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Looking into reservoir geophysics – emerging technologies

J E HAMLYN, TerraDat
C L BIRD, TerraDat
M J COOPER, Arup
R J COTTRELL, Arup
M HAYWARD, Fairhurst

SYNOPSIS As the UK reservoir stock continues to age, further deterioration of these assets should be expected. In particular, leakage and erosion through embankment dams present a significant risk to public safety. Traditional risk management relies on surveillance, and where leaks have been detected this is often supplemented by monitoring of leakage rates and turbidity. However, these techniques are limited to leaks which emerge through the downstream face of the embankment dam. Understanding and monitoring the conditions within the embankment structure are therefore often limited; however, new innovative geophysical techniques are now available that enable medium to long-term monitoring of subsurface flows.

Here we present results from long-term geophysical monitoring of Oakenholt embankment dam, where subsidence and settlement had been identified as possible symptoms of potential internal erosion. An Electrical Resistivity Tomography (ERT) survey mapped the internal structure and surrounding geology of the dam and found a localised zone of potential moisture ingress. Subsequently, a geophysical monitoring system was installed along the embankment for continuous monitoring of the electrical potential field, which changes in direct response to subsurface ground water flow. Water seeping through the dam was identified in relation to the corresponding reservoir level at which it is initiated. The data provided evidence that the seepage is not currently developing further. This study demonstrates that geophysical monitoring is an effective tool for engineers and reservoir Undertakers.

INTRODUCTION

As the UK reservoir stock continues to age, further deterioration of these assets should be expected. Common deterioration mechanisms that have the potential to present a risk to public safety include leakage and associated erosion through or beneath embankment dams. The Environment Agency, which is responsible for collating and reviewing information on reservoir incidents in England, regularly reports leakage and associated erosion through embankment dams to be one of the most common causes of reservoir safety incidents.

Typically, the management of risk posed by these mechanisms is primarily led by routine visual surveillance, which is limited to observation of only those features that are visible at the ground surface. Where a leakage issue is known, surveillance is often supplemented by monitoring the rate and turbidity of the leak, but this approach is generally limited to only those leaks that happen to emerge through the downstream face of the embankment dam. Understanding and monitoring the conditions within the embankment structure are therefore often limited – as even the most experienced asset manager or dam engineer cannot see into the ground.

Whilst geophysical surveys are not a new concept, the range of techniques and approaches that are available, economical, and effective for reservoir-specific applications has continually developed over recent years. Recent innovations include techniques that embed geophysical equipment into dams, for longer term monitoring of changes to conditions over time. The ability to record temporal / time related changes deep into the structure of an embankment dam has potential to provide compelling evidence of emerging issues.

TerraDat has already presented papers on the research phase of its proprietary SP (Self-Potential)-based water flow mapping and monitoring system (SPiVolt). Examples have also been published showing the system monitoring water flow through an embankment dam (Hamlyn et al., 2021 and 2022). Here, we show how SP monitoring has been used to satisfy the recommendations of a Section 10 report for a dam in North Wales while providing higher spatiotemporal measurements than traditional surveillance techniques.

OAKENHOLT EMBANKMENT DAM

An earth-fill embankment with a puddle clay core was constructed around 1876 across Lead Brook to form Oakenholt Reservoir. The dam is approximately 65m long and 15m high, with a grassed downstream face and an upstream face protected by stone pitching.

On the left-hand side (LHS) of the dam, there has been an overall settlement of the downstream crest of about 10mm since 2002. Superimposed onto this is a localised area of increased settlement (up to 27mm), which has also begun to accelerate (Figure 1). The increased settlement correlates with a zone of subsidence that can be observed in the crest wall; there is also a zone of damaged masonry in the upstream wave wall and downstream of the subsided wall is a small void. These on-site observations were made during an integrated geophysical investigation in 2021, which included an Electrical Resistivity Tomography (ERT) survey. The ERT survey provided a cross-section along the length of the embankment, defining it in terms of geo-electrical units (Figure 2). Most notably, a deep, low resistivity zone was interpreted to be clay-rich material within the core of the embankment. The clay core extends from the valley floor to ~ 29mAOD; overlying this is a 4m thick layer of material which is significantly more resistive, i.e. relatively clay deficient; this material 'pinches out' at ~ 85m chainage, coincident with the zone of settlement of the embankment crest wall. This localised decrease in resistivity is thought likely to be caused by increased moisture within the more granular material beneath the crest. The ERT data was acquired when the reservoir was close to top water level (TWL).

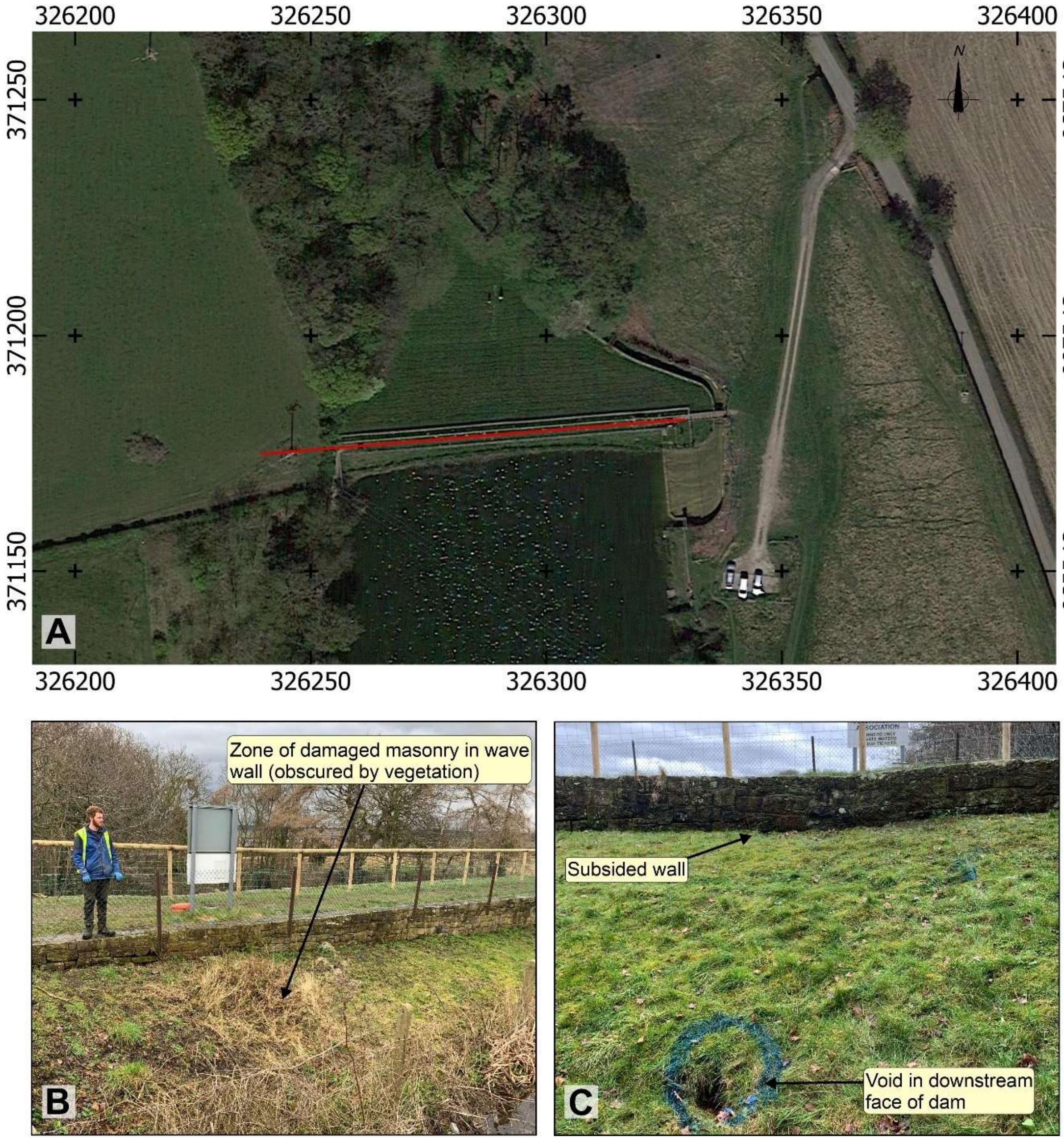

Figure 1. A) Google maps image of Oakenholt dam and location of subsection of ERT profile shown in Figure 2 (red line). **B)** Damaged masonry in upstream wave wall. **C)** Evidence of internal erosion in downstream face.

Based on the void features that have been identified and the localised nature of the subsidence evident at the ground surface and from crest monitoring, the subsidence has been interpreted as most likely caused by loss of fines within the dam due to internal erosion under seepage/leakage. In 2015, Arup completed a S10 Statutory Inspection Report. The inspection identified that the risk of internal erosion (leakage carrying fines) through the body of the dam is credible and significant. Regular surveillance for signs of leakage is noted as the means to mitigate and manage the risk. Annual levelling of the dam is recommended, to keep a record of the surface expression of the subsidence but it should be acknowledged that this will not provide any further information about the ongoing internal processes. Further, there are no obvious flows emerging from the surface of the downstream slope of the embankment, meaning any potential leaks cannot be quantifiably recorded to identify potential change over time. An additional high spatiotemporal resolution surveillance technique with the ability to provide information on any subsurface water movement and its relationship to reservoir level and rainfall is, therefore, highly desirable.

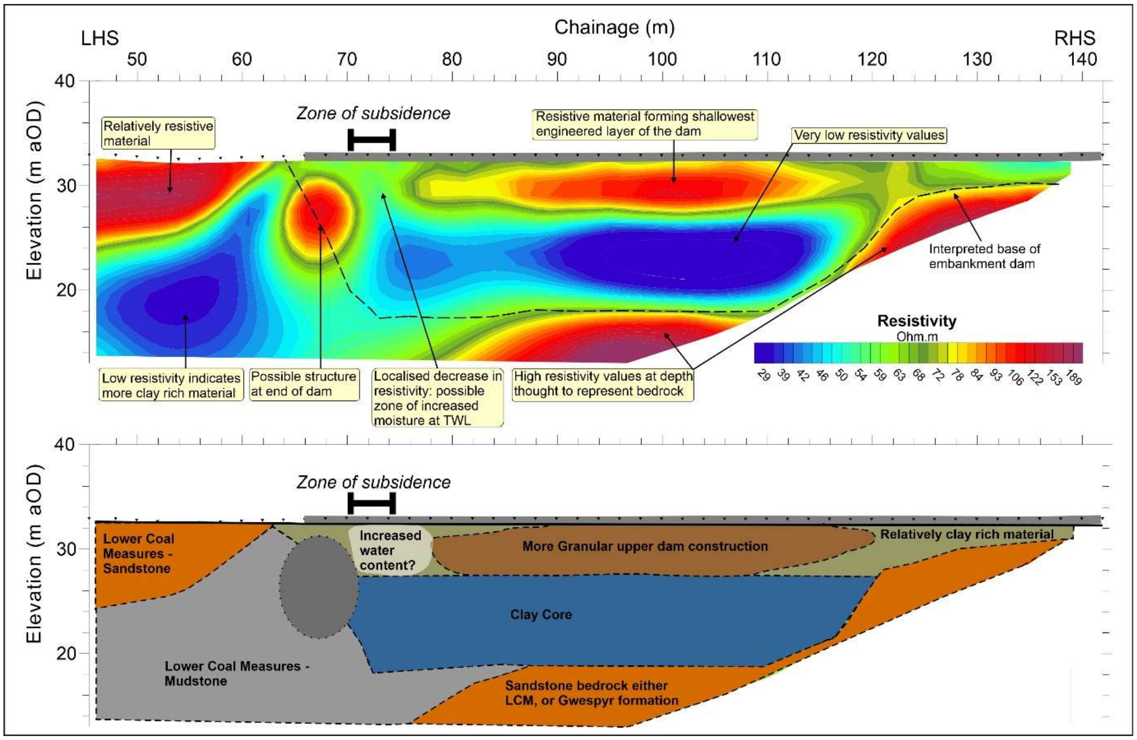

Figure 2. Upper: A subsection of an ERT profile showing the electrical character of the subsurface. Low resistivity (blue) indicates the material is more clay-rich or has an increased moisture content, and increased resistivity (red) indicates drier, clay-deficient material, or competent bedrock. The black bar indicates the zone of settlement observed at the surface. The grey bar shows the location of the wave crest wall. **Lower:** Conceptual model of the dam construction and surrounding geology based on ERT data.

The interpretation of the initial geophysical survey established a detailed model of the geological setting of the dam and its internal structure; this also included a hypothesis of moisture ingress into a shallow zone of more granular material beneath the subsidence in the crest wall. This hypothesis required further verification, and a monitoring array was installed across the embankment to provide information on subsurface water flow and its relationship to the reservoir level and any other hydrogeological factors.

GEOPHYSICAL MONITORING

Geophysical monitoring systems present a step change in geophysical technology from traditional techniques whereby one-time surveys determined the geophysical characteristics of the embankments, including their composition and groundwater conditions. The system used in this instance adopts an array of Self-Potential (SP) monitoring electrodes embedded into the embankment dam for the medium to longer term. This enables long-term temporal / time-based monitoring of the change in geophysical characteristics over time which therefore presents the potential to identify changes in leakage/seepage flows.

The monitoring array continually measured the passively occurring SP field over the area of interest. It is possible to interpret this data to indicate subsurface flow, as discussed in numerous academic papers, such as Boleve et al. (2009} and references therein. Such systems have been created in response to the perceived need for a cost-effective monitoring solution as embankment dams age and inevitably deteriorate.

In brief, SP surveys measure the naturally occurring subsurface electric potential (in millivolts) between two non-polarising electrodes (a reference electrode and a measurement electrode). The reference electrode is situated in an 'electrically quiet' environment, and the measurement electrode is situated within the area of interest. The voltage measurement across the two electrodes is indicative of the naturally occurring electrical potential at the measurement electrode. The system used at this site utilised an array of semi-permanent measurement electrodes positioned across the area of interest to automatically acquire readings at a specified frequency.

Filters and algorithms can be applied to remove the effects of time-varying interference to extract the part of the signal directly attributable to water flow.

INSTALLATION

TerraDat installed a SPiVolt SP monitoring system comprising 32No, 2m spaced, non-polarising electrodes into the embankment as a single monitoring profile across the dam crest (Figure 3). It was configured to record data every ~20 minutes and upload the readings to a server every hour. Rainfall, ground temperature, and air temperature are also recorded to provide additional data for interpretation. The monitoring array was installed by hand behind the downstream crest wall at a depth of ~150mm (Figure 4).

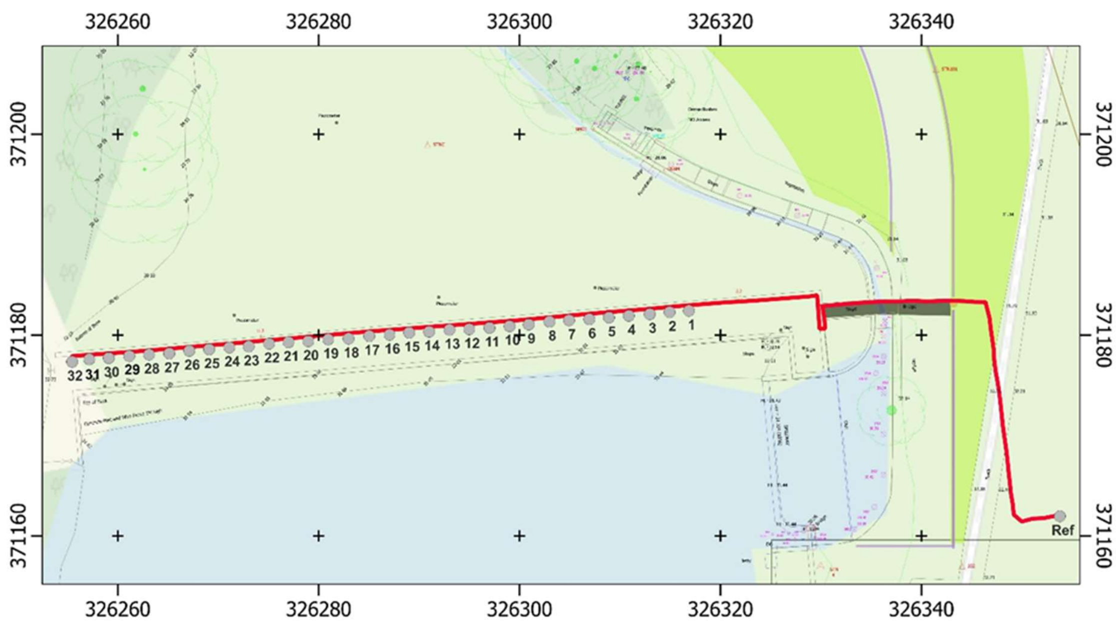

Figure 3. SP monitoring array location plan. Grey circles represent the position of non-polarising electrodes. The red line is the location of the cabling.

Figure 4. SP monitoring array installation at Oakenholt Reservoir. **A)** During installation. **B)** Site conditions following installation.

RESULTS AND INTERPRETATION

The ground exhibits a constant SP field caused by the geology and geochemistry of the subsurface with small temporal fluctuations caused by temperature, atmospheric effects, and subsurface water flow. The contribution from the constant geological effects can be negated by establishing a baseline SP field, which is then removed. The temporal effects not of interest (temperature, atmospheric, and tidal) are removed by appropriate filtering to reveal the time-varying subsurface water flow. Data from the first few days of acquisition are discarded as the electrodes reach an electrochemical equilibrium with the ground.

Subsurface seepage below the dam crest manifests as localised zones of increasingly negative SP response, which typically correlates with high reservoir levels. When the reservoir level is high, shallow flow pathways within the dam crest may be initiated and the increased pressure head will force water through any defects in the core. The SP response across the whole dam structure may also decrease following periods of rainfall as water infiltrates the shallow ground surface and migrates past the electrodes. This effect is reversed when the dam dries out. Positive SP values occur when static water ponds or saturates an area.

The reservoir level was low when the monitoring array was installed; therefore, initial measurements were acquired as the water level increased to TWL (Figure 5). At the beginning of the time series, the monitoring array records negative SP at the LHS of the dam as the reservoir level increases to 30.75mAOD. As the reservoir level rises to 31.2mAOD, evidence of subsurface water flow extends across the dam's left-hand side (LHS) to electrode 23. During this initial observation period, there were two occasions when the reservoir level was drawn down for a couple of days for maintenance works; however, the monitoring array did not record any significant changes or trends in the SP values. This lack of reactivity is likely to reflect the permeability / hydraulic conductivity of the embankment materials, with the embankment holding onto the water within its saturated zone causing a lag between the reduction in reservoir level and significant changes in measurements when conducted over very short time periods.

As the reservoir level remains high, the SP field at this location becomes positive. Positive SP values are observed if the water stops flowing and begins ponding or rising within the structure. It is, therefore, most likely that the ground on the LHS of the dam is becoming saturated over time, with limited discernible flow out of the downstream slope of the embankment. This correlates with on-site observations from the Supervising Engineer, who confirmed that no significant anomalous water flows out of the structure had occurred.

As the water level remains stable for extended periods, the observed SP field shows little variation (within 1 or 2 mV), implying that no other significant hydrogeological factors influence the SP field. Therefore, it is concluded that changes in SP and associated groundwater flow are governed by fluctuations in the reservoir level. Furthermore, as the SP readings through the LHS of the embankment dam remain stable over time, this presents strong evidence that the interpreted ongoing seepage/leakage is not developing. Whilst the monitoring array remains in place, the situation can continue to be monitored against potential development, which provides the Undertaker and Supervising Engineer a level of assurance which in this instance could not be provided through traditional site surveillance and physical leakage monitoring techniques.

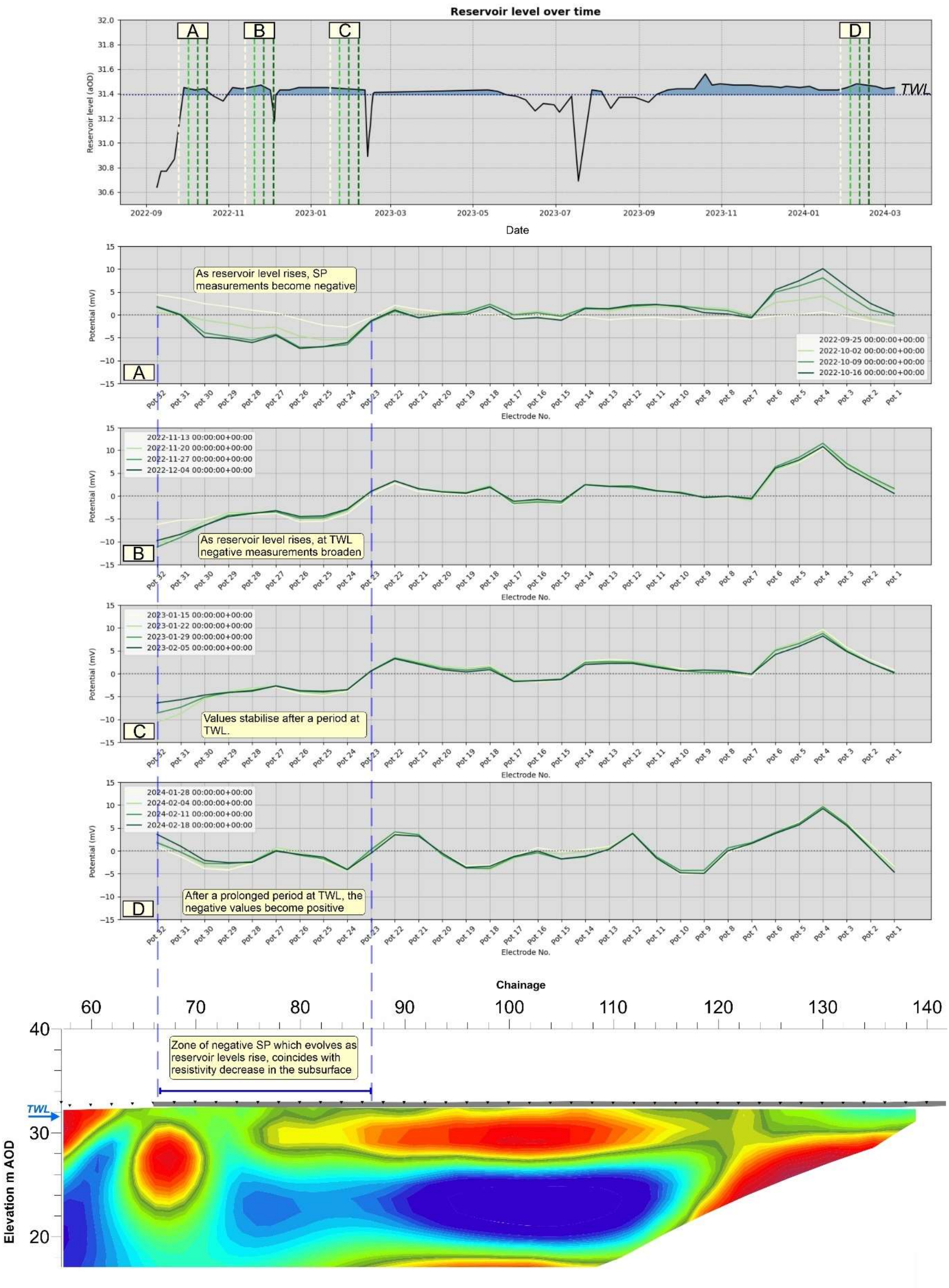

Figure 5. Top) Reservoir levels as recorded by the Client between September 2022 and March 2024. Dashed coloured lines show the reservoir level for the corresponding week of SP data below. **A to D)** Weekly average SP field across the array for the corresponding periods. **Bottom)** Location of the SP data relative to the ERT section collected before installation.

CONCLUSIONS

The on-site observations and initial geophysical survey suggested an area of water seepage/leakage through the LHS of the dam. Geophysical monitoring has proven that water is seeping through the dam and has identified the reservoir level at which it initiates (30.75mAOD). The data also shows that after prolonged periods at TWL the embankment material becomes saturated. This occurs within the upper part of the embankment indicated by the ERT survey as comprising relatively clay-deficient material (Figure 6). SP monitoring has provided a methodology for observing leakage when there is little or no surface expression of a leak.

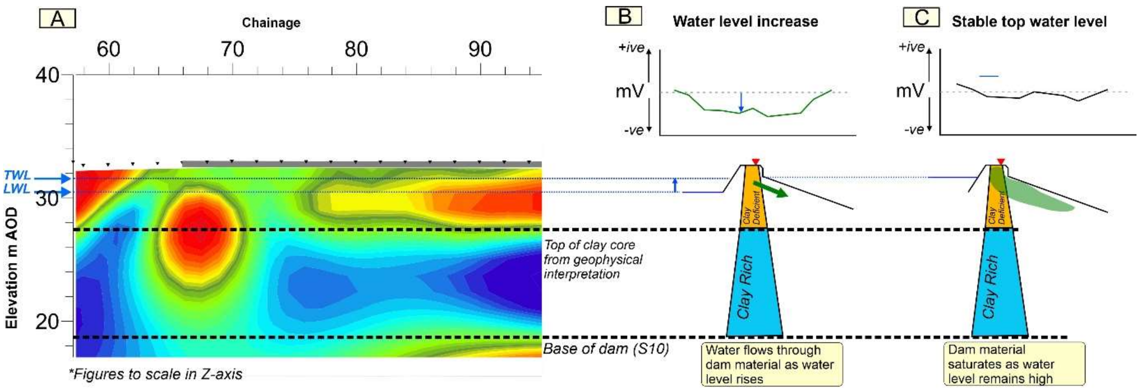

Figure 6. Summary conceptual model of water flow into Oakenholt dam. **A)** ERT profile over area of leakage, with top water (TWL) and low water level (LWL, the level when the SP monitoring array was installed) shown**. B)** Schematic of water moving through material under the SP monitoring array as water level is raised (green arrow). **C)** Material becoming saturated after prolonged period.

Geophysical monitoring systems provide methods of measuring and monitoring the SP field, which is interpreted to describe areas of water flow. In this instance, it provides a valuable surveillance technique making nearly 29,000 measurements over a 14-month surveying period. This study demonstrates that SP monitoring is an effective tool which engineers and reservoir Undertakers can deploy to provide objective long-term monitoring of seepage/ leakage through embankment dams, in common situations where the symptoms of such mechanisms cannot be viewed through routine surveillance or traditional flow measurement techniques. It is widely applicable to embankment reservoirs as it is minimally invasive, cost-effective, and expandable.

REFERENCES

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