The British Dam Society

# Novel geophysical ground imaging technology for the automated long-term monitoring of reservoir dams

S BUTLER, Canal & River Trust
O SPINOLA-RICHARDS, Mott MacDonald
T WEBSTER, Mott MacDonald
P B WILKINSON, British Geological Survey
P MELDRUM, British Geological Survey
J BOYD, British Geological Survey
O KURAS, British Geological Survey
H HARRISON, British Geological Survey
A WHITE, British Geological Survey
R SWIFT, British Geological Survey
J NGUI, British Geological Survey
M CIMPOIASU, British Geological Survey
J CHAMBERS, British Geological Survey

**SYNOPSIS** This paper covers the use of a novel geophysical investigation technique, PRIME, undertaken at two Canal and River Trust reservoirs, Slaithwaite and March Haigh. Due to concerns over seepage the Trust commissioned the surveys to try and establish the cause of the potential seepage pathways. This paper will give an overview of the 4D imagery, its methodology, and the results of which have been interpreted with the use of each of the reservoirs' known geological settings, available ground data and construction information. As with all geophysical techniques, it does have its limitations, however these surveys have provided an insight into the suitability of this technique for identifying seepages within embankment dams through long term monitoring and how it can be further developed for use across the Trust's assets.

## INTRODUCTION

The technique, timelapse electrical resistivity tomography (or imaging), ERT, is a spatially sensitive geophysical method used to non-invasively image subsurface resistivity to depths of tens of metres. Electrical resistivity is a useful geophysical property for dam monitoring due to its sensitivity to compositional variations and changes in moisture content. The technology is used to generate time-lapse resistivity images, sensitive to changing subsurface conditions that are otherwise obscured. The addition of moisture to geological materials (generally) decreases the electrical resistance of the material, while a reduction in moisture content results in void space being unoccupied and therefore increases the resistivity of the soil or rock.

**Managing Risks for Dams and Reservoirs**

The two case studies; March Haigh and Slaithwaite Reservoirs, are presented herein. ERT monitoring has taken place on the downstream faces of the dams; 4D enabled images have been produced of the internal moisture dynamics to gain an insight into the potential seepage pathways within the embankment dams, which could ultimately, if further deterioration occurs, could cause internal erosion to potentially progress.

## METHODOLOGY

In order to capture changes in electrical resistivity with respect to time we installed PRIME (Proactive Infrastructure Monitoring and Evaluation) resistivity instruments on two earth reservoir dams (see following sections). PRIME is designed to be an automatous resistivity instrument which is left (semi) permanently deployed in field conditions; the instrument can then be interfaced via telemetry and left to automatically collect resistivity measurements at specific times of day. The PRIME instrument uses arrays of electrodes connected via multicore cables, usually routed through shallow trenches/pits. This instrumentation was originally developed as a low cost and low power system to complement already existing monitoring technologies on geotechnical earthwork assets. To generate resistivity images, raw electrical resistance measurements are processed via a 4D smoothness constrained least-squares inversion algorithm described by Loke et al (2022).

Electrode arrays were custom designed to span the width of the earth dams. The electrode spacing affects the resolution of the resistivity images; closer spaced electrodes provide better near surface resolution at the cost of sensitivity at depth. PRIME has a maximum limit to the number of electrodes that can be addressed at one time (256 electrodes for the instruments used in this study), additionally the more cabling and electrodes required the higher the financial cost of deployment. Therefore the electrode spacings were optimised to provide sensitivity to the expected valley depths of the corresponding dams given associated budget and physical constraints (256 and 168 electrodes for case studies 1 and 2 respectively). The electrodes were placed on the downstream side of both dams and routed in either shallow trenches (case study 1) or pits (case study 2). Cabling was then routed into an enclosure (Figure 1 & 2) to connect to the respective PRIME systems. In both cases, the resistivity instrumentation was powered by a solar panel and battery. The electrodes comprised stainless steel spikes, with a length of 300 mm and a diameter of 8 mm. The spike electrodes were installed in small holes packed with graphite granules, which ensured an improved electrical contact with the soil.

**Figure 1**. Photo of the PRIME enclosure at Slaithwaite Reservoir (case study 1).

**Figure 2.** Photo of the PRIME enclosure at March Haigh Reservoir (case study 2).

## CASE STUDY 1 SLAITHWAITE RESERVOIR

Slaithwaite Reservoir is situated near Marsden, West Yorkshire and was constructed between 1795 and 1799 by the Huddersfield Canal Company. It impounds the waters of Merry Dale Clough which is a tributary of the River Colne and has a volume of 277,400m³.

Published geology (BGS, 2003) indicates that the dam is underlain by alternating sandstones, mudstones, shales, and coal seams of the Carboniferous Millstone Grit Series. The published geological maps indicate no superficial deposits present at the site. However, it is highly likely that prior to construction, there were residual soils in the valley formed from the weathering of the Millstone Grit Series. Complete weathering of the mudstones within the series would form cohesive deposits with the sandstones forming materials of a higher granular nature. Geological mapping data combined with available ground data indicates that the rocks in the Slaithwaite area are mostly mudstone with occasional sandstone. Due to the date of which the embankment was built, it is highly probable that material was sourced locally from within the valley. This would suggest that the embankment is made of the completely weathered solid geology and associated residual soils. Ground investigations were completed in 2020, 1989 and 1974, which covered the dam crest and downstream shoulder and were targeted for spillway upgrade works and core location.

From the available ground data, the embankment fill is described as a dominantly sandy silty clay which is founded directly onto weathered rock. Due to the age of the asset, there are no reliable construction drawings and the presence of a “Pennine type” puddle clay core was assumed. A review of the historical geotechnical testing, specifically plasticity index and particle size distribution, indicated the presence of an engineered core. There are no known records or evidence to support a cut-off trench.

An indicative longitudinal section through the dam axis is presented in Figure 3 and shows a conceptual model through the embankment and foundation using historic boreholes and rock mapping data. The section identifies sandstone units at lower elevations in the right abutment which are interbedded with mudstones. The left abutment appears to consist of a single sandstone unit at approximate crest level elevation with the remainder of the abutment formed from mudstone. The geology of the left abutment is confirmed via rock exposures within the spillway chute. The differences between the geological sequences in the left and right abutment suggest the presence of a fault within the valley bottom. In terms of rock mass permeability, mudstones are typically known to have low porosity and low permeabilities with sandstone tending to have relatively higher porosity and permeability.

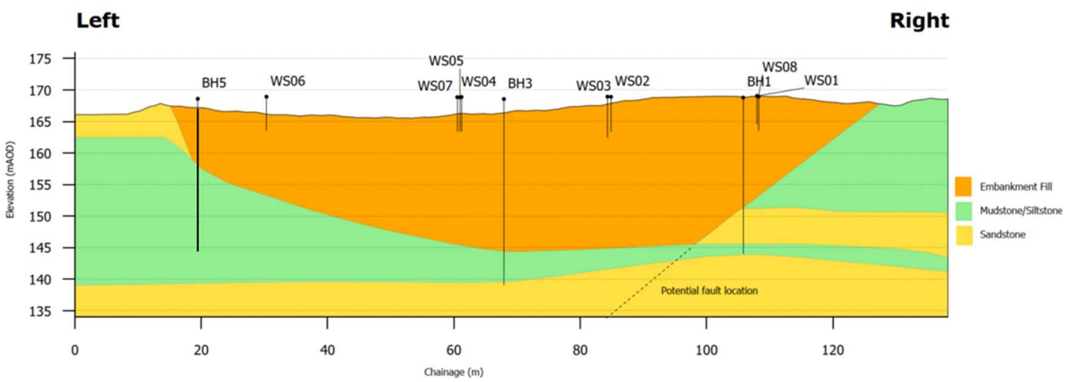


**Figure 3**. Slaithwaite indicative geological long section.

The outlet arrangement is typical of that found in most early canal reservoirs with masonry outlet tunnels located within the upstream and downstream embankments connected by a cast iron pipe that passes through an engineered core.

The embankment has a history of leakage with references going back to 1797 of leakage associated with the original outlet tunnel. In 1803 settlement, leakage and crushing of the outlet pipe resulted in the canal company abandoning the original outlet position and a new one was constructed which is still in use to this day. The outlet tunnel today is quite damp, and a concentrated leak appears at the upstream end of the outlet tunnel when the reservoir is within 1.2m of top water level (TWL). A telemetry-linked V-notch gauge has been installed at the back of the outlet tunnel to allow seepage flows to be continuously monitored. A PRIME survey was commissioned to contribute to an improved understanding of the leakage sources and pathways within the dam.

Installation of the PRIME system took place during July 2022. ERT lines were installed in shallow hand dug trenches to hide and protect the cables and electrodes. Electrodes within the outlet tunnel were installed as 100 x 100mm$^2$ stainless steel plates secured by masonry anchors to the soffit, with a bentonite grout between the plate and wall to ensure a good electrical contact between the electrode and the surrounding ground.

A baseline resistivity survey was conducted at a lowered reservoir level of 164mAOD. Following which, the reservoir was refilled to TWL at 167mAOD. The water level was held there for several weeks while data was continuously collected. Rainfall and leakage rate data were also collected during this period. The baseline survey (Figure 4, top image) indicated that the embankment structure displays significant heterogeneity in terms of its resistivity distribution. It is possible that this heterogeneity is a combination of both embankment material characteristics and moisture related variability. In terms of ERT interpretation, low resistivity could represent a higher content of clay or saturated material with high resistivity possibly representing a more granular material. The baseline ERT survey indicated the crest region suggests there is a transition from higher resistivities in the near surface to lower resistivities at depth – potentially indicating an increase in moisture content or clay content.

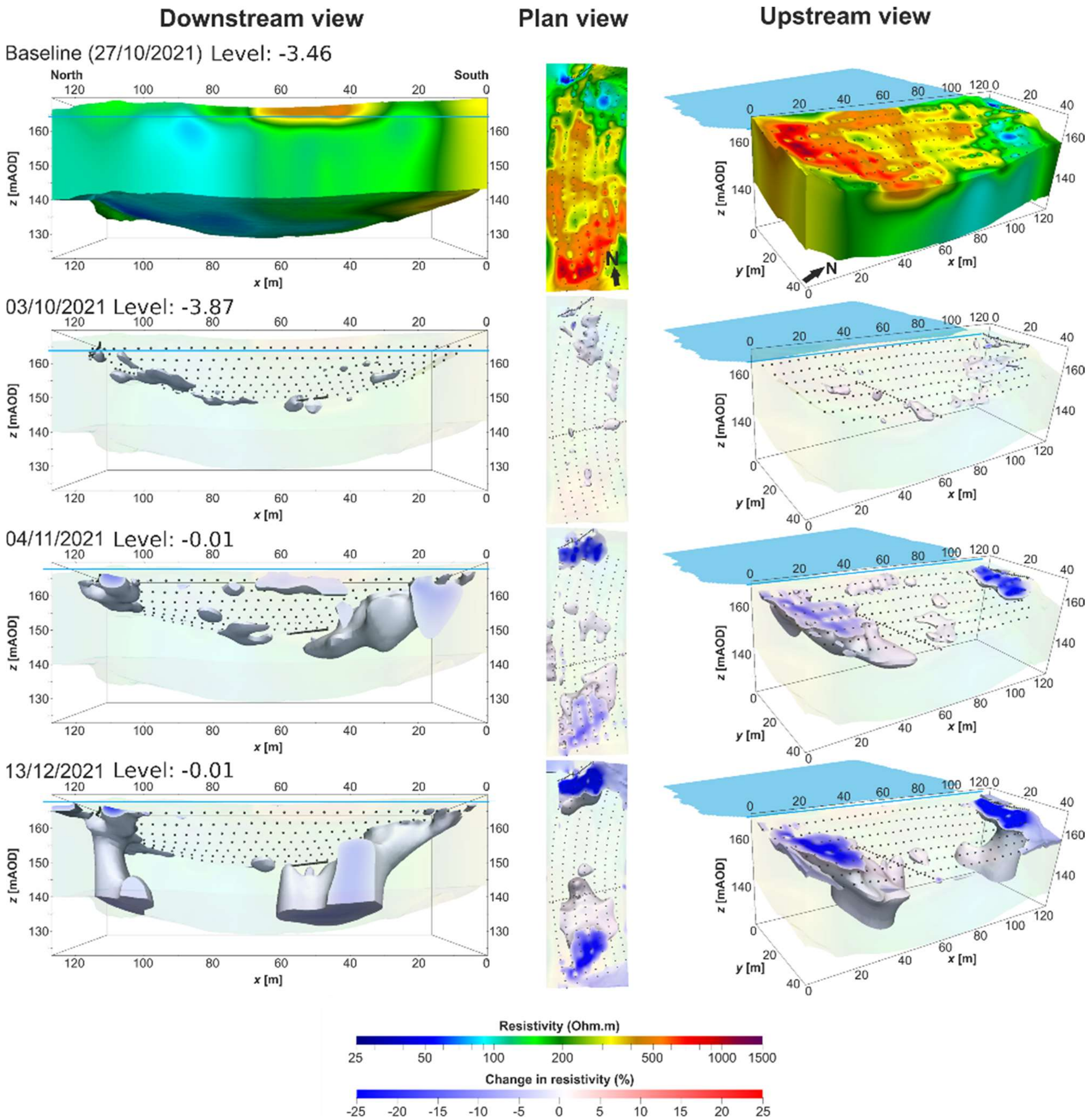


**Figure 4**. Baseline resistivity images (27/10/21) and a series of 'change' images representing the percentage change in resistivity ranging from 04/11/21 to 13/12/21. Iso-resistivity change set to a minimum of 2.5%. Reservoir level represented by blue line/plane.

During the raising of the reservoir level, PRIME reported significant changes in resistivity across the length of the outlet tunnel, in the dam crest and in the vicinity of the abutments. Figure 4 presents images from the time-lapse data at various stages of reservoir rise and fall. The most substantial changes in resistivity are concurrent with the rapid rise in level of the reservoir and a period of heavy rainfall in early November 2021. Figure 5 presents this monitoring period and changes in resistivity in graphical form. Reductions in resistivity during this time are initially concentrated: (1) in a thin layer in the crest region (represented as red); (2) at deeper levels within the right side of the dam (represented as green); and (3) within the left side of the dam (represented as blue).

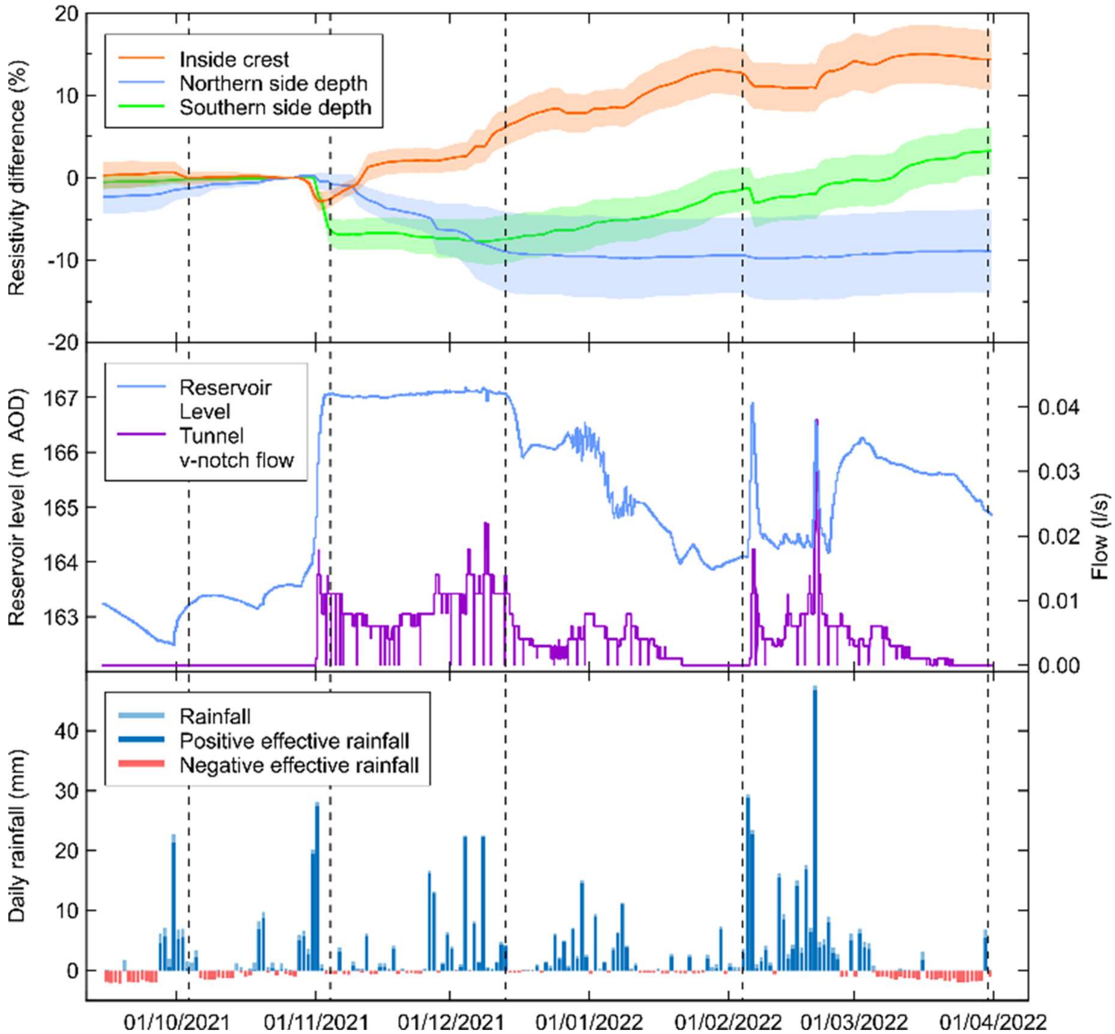


**Figure 5.** Selected regions of the dam for the period ranging from 15/09/21 to 31/03/22. Resistivity change, rainfall, effective rainfall, seepage flow and reservoir level.

## CASE STUDY 2 MARCH HAIGH RESERVOIR

March Haigh reservoir is situated near Marsden, West Yorkshire and was constructed in the 1830s to supply the Huddersfield Canal. It impounds the Haigh Clough stream at the upper reaches of the River Colne catchment and has a volume of 275,550m³. The final constructed height was 20m, but it is thought construction was staged over several years as demand for the canal increased. Evidence of a raising can be seen in a sketch from the Early Dam Builders in Britain (Binnie, 1987) that suggests that the core is to the upstream of the current embankment crest. However, geotechnical investigations and associated lab testing does not support this.

Published geology (BGS, 2012) indicates that the dam is underlain by Upper Kinderscout Grits of the Millstone Grit Series. Observations made of the site-specific geology indicate that the left side of the valley was more shaley with the right side dominated with thickly bedded sandstone units.

Published geology does not indicate superficial materials are present in the area, therefore they are not considered to be of substantial thickness. It is likely that the dam was constructed from the residual soils formed from the complete weathering of the Millstone Grit Series.

Ground investigation at March Haigh was completed in 1999. A review of this data provided an indication of an engineered core with particle size distribution curves showing a higher proportion of fines along the dam axis when compared to the shoulder material. An indicative longitudinal section through the dam axis is presented in Figure 6 and shows a conceptual model through the embankment and foundation using historic boreholes and rock mapping data.

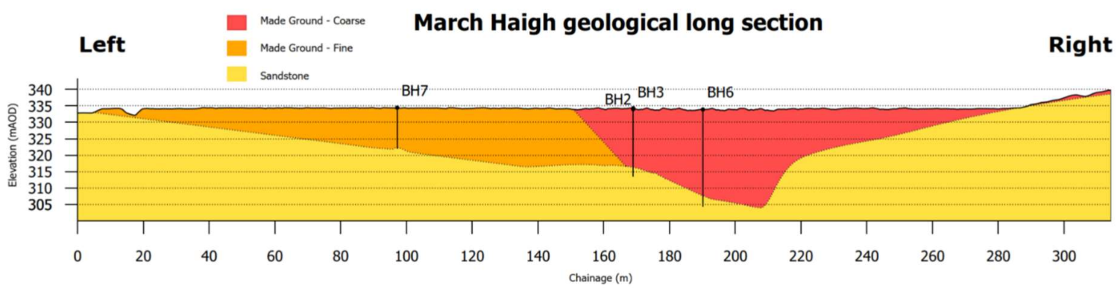


**Figure 6.** March Haigh indicative geological long section.

As with Slaithwaite, the dam has a typical canal-style reservoir outlet arrangement. The dam has undergone substantial settlement over the years. Following the first statutory inspection settlement was observed in the order of 0.5m over the outlet structure and a subsequent crest “topping up” exercise was completed. Disrupted pitching on the upstream face also indicates a long history of ongoing settlement and raising. Leakage in the outlet tunnel was first noted in the 1978 S10 inspection report. A programme of TAM grouting was undertaken in 1999 to remediate the issue. Leakage reduced following the grouting works but has since returned. To investigate seepages further the Trust commissioned a PRIME survey. The scale of the PRIME instrumentation is smaller than that of Slaithwaite.

Raw electrical measurements were processed in the same manner as for Case Study 1. Figure 7 presents the ERT baseline survey. There are two distinct regions of electrical resistivity in the dam and indicate the embankment-foundation contact is asymmetrical of the left-hand side and right-hand side of the embankment. The left side of the dam is more electrically conductive than the right, both being characterised by resistivities of either less than 100 Ωm or 500 to 2,000 Ωm, respectively. The lower resistivity of the left side of the dam indicates that it is compositionally different to that of the right side. This means it is likely to have a higher clay content in comparison to the right side of the dam. The apparent boundary between the regions of the dam is sharp and represents the construction methodology of the embankment where material is believed to have been sourced from each side of the valley. Weathered shales from the left are likely to contain a higher proportion of silts and clays with the right side of the valley dominated by more sandy material. This boundary also corresponds to the alignment of the outlet culvert indicating that the dam was constructed in two halves.

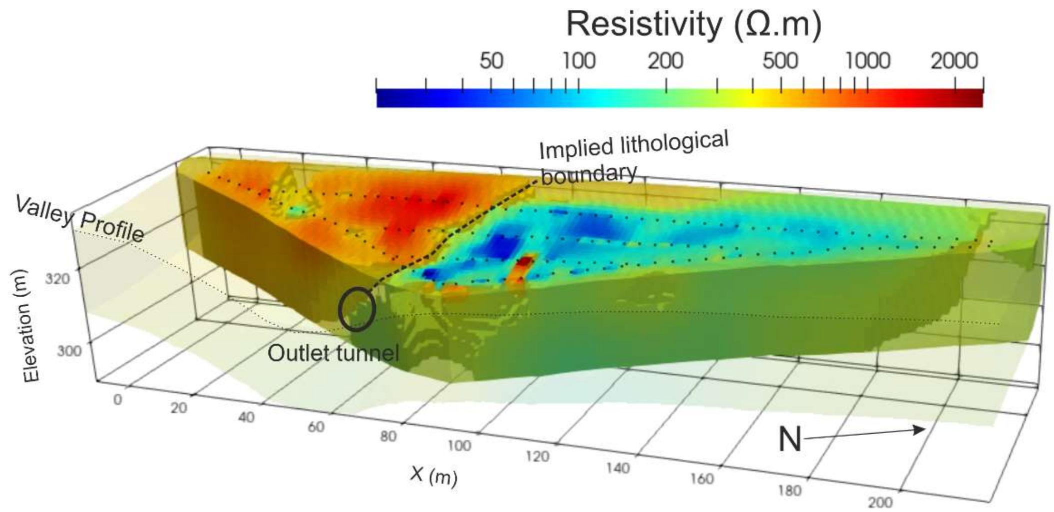


**Figure 7**. Baseline resistivity image of the downstream side of the March Haigh dam. The boundary between the two dominant resistivities regions of the dam (and by extension lithologies) has been indicated.

We show negative resistivity anomalies that occur in comparison to when the reservoir was recorded at 12.0m below TWL (14$^{th}$ of June through to 7$^{th}$ of July 2023). During the drawdown of the reservoir level the resistivity of the area surrounding the outlet tunnel increased, indicating this area responds rapidly to changes in reservoir level. Changes in resistivities rapidly became negative after a period of rainfall (18$^{th}$ to 21$^{st}$ of June). This was observed across the surface of the dam face, likely because of near surface moisture contents increasing due to infiltration of rainfall. Figure 8 presents the change in resistivity, noticeably decreasing in resistivity surrounding the outlet tunnel, indicating that this part of the dam has a relatively high hydraulic conductivity. The negative resistivity anomaly surrounding the outlet tunnel does increase in size and magnitude as the reservoir level recovers (7$^{th}$ of July through to 31$^{st}$ of July). However, this period also corresponds to days with elevated levels of recorded rainfall. It is therefore difficult to fully decouple the contribution of rainfall and reservoir level increase to the negative resistivity contrast. On the other hand, the rapid response of this part of the dam to reservoir drawdown and rainfall, and differing resistivities, does indicate this part of the dam has a relatively higher hydraulic conductivity. Ongoing observations of leakage made in the outlet tunnel support this hypothesis. Figure 9 shows the average resistivity (and changes) in the outlet tunnel area (in green) for the duration of the study, alongside effective rainfall and reservoir level records.

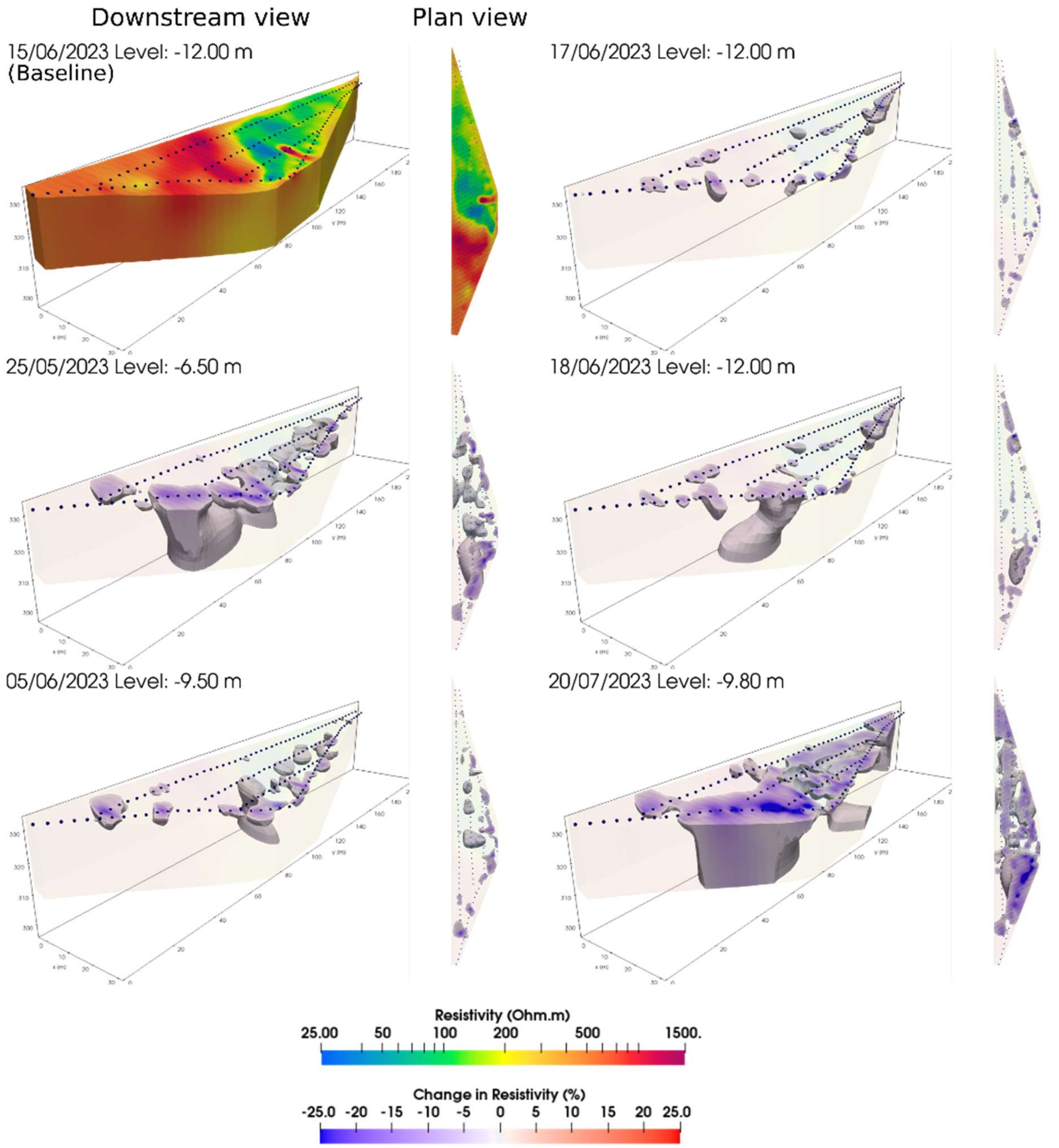


**Figure 8.** Baseline resistivity images (15/06/23) and a series of change images (% resistivity change) ranging from 25/05/23 to 20/07/23, focussed on the period reservoir level change at March Haigh. Iso-resistivity level in the change images set at -2.5%.

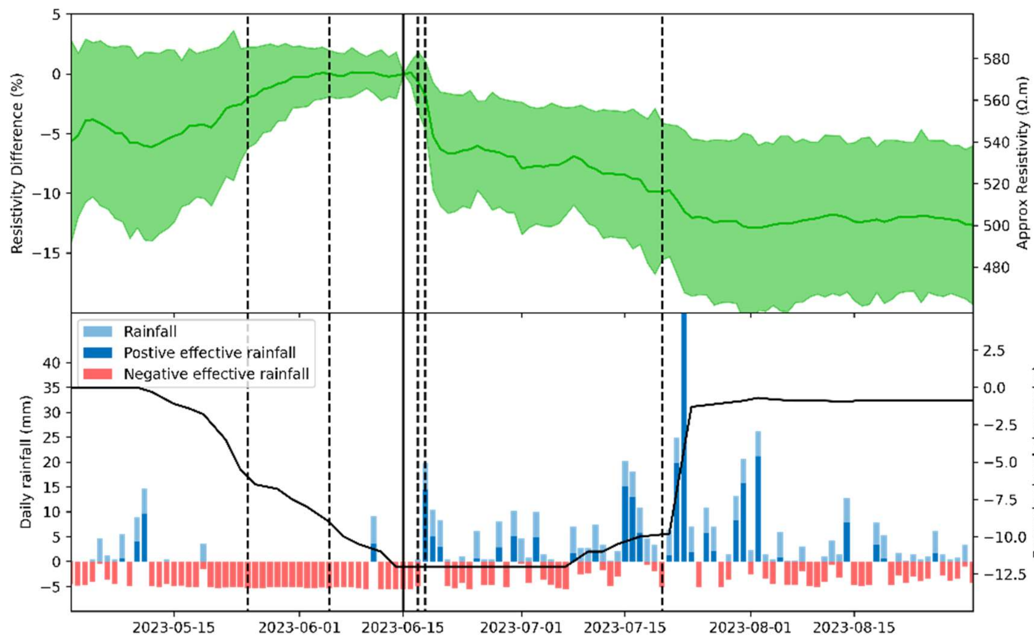


**Figure 9.** Rainfall, effective rainfall, reservoir level, and resistivity changes (shaded area indicates ± standard deviation) in material surrounding the outlet tunnel, for the period ranging from 01/05/23 to 31/08/23.

**DISCUSSION**

As with any investigation technique, geophysical survey methods are known to have limitations in their application. The extent of the technique is subject to the array of nodes placed on site. In areas where the site is constrained, this may not always extend outside of the query area to provide control points. In addition, the quality of the resolution decreases with depth, and therefore useful information may not be retrieved for dams in excess of 20m. Downhole sensors could be installed to mitigate these effects of sensors used at the surface.

This report has shown the necessity of having initial geotechnical information available for the site to enable the interpretation of the geophysical surveys. A comprehensive geotechnical desk study including all records ranging from historic drawings to seepage monitoring data is recommended, and ground investigation undertaken if not already available. The ground model should be agreed with technical experts and this information made available to the geophysical contractor prior to commencing. This will enable surveys to be tailored to the potential ground conditions, to target areas of interest and provide maximum value in the data obtained.

March Haigh and Slaithwaite reservoir are both constructed on rock foundations and therefore highlight a distinct boundary change at the embankment-foundation contact. Where embankment dams are founded on soil, the embankment material to foundation material interface may not be as obvious within a geophysical survey due to similar material characteristics.

ERT is unable to differentiate between diverse sources of the moisture change. Although results from the survey indicate there is a relationship between the changes in resistivity and reservoir levels, the changes in resistivity may also be a result of the infiltration of rainfall or groundwater sources from the foundation and abutments.

The ability to vary the reservoir level during the survey is advantageous. This enables the analysis of the relationship between the changes in resistivity within the embankment and the hydraulic head formed by the reservoir level. In these case studies a maximum of 4.5m at Slaithwaite and 12m at March Haigh was able to be achieved. Greater changes in hydraulic head, over longer periods of time, may provide better results and higher changes in resistivities.

There is potential that areas of the embankment remained saturated throughout the monitoring period. Completely saturated material will not show changes in resistivity, therefore not provide data. This may be interpreted that no seepage is occurring, which could lead to an inaccurate representation of the potential seepage pathways through the embankment or abutments.

The PRIME survey from Slaithwaite has indicated some regions of interest within the embankment and abutments which will be further investigated by a targeted intrusive investigation. Results from March Haigh indicate a localised area of interest around the outlet tunnel which coincides with previous remedial works.

## CONCLUSION

The 4-dimensional aspect of PRIME has proven useful in identifying potential pathways of seepage and further understanding the embankment construction at both March Haigh and Slaithwaite reservoir. With the ability to change the reservoir level over time, ERT can establish a number of geotechnical aspects of the embankment and its foundations, including its composition, the embankment-foundation boundary, and potential areas of higher porosity or permeability. As discussed above, there are limitations within the current surveys which have taken place using this technique. These warrant further research and consideration when using PRIME on other embankment dams. However, this long term non-intrusive survey could be used as an early identification of changes in embankment composition which could lead to seepage. Further guidance on geophysical surveys specific to dams is needed to enable a consistent approach across the industry.

## ACKNOWLEDGEMENTS

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