Observing waterflow within an embankment dam using Self Potential monitoring

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Sustainability of British Dams

ABSTRACT Geophysics has become a fundamental tool for the characterisation of dam structures and the identification of subsurface defects. However, evolving a geophysical technique to a monitoring solution for observing subsurface water flow is considered an important step to help water companies and governing bodies achieve their aims related to climate resilience, water supply targets and for lengthening the design life of critical infrastructure. Here, we show how monitoring of Self-Potential (SP) voltages using the SPiVolt system developed by TerraDat has successfully mapped water flow through the downstream shoulder of a Victorian-era embankment dam, and how these water flow paths responded to changes reservoir level and weather events such as heatwaves and rainfall. The study has also shown the importance of using a multi-technique geophysical survey to provide a wider context and deeper understanding of dam structures.

The methodology described in this paper has the potential to not only provide a low-cost solution to monitoring embankment dams but can also be applied to numerous scenarios including landslide investigations, peatlands and flood defences.

Keywords:
Dams, barrages & reservoirs,
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Site investigation

INTRODUCTION

Geophysics has become a fundamental tool for the characterisation of dam structures and the identification of subsurface defects. The results from geophysical surveys are integral to the design of effective intrusive investigations or remediation strategies. They are inherently minimally invasive, cost-effective and have a high spatial resolution; Hamlyn and Bird (2021) discuss how the correct use of geophysics can answer common quandaries facing dam engineers. However, while comprehensive geophysical surveys can reveal the condition of the subsurface at a fixed moment in time, they cannot observe the temporal evolution of features.

Evolving a geophysical technique toward a monitoring solution to observe subsurface water flow is an important step to help water companies and governing bodies achieve their aims related to climate resilience, water supply targets and for lengthening the design life of critical infrastructure. The Self-Potential (SP) method is the only geophysical technique which directly observes subsurface water flow. Data can be acquired quickly, with minimal and environmentally sensitive equipment. Therefore, it is of critical importance to transform this method into a tool for observing subsurface water flow. SPiVolt is a semi-permanent monitoring system which continuously measures SP to achieve this. In this paper, we describe how a three-dimensional array of electrodes successfully mapped water flow through the downstream shoulder of an embankment dam and how these water flow paths respond to reservoir level and weather events such as heatwaves and rainfall. In doing so we ultimately answer two important questions:

- Is there anomalous water flow through the dam core?
- Where is the observed anomalous seepage originating from?

WHAT IS SELF POTENTIAL AND HOW IS IT MEASURED

SP surveys measure the naturally occurring subsurface electric potential (in volts) between two non-polarising electrodes; a reference electrode and a measurement electrode. The reference electrode is located in a remote and 'electrically quiet' environment, and the measurement electrode is situated within the area of interest. The voltage measurement across the two electrodes is taken to be representative of the naturally-occurring electrical potential at the measurement electrode. SPiVolt utilises an array of semi-permanent measurement electrodes positioned across the area of interest, automatically acquiring readings at a specified frequency.

The voltage measured ($\mathrm{SP}_{\mathrm{Measured}}$) is a relative value between the measurement and reference electrodes. The value recorded is a summation of voltages generated by subsurface water flow (known as the 'Streaming Potential', $\boldsymbol{SP_{Stream}}$) and other processes such as temperature changes, atmospheric effects and the geology/geochemistry of the subsurface, which can be summarised as a noise term (SP_{Noise}):

$$\mathrm{SP}_{\mathrm{Measured}} = \mathbf{SP}_{\mathbf{Stream}} + \int \mathrm{SP}_{\mathrm{Noise}}$$

SPiVolt proprietary filters and algorithms remove the effects of time-varying contributions to SP_{Noise} and by differencing SP measurements in time or space SP_{Noise} can be removed entirely from the measurement allowing for direct observation of groundwater flow (SP_{Stream}). Self-potential measurements are the only geophysical means of measuring groundwater flow directly.

CASE STUDY

Anomalous seepage into the outflow tunnel that runs through a Victorian-era embankment dam was noted in a recent Section 10 inspection report. As a result, TerraDat UK Ltd was tasked to investigate the preferential seepage pathways within the dam. Given the objective, TerraDat designed an integrated geophysical survey to derive a holistic understanding of the dam structure before installing a SPiVolt array to identify water flow paths and the response to changing conditions such as reservoir level and weather events.

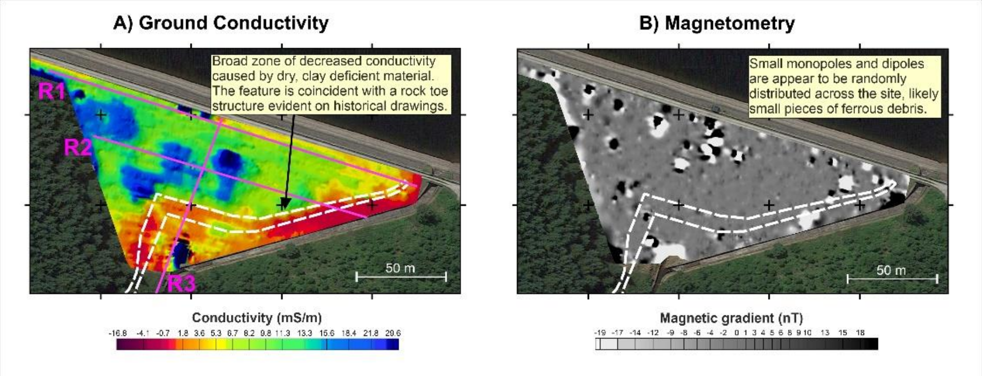
The subject dam is an approximately 400m long, earth-fill embankment with a puddle clay core extending across a glacial corrie. The dam is approximately 20 m high with respect to the downstream toe. The downstream embankment is grassed with large hummocks in some areas. The slope of the embankment is steep and irregular, with topographic highs in the east and west, creating a subtle 'amphitheatre' shape.

Pre-Installation survey

The objectives of the pre-installation survey were:

- To characterise the embankment materials and underlying geology.
- To locate possible preferential seepage pathways causing the observed seepage.

To provide this information, electromagnetic ground conductivity (EM), magnetometry, Electrical Resistivity Tomography (ERT) and Induced Polarisation (IP) surveys were conducted. Subsets of the results are shown in Figures 1 and 2.



Broad zone of decreased conductivity caused by dry, clay deficient material. The feature is coincident with a rock toe structure evident on historical drawings.

Small monopoles and dipoles are appear to be randomly distributed across the site, likely small pieces of ferrous debris.

Figure 1. A) Electromagnetic ground conductivity results. B) Magnetometry survey results across the downstream shoulder of the dam. The white dashed lines outline the location of a rubblestone toe structure built into the dam.

The embankment generally exhibits ground conductivity values of between 5 and 11 mS/m (Figure 1A), which correlate with clay deficient engineering materials and shallow clay-rich geological materials consistent with geological mapping and historical cross-sections. Across the southern and eastern sides of the embankment, the dam is characterised by lower conductivity (red), suggesting the ground is drier and/or clay deficient. This zone is consistent with the location of the rock toe structure indicated by the historical drawings. Higher conductivity material on the western side of the embankment is caused by either an increase in clay content within the shallow subsurface or an increase in moisture content. Data collected close to metallic surface infrastructure (e.g., metal fences and pipes) has caused instrument overload (extreme high and low values).

The magnetic survey was primarily conducted to advise on the location of any buried ferrous material, utilities or structures across the dam, as these features would affect the SPiVolt monitoring array data. Numerous small monopoles and dipoles are randomly distributed across the site (Figure 1B). These are likely small ferrous debris unrelated to remnant structures.

The ERT data are shown in Figure 2, and the positions of the ERT lines on the dam crest are shown in Figure 1A (R1 to R3). Shallow, low resistivity values which thin down the embankment delineate material with a high clay content and are thought to represent the engineered fines which abut the dam core. Further away from the crest, this material is likely to indicate the superficial boulder clay. Due to the geo-electrically non-unique nature of these two materials, it is not possible to differentiate between the engineered and natural superficial material. Increased resistivity values that extend to depth are thought to indicate bedrock geology. These values tend to be heterogeneous across the survey area due to variations in the clay content within the interbedded bedrock. Variations in moisture content may cause the more localised changes in resistivity.

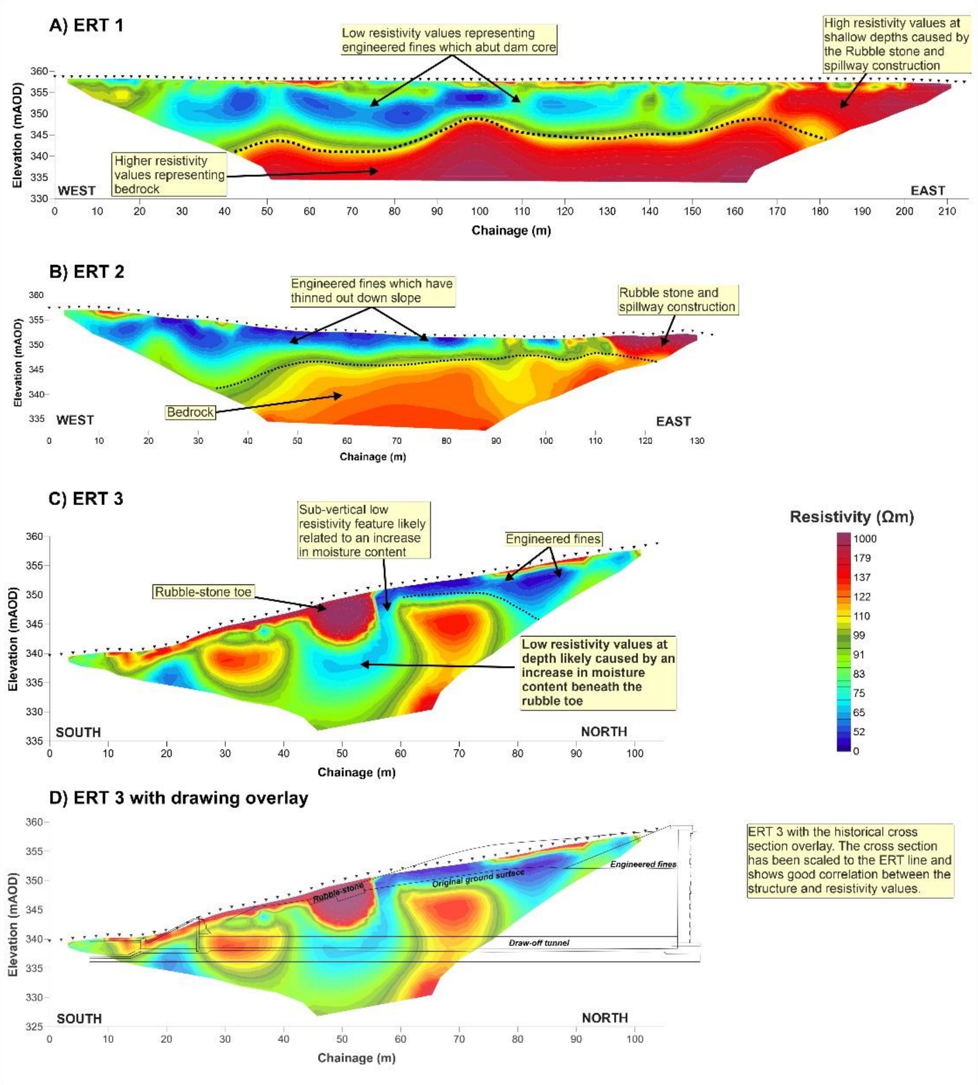


Figure 2. Electrical Resistivity Tomography (ERT) results. See Figure 1A for a map of profile positions.

ERT 1 (Figure 2A) is positioned ~3 m downstream of the dam crest, parallel to the dam core. The bedrock and overlying engineered material is well defined; however, shallow, high resistivity values dominate the section between 0 m and 45 m chainage; this is likely granular material related to the rubblestone toe and construction of the spillway.

ERT 2 (Figure 2B) is positioned ~30 m down the embankment, parallel to the core. Shallow engineered fines are characterised by low resistivity values, which extend to a depth of ~345 m AOD. This layer is thinner here than observed closer to the crest. There are very shallow lenses of highly resistive material at the surface. The resistive values at depth are more heterogeneous than observed along ERT1; this may be related to variations in clay content due to the interbedded nature of the bedrock geology.

ERT 3 (Figure 2C) is located perpendicular to the dam extending from the crest past the northern toe of the embankment. At the southern end of the profile, from 60 m to 100 m chainage, engineered fines can be observed above 345 m AOD. At ~55 m chainage, a sub-vertical, low resistivity feature extending from the surface is observable. Beneath the rock toe, the resistivity values are anomalously low where bedrock is expected. A scaled schematic of the historical cross section shows a good fit between the resistivity values and the dam structure (Figure 2C). Normalised conductivity calculated from the corresponding IP data, shows that the anomalously low resistivity values are caused by an increased water content rather than an increased clay content.

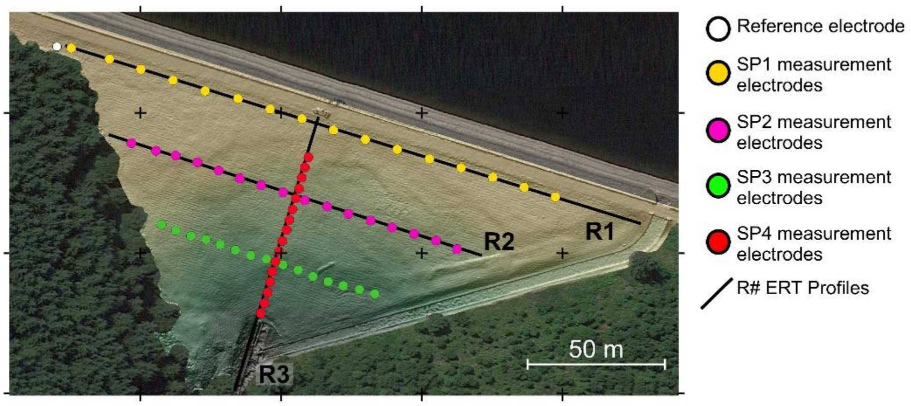
Multi-disciplined Geophysics Summary

The ground conductivity and ERT surveys have delineated both shallow and deep zones of increased clay and moisture content, as well as the location of the rubblestone toe. The ERT profiles appear to show a potential leakage pathway which extends from the surface to depth beneath the rubblestone toe structure. In conjunction with the normalised chargeability, the ERT data suggest moisture 'ponding' beneath the rubblestone toe structure. It is hypothesised that the seepages observed within the tunnel are attributed to the ingress of surface waters higher up the embankment upstream of the rubble toe, ponding beneath it, before leaking through the tunnel wall.

SPiVolt Monitoring Results

As previously mentioned, the SP technique is the only geophysical method which is directly affected by the subsurface movement of water. The SPiVolt system continuously measures the SP field to identify leaks and observe how they respond to time-varying factors such as reservoir level and rainfall events, in this case, this information was supplied by the Client.

The SPiVolt installation comprised 64 electrodes arranged as four profiles (SP1 to SP4) across the downstream shoulder of the dam (Figure 3A). The electrodes were installed by hand, 30 cm deep across the area of interest. Figure 3B and Figure 3C show the system during and after installation (at a separate study site). Data were collected near-continuously at 17-minute intervals and uploaded to a server every hour. The electrodes used on the site are thought to last for a year of monitoring and can be removed after use, however for more permanent arrays an alternative electrode design can be used.


A) SPiVolt Electrode Locations


B) SPiVolt Installation

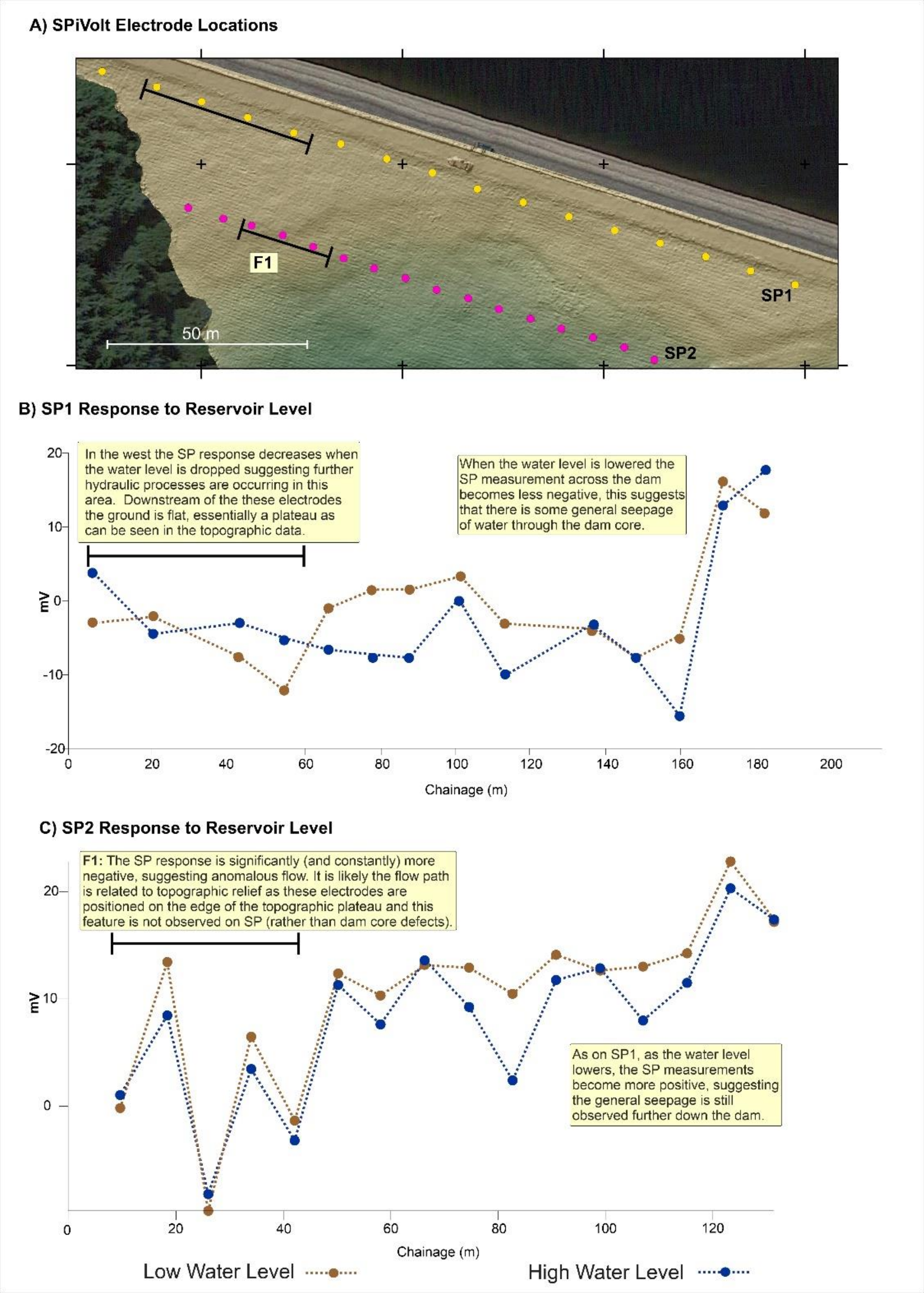
C) Fully Installed SPiVolt system

Figure 3. A) Location of SPiVolt electrodes on the case study site. B) An example of the SPiVolt system mid-installation (at a different site). C) An example of the ground conditions following the installation (at a different site). SP1 to SP4 refer to four SPiVolt measurement profiles.

The results of the SPiVolt survey are discussed in relation to the survey objectives.

Is there anomalous water flow through the crest?

Anomalous water flow through the dam crest will appear as localised zones of significantly negative SP response along SP 1 and SP 2 during periods when the reservoir level is high. When the reservoir level is high, shallow flow pathways within the dam crest may be initiated and/or, the increased hydraulic head will force water through any defects in the core.


A) SPiVolt Electrode Locations

B) SP1 Response to Reservoir Level

In the west the SP response decreases when the water level is dropped suggesting further hydraulic processes are occurring in this area. Downstream of the these electrodes the ground is flat, essentially a plateau as can be seen in the topographic data.

When the water level is lowered the SP measurement across the dam becomes less negative, this suggests that there is some general seepage of water through the dam core.

C) SP2 Response to Reservoir Level

F1: The SP response is significantly (and constantly) more negative, suggesting anomalous flow. It is likely the flow path is related to topographic relief as these electrodes are positioned on the edge of the topographic plateau and this feature is not observed on SP (rather than dam core defects).

As on SP1, as the water level lowers, the SP measurements become more positive, suggesting the general seepage is still observed further down the dam.

Figure 4. A) Electrode locations of SP1 and SP2 shown in yellow and blue, respectively. B) SP1 response to changing reservoir level. C) SP2 response to changing reservoir level.

Figure 4 shows the SP measurements along SP1 and SP2 during two periods; when the water level within the reservoir was high (between the 28th of March and the 1st of April 2022), and when it was low (15th to the 17th of June 2022). These time periods also coincided with dry weather, negating the possible additional effects of rainfall (see figure 5A).

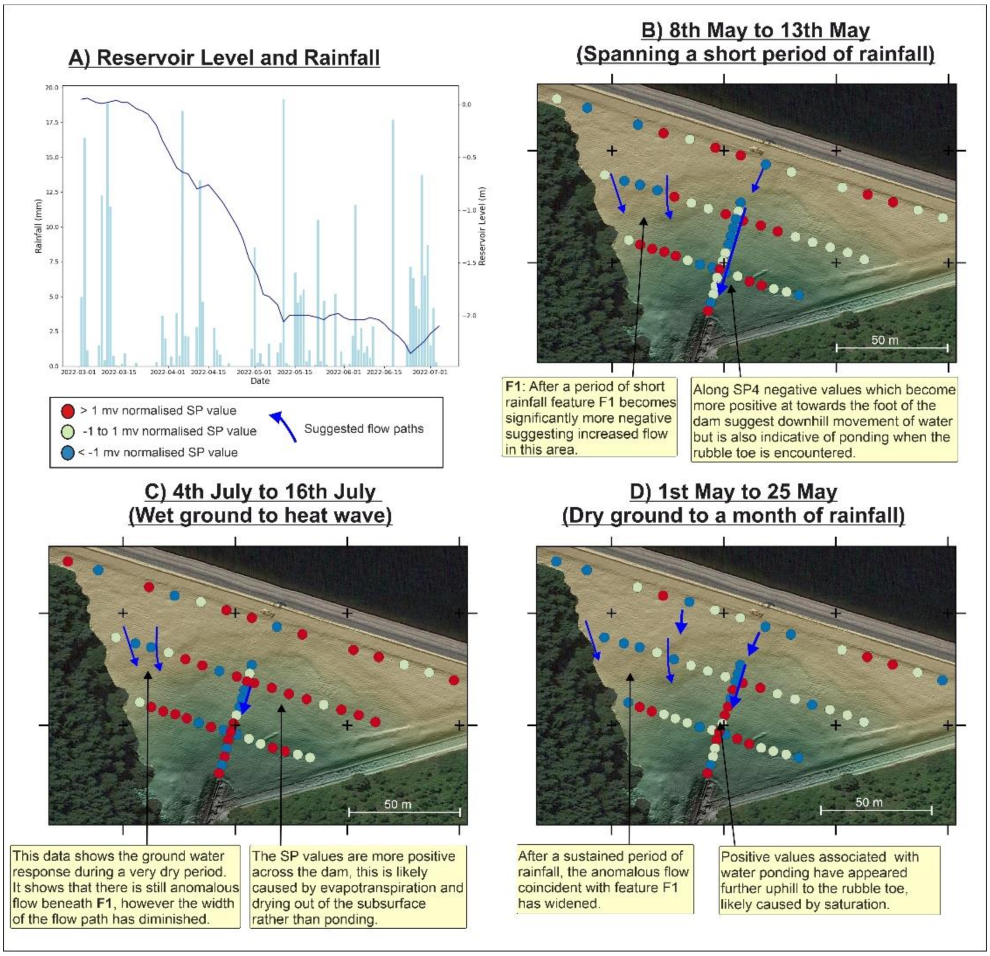
Figures 4B and C indicate that as the reservoir's water level is lowered, the SP response across the dam crest becomes more positive. Therefore, it is highly likely that a general seepage occurs through the core that ceases when the water level is dropped. Historical drawings of Victorian-era embankment dams often label the core to comprise 'puddle' clay with profiled engineered fines to create the downstream shoulder. However, the puddle clay core is likely to be composed of the most clay-rich material that can be found close to the dam, rather than a material of a given specification. Given that the dam is over 100 years old (construction contracts and tenders suggest work began in 1906), and that a pure puddle clay core seems unlikely, it is probable that some amount of seepage across the dam core is likely and this is observed by the SPiVolt survey.

The SP response does not correlate with the reservoir level at the western end of SP1, between 155 and 210 m chainage, suggesting a different mechanism controlling the SP response in this area. The electrodes here are situated on a plateau where the topography is unusually flat allowing the area to act more of a water store. Therefore, the groundwater flow is more likely to be related to rainfall, despite trying to negate the effects of the rainfall with the analysis. At the western end of SP2, from a chainage of 90 m, the measurements are significantly (and constantly) more negative than along the rest of the profile (**F1**). These electrodes are directly downstream of the topographic plateau and suggest a zone of drainage from the plateau, rather than a flow path through the dam core, as this feature is not observed on SP1.

Does SPiVolt data observe anomalous water flow into the rubble toe?

Based on the pre-installation geophysical survey and observations by the Client, it was hypothesised that the seepages observed within the tunnel are attributed to surface waters higher up the embankment infiltrating the embankment at the rubble toe and ponding beneath it before leaking into the tunnel below at a constant rate.

The difference between SP measurements following dry and wet periods needs to be analysed to observe water flow pathways related to rainfall. Given that the reservoir level significantly contributes to the measured values, analysis was restricted to after the 1st of May 2022 when the reservoir level was consistently low. The rainfall and reservoir levels supplied by the Client are shown in Figure 5A.


A) Reservoir Level and Rainfall

B) 8th May to 13th May
(Spanning a short period of rainfall)

C) 4th July to 16th July
(Wet ground to heat wave)

D) 1st May to 25 May
(Dry ground to a month of rainfall)

F1: After a period of short rainfall feature F1 becomes significantly more negative suggesting increased flow in this area.

Along SP4 negative values which become more positive at towards the foot of the dam suggest downhill movement of water but is also indicative of ponding when the rubble toe is encountered.

This data shows the ground water response during a very dry period. It shows that there is still anomalous flow beneath **F1**, however the width of the flow path has diminished.

The SP values are more positive across the dam, this is likely caused by evapotranspiration and drying out of the subsurface rather than ponding.

After a sustained period of rainfall, the anomalous flow coincident with feature F1 has widened.

Positive values associated with water ponding have appeared further uphill to the rubble toe, likely caused by saturation.

Figure 5B to 5D present maps of normalised SP response following dry and wet periods. Electrodes which record normalised negative values (shown in blue) indicate localised increased water flow, electrodes that record positive values (shown in red) indicate water ponding or drying of the subsurface, electrodes with values around 0 (+/- 1 mV) suggest no significant localised effects from rainwater. Suggested flow paths are indicated by blue arrows.

Figure 5B shows the response of the SP array following four days of rainfall (13th of May) after an initial dry period (8th of May). On the east side of the embankment, the electrodes positioned down-slope of the plateau record more negative values. It is likely that following rainfall, subsurface water moves through this zone. This area was suggested as a flow path previously (**F1**). On the east side of the embankment, there are no zones of anomalous water flow. The electrodes along SP4 show negative values, becoming positive downslope which suggests the downhill movement of water (as to be expected) but also some ponding at the rubble toe.

Figure 5C shows the SP response during a hot and dry period which was followed by a heatwave. These data were acquired between the 4th of July and the 16th of July. The rainfall and reservoir level data for this period are not available; however, a local weather station records almost no rainfall during this time. The plot shows the SP response to the drying dam. Feature **F1** appears to remain an active flow path; however, the flow has become narrower. SP 4 still displays negative values, becoming positive downslope which suggests the downhill movement of water and ponding within the rubble toe. Across the dam, the SP values are generally more positive and are likely caused by evapotranspiration and 'drying out' rather than water ponding.

Figure 5D shows the SP response following ~3 weeks of sustained rainfall during May. The anomalous groundwater flow associated with feature **F1** has become wider. The positive values along SP4 have moved further upslope, possibly caused by water saturation immediately uphill of the rubble toe.

CONCLUSIONS

The SPiVolt system has directly mapped water flow through the subsurface at the dam and observed changes to the flow regime caused by changing the reservoir level and in response to weather events. By using a monitoring approach, we were able to observe changes that were only caused by variation in ground water flow. The SP method also allows for the determination of discharge volumes or seepage velocities if information on the porosity, saturation or hydraulic conductivity is measured or approximated (for example Bolève et al., 2009 and Rozycki , 2009). SP data can also be inverted for source depth using well established software such as SP2Dinv (Souied Ahmed et al. 2013) or ZondSP2D.

The pre-installation geophysics has provided a holistic understanding of the dam structure and allows us to understand how water can move through it. ERT, electromagnetic ground conductivity (both used on this dam), and traditional leak detection (Direct Current leak detection, and Controlled Source Audio-Frequency Domain Magnetics), all rely on the identification of conductive zones to infer areas of moisture and therefore the presence of subsurface water. Here, we have shown that the varying clay content in Victorian-era embankments can manifest as isolated conductive zones and be identified by these techniques; however, these conductive zones are not necessarily related to subsurface water content. The magnetometry results also define conductive zones related to ferrous material associated with services, dam infrastructure or metallic debris. We have shown it is of critical importance that complimentary geophysical methods are employed in detecting and mapping leaks in reservoir dams with confidence. We have demonstrated the ability of the SPiVolt system to map subsurface waterflow patterns and their changes over time. The pre-installation multi-technique geophysical surveys have provided the wider site context that was integral to this success.

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