Investigating seepage at the Bartley dam, UK

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A method to detect seepage paths based on magnetometric resistivity has recently been applied at a dam in the UK. The authors describe the technology, and the survey carried out at Bartley dam which demonstrated the effectiveness of the method.

The Willowstick® methodology which will be described here (referred to as the 'methodology' or the 'method') evolved from magnetometric resistivity [Edwards and Nabighian, 1991[1]] and is specifically designed to map preferential seepage pathways and zones of highest transport porosity [Jessop *et al*., 2014[2]]. It is a quick way to identify, map and model preferential seepage flow paths. Like an angiogram, which enables medical personnel to 'see' flow paths of blood inside the human body, the method is able to render quickly either 2D or 3D maps and models of seepage flow paths.

The methodology works by establishing a signature electric circuit within the groundwater of interest [Kofoed *et al*, 2012[3]]; the distribution and flow of subsurface electric current is then revealed by measuring the signature magnetic field (Biot-Savart law). Measured data are processed and compared with the predicted magnetic field from a theoretical homogeneous earth model to highlight the deviations from the 'uniform' model. Finally, 2D maps and 3D models are generated and interpreted in conjunction with other hydrogeological data to provide enhanced definition of preferential seepage flow paths. Fig. 1 presents a survey layout designed to investigate seepage through Bartley dam, owned by Severn Trent Water of Warwick, UK.

1. The method

As shown in Fig. 1, to investigate a leaking dam, for example, the methodology makes use of strategically placed electrodes upstream and downstream of the dam. The upstream electrode is placed in the reservoir water. The downstream electrode is typically placed in a seepage zone, observation well, or seepage collection system such as a toe drain, to facilitate contact with water seeping through the dam. The circuit wire connecting the electrodes is positioned in a large loop around the study area to minimize interference from the electric current flow in the wire.

Because magnetic field measurements can only be obtained on the earth's surface, it is a challenge to identify the depth of preferential electric current flow. For this reason, the data are subjected to an inversion algorithm (mathematical model) designed to predict the electric current distribution in three dimensions through the subsurface study area. The inversion model is referred to as an electric current distribution (ECD) model. Fig. 2 presents a slice through the ECD model, 20 m below the dam's crest.

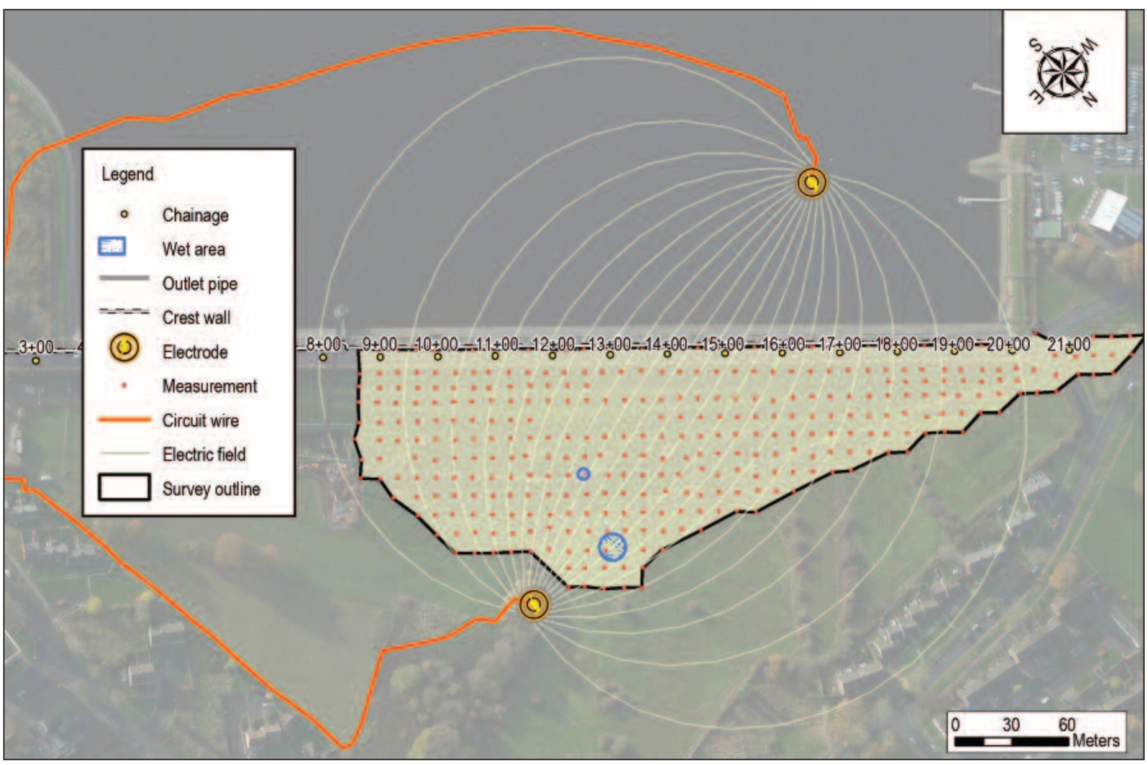

Fig. 1. Survey layout to investigate seepage at Bartley dam.

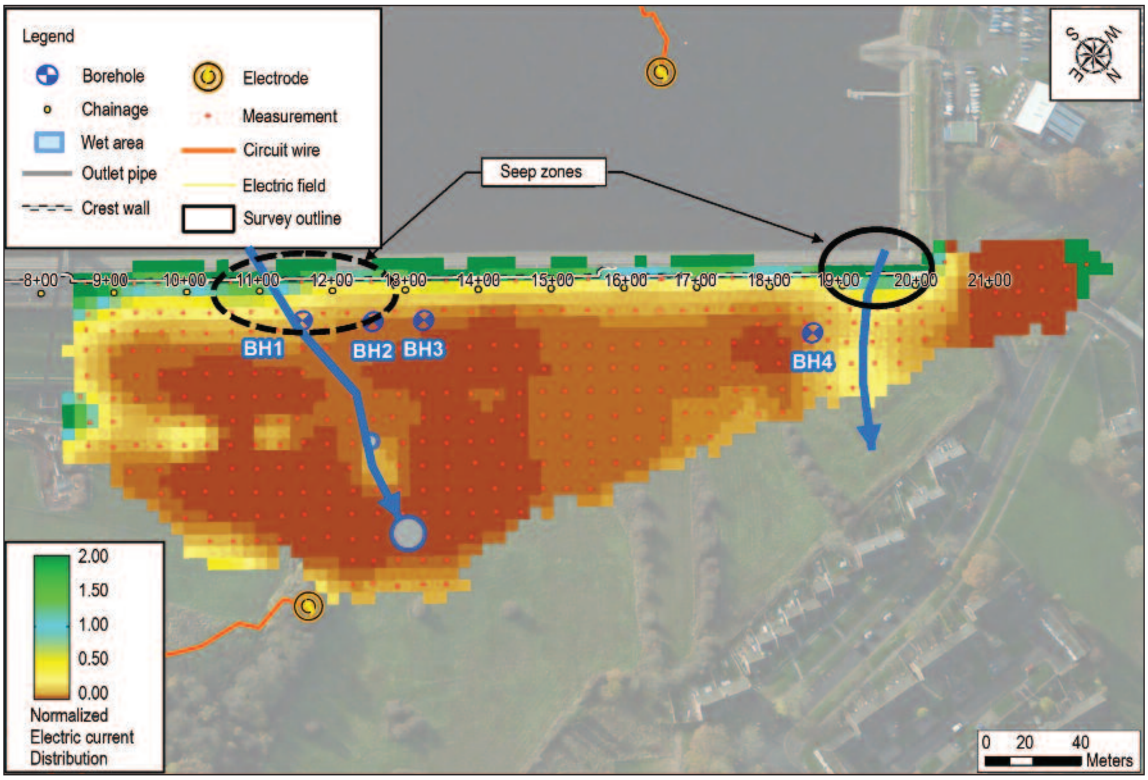

Fig. 2. Electric current distribution model elevation slice with interpreted seep zones and flow paths. BH1 – BH4 are four boreholes drilled by the dam owner that independently verified the findings of the investigation when drillers encountered a layer of fractured sandstone about 20 m below the crest of the dam.

2. The Bartley dam case study

In the case study example, two preferential seepage paths were identified. Severn Trent Water then drilled four boreholes within or near the seep zones. At a depth of about 20 m in BH1, BH2, and BH4, drilling fluid was lost in a 6 m-thick highly fractured sandstone layer. Drilling fluid also appeared downstream in the drainage system within about 10 min. Drilling fluid was not lost in BH3, which was drilled furthest away from the interpreted seep path. For the owner, the appearance of drilling fluid downstream gave them confidence in the results of the investigation. As with most embankments, the fill materials are successfully engineered to prevent seepage paths developing. The foundation, however, can be much more difficult to predict because fractures, faults, weathered layers and other permeable zones may not be readily apparent during construction. In this example, the preferential seepage path beneath the dam was not fully characterized without the aid of a geophysical survey.

The methodology differs from traditional resistivity and other electromagnetic (EM) methods in many ways. First, it capitalizes on the fact that the water content is a dominant factor in enhancing the electrical conductivity of subsurface soils and rocks. Second, by directly energizing a conductive groundwater medium, the electric current can more effectively 'illuminate' the target of interest with fewer encumbrances from overlying earthen materials. The methodology measures the magnetic field produced by the electric current to track patterns that help to characterize preferential groundwater paths; thus it requires no direct contact or galvanic measurement as traditional resistivity generally does [Kofoed *et al.*, 2011[4]]. Because the methodology operates at a low frequency and measures a magnetic field emanating from conductors that are directly energized, there is the potential to characterize groundwater at significant depths.

Like EM and resistivity methods, the methodology highlights conductive and resistive zones and works best in environments where the degree of water saturation varies (between dry and highly saturated areas). However, the method also works well within a completely saturated environment. When electrical conduction occurs primarily in open pore space of a saturated matrix, a positive slope correlation exists between electrical and hydraulic conductivities, meaning that hydraulic conductivity can be tracked along the higher electrical conductivity zones [Wong *et al*, 1984[5]]. When electrical conduction occurs primarily along pore surfaces, such as in wet clay, the positive correlation may disappear and can in fact become a negative correlation [Purvance and Andricevic, 2000[6]]. In each environment, the method provides valuable information by highlighting the edges of zones with a marked change in effective porosity, thus revealing where groundwater preferentially flows and where it does not.

To illustrate the point better, consider water flowing around a large boulder in a river (Fig. 3, left). Even if the boulder itself cannot be observed directly, its shape and location will still be revealed by the pattern and direction of water flow around it. Electric current density in a volume behaves in much the same way. If one considers the opposite case, where a large conductive body attracts the electric current flow to itself, the analogy would be more like that of water rushing by a submerged drain, which attracts the water towards it (Fig. 3, right). Here the anomalous gradient in the water surface would reveal the drain's location, just like an electric current density increase within a conductive body would reveal its location.

3. Conclusion

Severn Trent Water's Dams and Reservoirs Manager, Ian Hope, said the following with regard to the Willowstick survey:

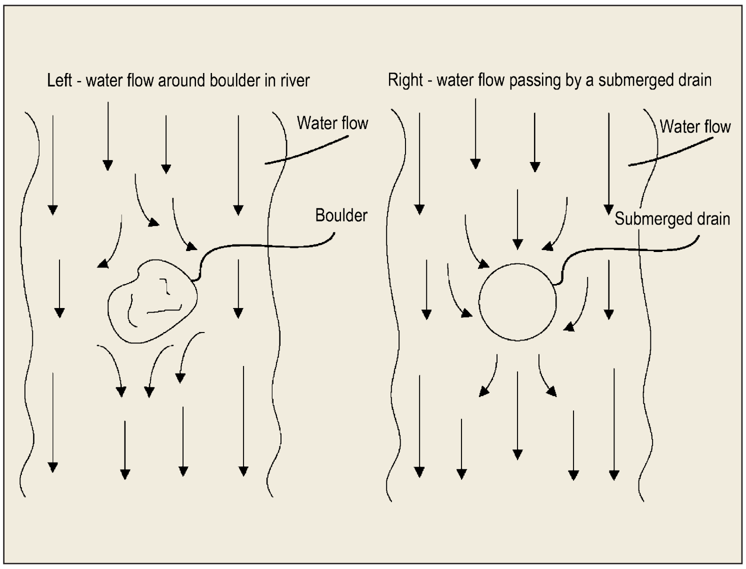

Fig. 3. (left) Water flows around a boulder; and (right) water flows past a submerged drain.

"We had a long established leak beneath Bartley reservoir and sought to locate it with a view to considering options for leak reduction/sealing. We commissioned a Willowstick survey through Atkins, which potentially identified the precise location of two seepage paths. Following expert deliberation and project approval, on the strength of the survey results we drilled four boreholes to prove the location of the seepage paths. The drilling was immediately followed up with trial pressure grouting. I am encouraged to report that the Willowstick survey was sufficiently accurate to track the seepage paths and would have no hesitation in recommending this methodology for similar applications."

The comments above demonstrate that the methodology tracks seepage pathways through dams, and the results derived from the methodology were accurate enough to be independently verified at Bartley dam. In conclusion, proper application of the methodology combined with other sample/test data will generally result in a more cost-effective and accurate characterization of seepage. The methodology is viewed as a means to guide and direct traditional exploratory work, such as drilling campaigns, to improve seepage characterization efficiencies (cost and time) and to arrive at conclusive answers about specific seepage issues. ◊

References

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