

Seepage Diagnosis of Earthen Embankments with Controlled Source Audio Frequency Domain Magnetism (CS-AFD-M)

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Summary

This paper examines both the theoretical basis and the practical implications of a minimally invasive groundwater mapping method as applied to seepage detection in earthen embankments. The method involves inducing a low voltage, low amperage, low frequency audio electrical current into the groundwater system. This electric current naturally gathers in areas of highest conductivity—which include high porosity regions within the saturated zone. Per the Biot-Savart law—which relates magnetic fields to their source electric currents—the technology can reveal vital information about the location, character and preferential flow paths of the groundwater system through which it is passing. When properly captured, measured, filtered, and reduced, the data derived from that magnetic field can be used to create both two-dimensional maps and three-dimensional models of the subsurface electric current distribution some of which can be interpreted as seepage flowpaths. This method can be applied to a host of seepage related issues, especially tracking and pinpointing the leak locations in a dam's embankment, abutments, foundation or outlet works. This paper will convey the findings of one case study in which the efficacy of this method has been demonstrated on a seepage issue.

Introduction

Torside Reservoir is the second of five reservoirs in the east-west trending Longendale Valley that supplies water to Manchester, UK (Kofoed et al., 2008). Upon filling the dam in 1851, it initially stretched on its base and ruptured drawoff pipes set in the foundation. The northern abutment lies on very porous, fractured rock that conducts groundwater from the northern hills to the valley center. Barriers and drains (Figure 1) were installed to collect and convey groundwater away from the dam and keep reservoir water from seeping into the rock. To channel groundwater away from the dam, a tunnel with drawoff pipes was installed through the bedrock and connected to a rubble trench through an adit and box drain. To keep water from leaving the reservoir, the rock was grouted and a clay liner was placed above the bedrock and connected to the dam's clay core. Also a puddle-clay filled arm trench was constructed as a barrier to groundwater entering the reservoir collection system. In 2004, engineers monitoring the dam noticed that discharge from drawoff pipes had increased significantly, so United Utilities went looking for a groundwater mapping tool to delineate seepage from the reservoir.

In December 2005, two Controlled Source Audio Frequency Domain Magnetism (CS-AFDM) or AquaTrack™ surveys were performed at Torside reservoir. These two surveys did a good job proving that the embankment was intact and that most seepage was related to the drawoff pipes underneath the reservoir. However, the surveys did not cover enough area to fully delineate the sources of water flowing into the drawoff pipes, and a new, more extensive survey was proposed and performed while the reservoir water was low. It is the results this latter survey performed in December 2006 that will be described in this paper.

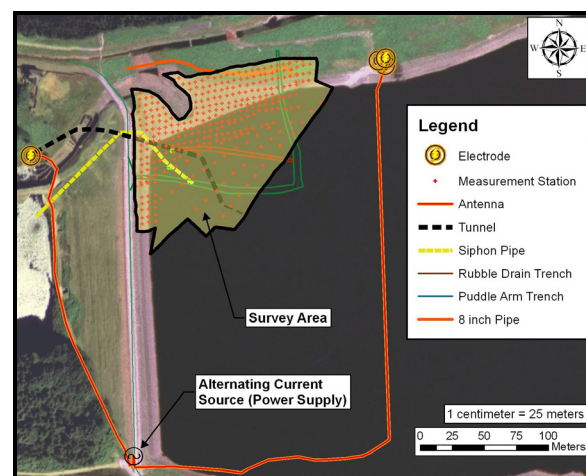


Figure 1: Survey layout and map of Torside Reservoir's subsurface cultural features

Methodology and Instrumentation

CS-AFDM utilizes a low voltage, low amperage audio frequency electrical current to energize the groundwater of interest. Electrodes are placed in strategic locations to facilitate contact with the groundwater of interest. Following the best available conductor, the electrical current concentrates in high porosity zones within the saturated subsurface. As the electrical current takes various paths through the subsurface area of investigation, it induces a magnetic field (Biot-Savart law) characteristic of the injected electrical current. This unique magnetic field is identified and surveyed from the earth's surface using highly sensitive equipment. The measured magnetic field data is then processed, contoured, modeled and interpreted in conjunction with other hydrogeologic data, resulting in enhanced seepage flowpath definition.

Seepage Diagnosis of Earthen Embankments

A portable instrument mounted on a surveyor's pole has been designed to measure the magnetic field. The principle instrument components are the receiver, GPS and handheld computer. The receiver consists of three high inductance coils, receiver electronics and a datalogger. The three coils, which measure the time derivative of the magnetic field, are oriented orthogonally in the X, Y, and Z directions. Signals from the coils are amplified, filtered and digitized by the datalogger. The datalogger calculates spectra and stacks to attenuate incoherent noise like spherics. An intelligent algorithm calculates the signal-to-noise ratio and will stack more or less data to improve the measurement precision. Measurements take between 3 to 5 minutes to complete depending on the signal-to-noise ratio. Data is then sent to a handheld computer where it is merged with GPS data. At present, the magnitude of the three orthogonal magnetic field vectors is measured, but planned improvements to the instrumentation and software will allow for determining the magnetic field's vector direction.

Survey Design

In an effort to find the source of water flowing through the drawoff pipes at Torside reservoir, a new horizontal dipole was set up (Figure 1). The survey consisted of placing the downstream electrode where water discharged from the drawoff pipes. The upstream electrode was placed in wet soils on the hillside north of the reservoir in order to map the paths groundwater took to reach the drawoff pipes. As shown in Figure 1, the antenna wire (orange line) which completes the above-ground part of the electrical circuit is positioned in a large loop around the survey area to minimize interference. A strong magnetic field is generated by electric current flowing through the antenna wire, and generally, very little discernable subsurface information can be obtained near the energizing equipment. Antenna-electrode configurations are designed to allow the greatest amount of electric current to flow through the area of interest while at the same time minimizing the interference from electric current flowing in and out of the electrodes and along the antenna wire. 403 measurement stations were recorded on the dam's upstream face, lake bottom, and in a boat on the reservoir. A tie line was used to stabilize the boat and guide field crew members.

Magnetic Field Contour Map

A footprint map or magnetic field contour map is the main dataset from which subsurface electric current flow is interpreted at a particular site. There are generally three strong influences that affect the subsurface electric current flow: groundwater, culture, and electric current bias.

1. First, CS-AFDM is based on the principle that its signature electrical current is strongly influenced by the presence of groundwater, or areas of higher porosity and permeability where groundwater can accumulate and/or flow.
2. Second, the magnetic field may be influenced by culture, which is any conductive, man-made feature such as pipelines, power lines, or other long continuous conductors. Culture is not always present, but it is often a factor and sometimes very problematic because it tends to be near-surface and can cause large anomalies that mask the subsurface signal.
3. Third, the magnetic field in any given survey is always subject to electrical current bias because 100% of the electric current must concentrate in and out of the electrodes (Kirchoff's conservation of charge in a circuit). The variable part of the circuit—and the interesting part—is what happens to the electric current when it is allowed to choose its own paths to flow between the electrodes.

The shading of the magnetic field contours helps people to see where the magnetic field is relatively high (blue) or low (white); however the shading is only a relative scale of magnetic field strength. To interpret the paths electric current takes through the subsurface, the shapes of the contours must be traced and noted for high magnetic field regions (ridges and mountains on a topographic map) versus low magnetic field (valley's and depressions). On a topographic map, the ridge lines connecting the peaks could be thought of as pathways offering the easiest traverse. In the same way, these lines in the magnetic field maps represent the paths of least resistance for electrical current to follow. By identifying these high points and ridges and connecting them together through the study area, the centroid of preferential electric current flow can be identified.

The CS-AFDM technology uses relative magnetic field contour lines to characterize patterns in electric current flow, in contrast to a topographic map where every contour line is related to a benchmark for standardization (e.g. mean sea level). To achieve standardization for CS-AFDM magnetic field strength would be very difficult due to the highly variable conditions of each survey. The magnetic field contour lines shown in Figure 2 are provided simply for comparison purposes to one another. Nothing more should be construed from the magnetic field contour lines.

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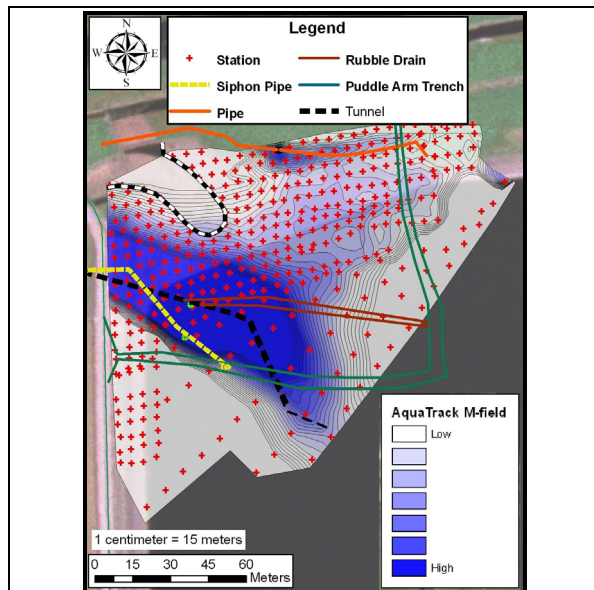


Figure 2: Magnetic field contour map shows current concentrates on cultural features.

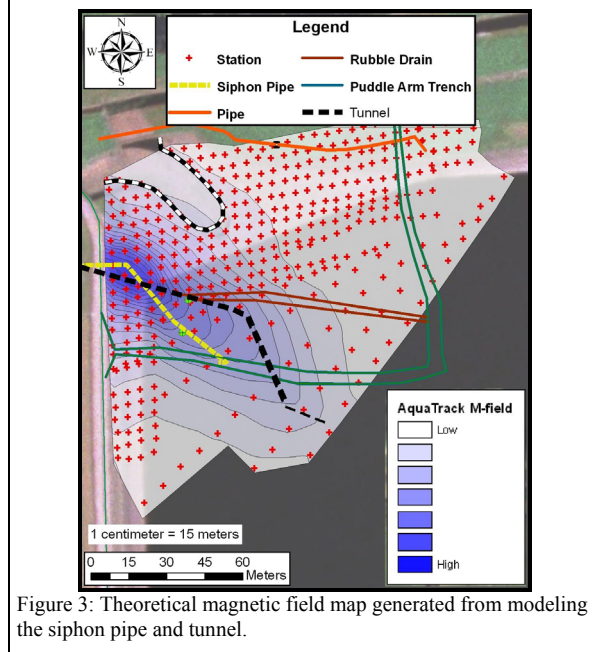


Figure 3: Theoretical magnetic field map generated from modeling the siphon pipe and tunnel.

Modeling

As explained, the magnetic field “footprint” map (Figure 2) is provided to help visualize the horizontal flow of electric current through the study area. However, it is not a simple matter to determine the depth of electric current flow since the magnetic field is measured from the earth’s surface. Electrical current flow (ECF) paths (in this case the siphon pipe and tunnel) were identified from the magnetic field contour map and placed below the topographic surface, representing preferential pathways of electric current flow. The model itself is made up of finite elements representing the center of the more intense ECF pathways. An electric current was simulated in the ECF model to generate a theoretical magnetic field. The theoretical magnetic field is calculated with an algorithm formulated from the Biot-Savart Law. The flow path depth, position and width are modified by a forward modeling or trial-and-error process until the model produces a magnetic field response that best matches the physical data.

The magnetic field contour map (Figure 2) is dominated by the magnetic field emanating from the siphon pipe (yellow dashed line) and drawoff pipes or tunnel (black dashed line). To illuminate the subsurface water pathways, the magnetic field from these two cultural features needed to be modeled and then subtracted from the original data. Figure 3 shows the theoretical magnetic field contours for current flowing along the cultural features. When the theoretical magnetic field is subtracted from the physical magnetic field (Figure 4), two dominant electric current flow paths appear. One flow path emanates from the north (point B) and intersects a region of east-west electric current flow interpreted to be the rubble trench. The rubble drain trench is identified by high magnetic field extending east away from the tunnel. Physically, this feature is designed to be porous and collect water making it an excellent path for the electrical current to follow. The second flowpath starts in the south and crosses the southern puddle arm trench at point C. This flowpath also intersects the interpreted location of the rubble trench. Point B and Point C are identified by the criteria described previously. Both points have the highest magnetic field reading locally and do not appear to be influenced by current bias or cultural effects. In Figure 3, the locations of certain cultural features have been highlighted on the map. Their interpreted location, based on the CS-AFDM data, as well as the location provided by United Utilities is shown for comparison. For example, Point A is the point where water from the rubble drain trench enters the adit because the magnitude of the magnetic field changes slightly (contour shading changes from darkest blue – dark blue).

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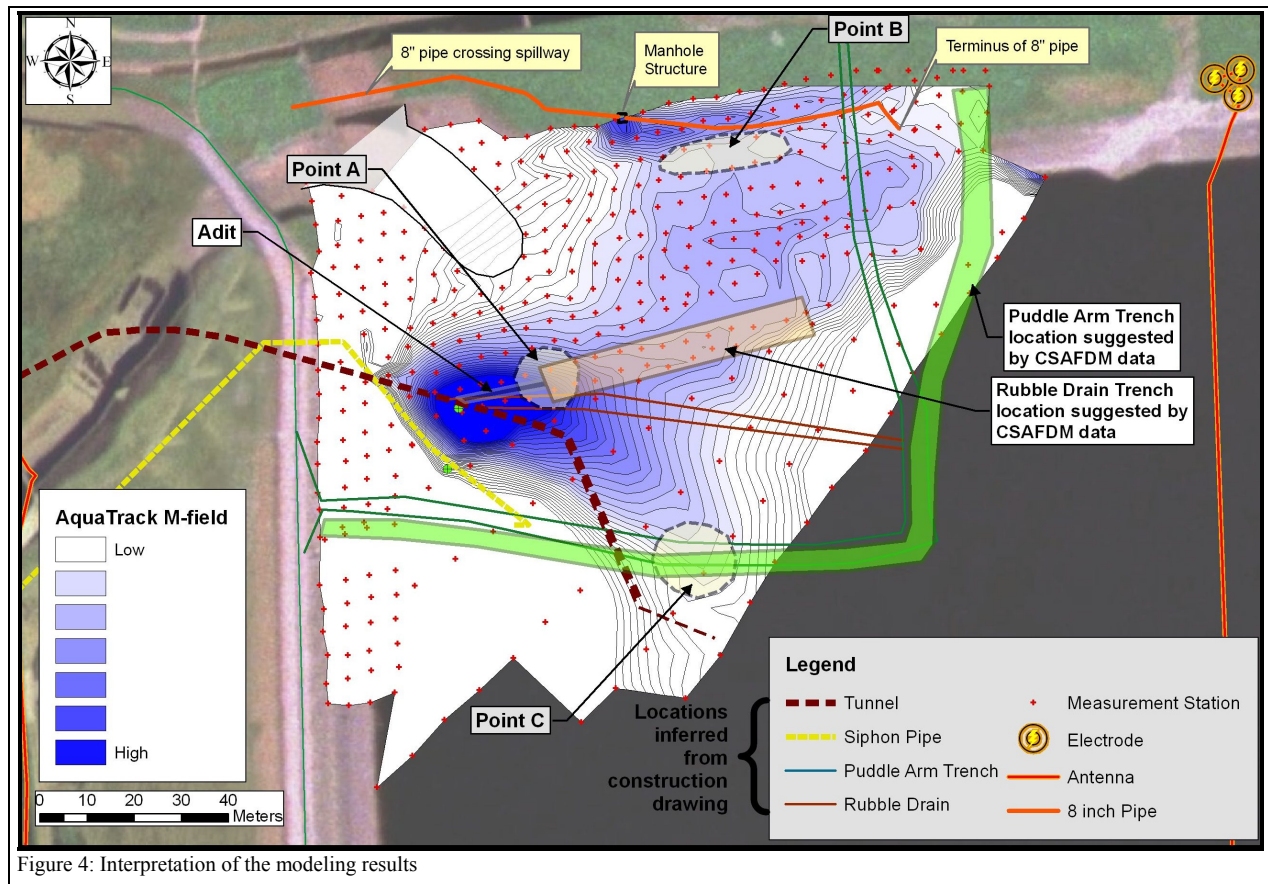


Figure 4: Interpretation of the modeling results

Conclusions

Two distinct sources of seepage into the drawoff pipes were identified and modeled after the magnetic field footprint of the pipes was removed. With this information, United Utilities felt confident to investigate the source of seepage by lowering the reservoir. A sinkhole (Figure 5) was found at point C above the puddle arm trench. The hole was excavated to discover that puddle clay in the arm trench was eroded by groundwater and the sediments on top collapsed compromising the clay liner in this area. The arm trench and clay liner were fixed, and upon filling the reservoir, the volume of water flowing from drawoff pipes was reduced by 75%.

United Utilities, Keith Gardner had this to say about CSAFDM (Kofoed et al., 2008).

The technique is very effective in locating leakage paths below ground and below water. This example of its use showed the technique to be accurate and gave the reservoir owner the assurance that draining the reservoir to the point where there was substantial loss

of yield and disruption to the amenity value of the reservoir was justified, while also giving re-assurance to the owner and the Panel Engineers involved that there was no danger to the embankment itself.

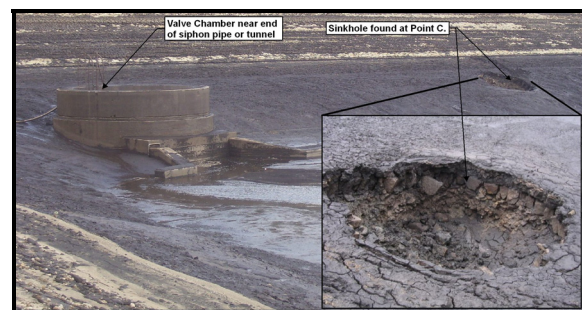


Figure 5: A sinkhole was found after lowering the reservoir.

Acknowledgments

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2009 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Kofoed, V., K. Gardiner, and A. George, 2008, Locating the leakage route at Torside Reservoir using the Willowstick AquaTrack system: Proceedings of the 15th Conference of the British Dam Society, 1–12.