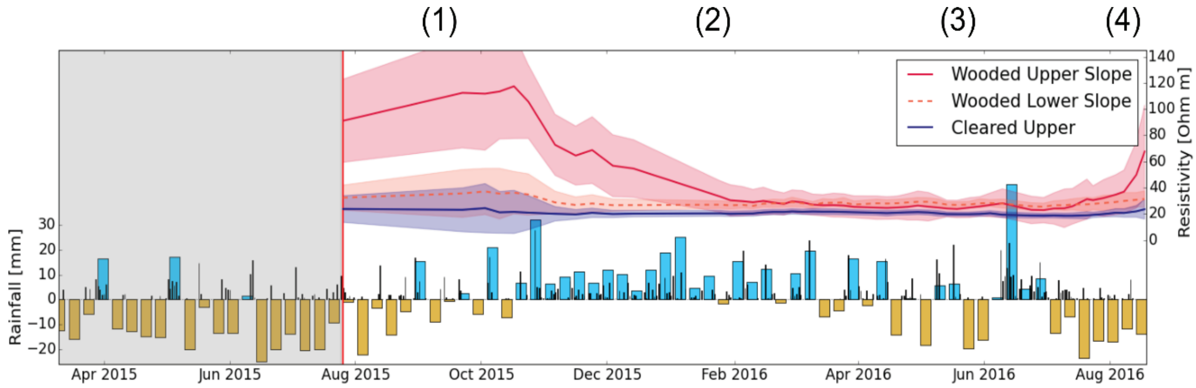

Figure 8 : Summary information during the PRIME monitoring period (July 2015 – July 2016) at Old Dalby, showing effective rainfall, and average subsurface resistivity changes in the wooded upper and lower slopes and the clear upper slope respectively. The greatest variation is seen in the wooded upper slope due to season-ally driven changes in evapotranspiration linked to the trees.

Daily resistivity monitoring results are summarised (Figure 8) and examples of the resulting resistivity images are given (Figure 9). The near surface was shown to respond rapidly to rainfall events, with both short term and seasonal wetting and drying cycles clearly observed. The ERT monitoring also revealed anomalous drainage to the toe of the cutting in the southern most section of the monitoring area.

Gravimetric moisture content (GMC) - resistivity relationships (left) were determined using laboratory testing on representative samples. Using these relationships analysis of the time-lapse ERT shows consistently higher moisture levels in the wooded areas (below) and an area of preferential wetting up in the toe of the slope – with the evidence indicating a link to damaged drainage.

4. CONCLUSIONS

4.1 Key benefits

Spatial subsurface information: The geophysical images generated using the PRIME approach complement surface-based monitoring and subsurface point sensors by providing spatially and temporally resolved information over the subsurface volume of the earthwork. This volumetric approach is important given that dams can be highly heterogeneous structures, in which small-scale deterioration (e.g. piping) can rapidly create larger-scale problems, and potentially give rise to catastrophic failures.

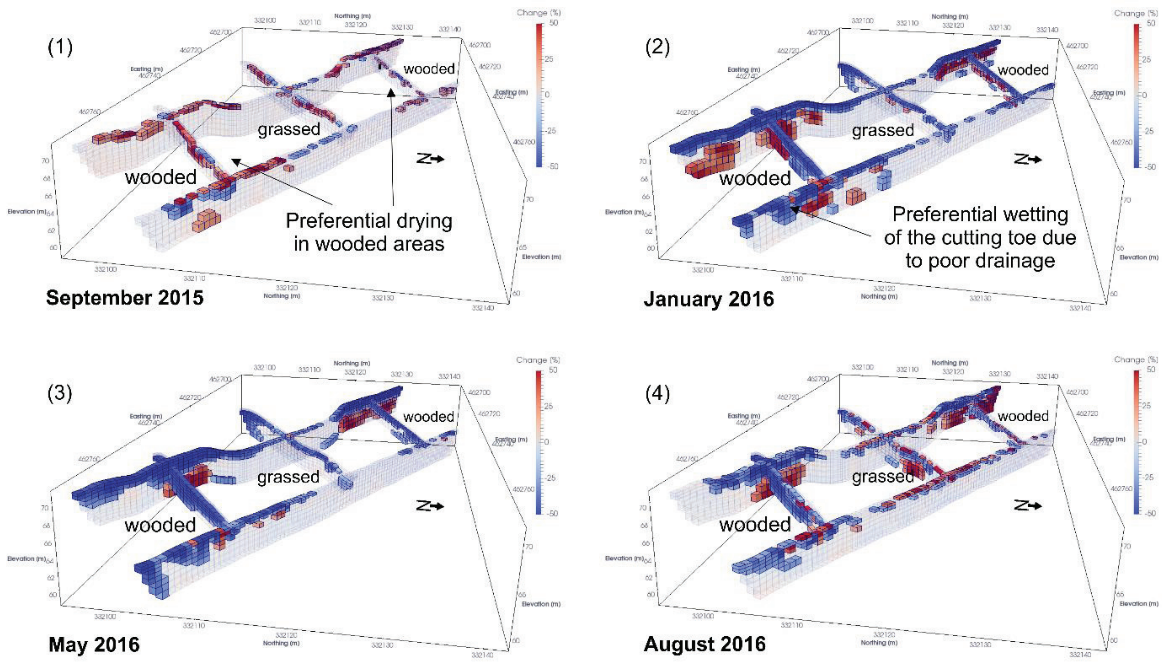

Figure 9 : Resistivity change images from the Old Dalby PRIME monitoring, showing wetting (blue) and drying (red) processes.

Sensitivity and resolution: The resolution of resistivity imaging is limited by the electrode spacing, which is typically between 0.5 and 5m. Despite this constraint however, even small defects (whose size is below the image pixel size, as small as 25 x 25 cm for a 0.5m electrode spacing) often remain detectable provided that property contrasts are sufficiently high and the sensor array configuration is sufficiently sensitive to the region in which the defect occurs.

Proactive management: The enhanced internal condition information provided by PRIME will enable a more proactive approach to dam management. With long term monitoring of internal drainage, stability and gradual changes in dam condition, potential problems should be identified at an early stage, thereby allowing remedial solutions to be implemented. It is important to note that PRIME detects change in conditions, so if the conditions are stable monitoring results will be unremarkable.

Near-real-time monitoring: PRIME is fully automated, with condition information accessible through a web-based 'dashboard' or provided through automatic alarms in the case of rapid deterioration. Using this approach, a high temporal resolution (i.e. minutes to hours) can be achieved compared to walk-over or remotely sensed surveys (i.e. days to weeks).

Minimally invasive: The deployment of the PRIME system and sensors will have negligible impact on the dam structure. Sensors can be installed at or just below the ground surface across the dam, thereby avoiding the need for intrusive subsurface installations that could impact on the integrity of the dam.

Novel: To the best of our knowledge, there is no equivalent low-cost low-power standalone remote geoelectrical monitoring system available on the market that automatically delivers full spatial/volumetric imaging information.

Compatible with existing approaches: The use of geophysical ground imaging technology will complement existing dam monitoring approaches. It extends the information provided by remote sensing (e.g. aerial photographs, LiDAR) by illuminating the internal structure of the earthwork. It also assists in interpreting data from point sensors installed in existing monitoring boreholes by providing spatial information to 'fill the gaps' between intrusive sample/data points. The monitoring system is designed to incorporate conventional point sensors – and so can serve as a unified geophysical-geotechnical monitoring platform. Development of a bespoke monitoring 'dashboard' or control centre is envisaged, integrating both geophysical and conventional geotechnical and point sensing data for a specific site.

4.2 Future developments

The PRIME monitoring system has been demonstrated to be effective in spatially tracking moisture driven changing conditions within vulnerable earthworks – enabled by permanently installed measurement instrumentation and sensors, data telemetry and web-delivery of ground imaging results. The PRIME Delivery Team now includes dam monitoring equipment installation experts (SOCOTEC) and dam safety engineering consultant experts (HR Wallingford) to ensure a complete package of design, installation, visualisation, interpretation and advice on interventions necessary for dam structures can be provided to dam owners.

We conclude that PRIME is ideally suited to providing valuable and cost-effective information on sub-surface changes within earth embankments to contribute to the long-term condition monitoring of dams.

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REFERENCES

Chambers, JE, Gunn, DA, Wilkinson, PB, Meldrum, PI, Haslam, E, Holyoake, S, Kirkham, M, Kuras, O, Merritt, A, Wragg, J, 2014. 4D Electrical Resistivity Tomography monitoring of soil moisture dynamics in an operational railway embankment. Near Surface Geophysics, 12, 61-72, doi:10.3997/1873-0604.2013002

Chambers, JE, Meldrum, PI, Wilkinson, PB, Ward, W, Jackson, C, Matthews, B, Joel, P, Kuras, O, Bai, L, Uhlemann, S, Gunn, D, 2015. Spatial monitoring of groundwater drawdown and rebound associated with quarry dewatering using automated time-lapse electrical resistivity tomography and distribution guided clustering. Engineering Geology, 193, 412-420.

Gunn, DA, Chambers, JC, Uhlemann, S, Wilkinson, PB, Meldrum, PI, Dijkstra, TA, Haslam, E, Kirkham, M, Wragg, J, Holyoake, S, Hughes, PN, Hen-Jones, R, Glendinning, S, 2014. Moisture monitoring in clay embankments using electrical resistivity tomography. Construction and Building Materials, 92, 82–94.

Huntley, D, Bobrowsky, P Hendry, M, Macciotta, R, Elwood, D, Sattler, K, Best, M, Chambers, J, Meldrum, P, 2019. Application of multi-dimensional electrical resistivity tomography datasets to investigate a very slow-moving landslide near Ashcroft, British Columbia, Canada. Landslides, 16, 1033-1042.

Uhlemann, S., J. Chambers, P. Wilkinson, H. Maurer, A. Merritt, P. Meldrum, O. Kuras, D. Gunn, A. Smith, and T. Dijkstra. 2017. Four-dimensional imaging of moisture dynamics during landslide reactivation, J. Geophys. Res. Earth Surf., 122, 398–418

Wilkinson P, Chambers J, Uhlemann S, Meldrum P, Smith A, Dixon N, Loke MH (2016) Reconstruction of landslide movements by inversion of 4D electrical resistivity tomography monitoring data. Geophysical Research Letters, 43,1166–1174.