Controlled Source Audio Frequency Domain Magnetics for Seepage Diagnosis of Laurel Bed Dam in Southwest Virginia, USA

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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, audio frequency 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 at Laurel Bed Dam, Virginia, USA.

Introduction

Laurel Bed Dam, Virginia, USA (Figure 1) is owned and operated by the Virginia Department of Game and Inland Fisheries (VDGIF). Seepage is visible at the end of the spillway flowing from drain pipes and cracks in the concrete. There are also wet areas on the dam's face and excessive discharge from the toe drain. Boreholes had identified porous, weathered rock below the spillway as the probable contributor to the seepage problem. After test grouting in front of the spillway failed to cut off the flow of water, Froehling & Robertson Inc., consulting engineers in charge of fixing seepage problems, decided to use Controlled Source Audio Frequency Domain Magnetics (CS-AFD-M) or AquaTrack™ to map and delineate seepage flowpaths through Laurel Bed Dam.

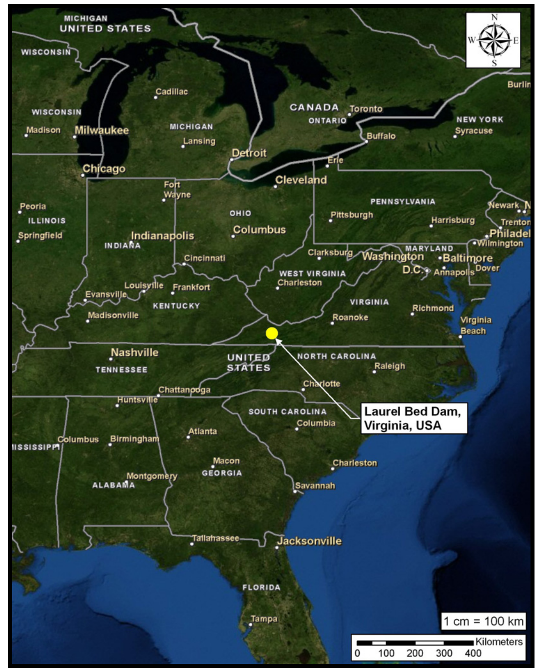

Figure 1: Laurel Bed Dam location map

Methodology and Instrumentation

CS-AFD-M 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.

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 varying 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 them 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.

Survey Design

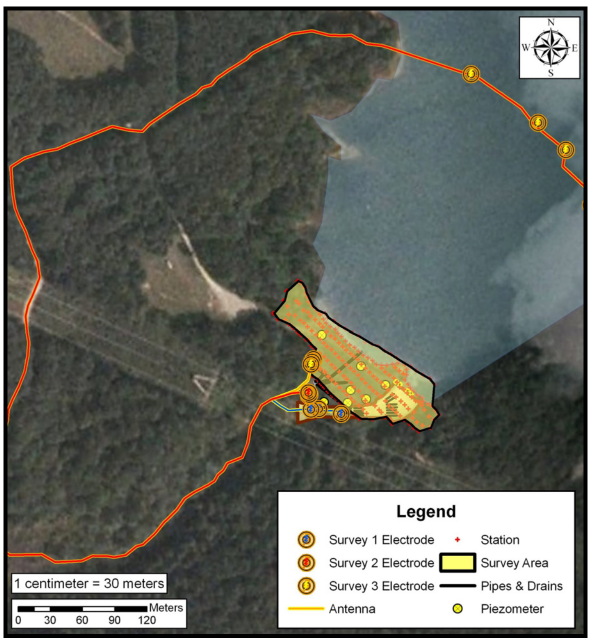

Figure 2: Survey layout for Laurel Bed Dam

Three surveys were used at Laurel Bed dam to investigate seepage flowpaths. Multiple survey configurations were used to bias electric current through specific seeps or regions of the embankment to better target individual seepage flowpaths. For instance, survey 1 (Figure 2) was designed to investigate the seepage appearing at the bottom of the spillway; therefore, downstream electrodes for survey 1 were placed at the end of the spillway in contact with the seepage. Survey 2 biased electric current through the entire dam to perform a more general investigation of the seepage flowpaths, and electrodes were centered on the dam near the toe drains. Survey 3 biased current through a small seep in right crotch to better investigate its source and path through the dam. All three survey areas overlap to some degree which helps to correlate results between surveys. The upstream electrodes were placed in the reservoir.

As shown in Figure 2, an 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. Magnetic field measurements or stations (Figure 2) were acquired on the dam's crest and downstream face, along the shore and from a boat on the reservoir. A tie line was used to stabilize the boat and guide 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. First, CS-AFD-M 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. 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. 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 (green) 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 (similar to 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-AFD-M 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-AFD-M magnetic field strength would be very difficult due to the highly variable conditions of each survey. The magnetic field contour lines shown in Figure 3a are provided simply for comparison purposes to one another. Nothing more should be construed from the magnetic field contour lines.

Modeling

As explained, the magnetic field "footprint" map (Figure 3a) 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 (dark blue lines with yellow dots in Figure 3a) were identified from the magnetic field contour map and placed below the topographic surface, representing preferential pathways of electric current flow. An electric current was simulated in the identified ECF paths, and theoretical magnetic field (red contour lines in Figure 3a) is calculated at each measurement station with an algorithm formulated from the Biot-Savart Law. The flowpath depth, position and width are modified by a forward modeling or trial-and-error process until the theoretical magnetic field footprint best matches the physical data. It is easy to see in Figure 3a that the red contour lines match fairly well where the flow paths pass under the upstream part of the spillway; therefore this model is one solution for electric current flow under the spillway.

In survey 1 electric current was biased to flow under the spillway. Two fairly shallow flowpaths were identified from the magnetic field anomalies. These flowpaths appear to be shallow because the anomaly is 5-10 m wide, so the flowpath to generate a comparable high intensity, narrow anomaly is estimated to be 1-2 m wide and 2.5-5 meters deep. In Figure 3b, the model depth is posted in meters below ground surface and shows that the anomalies fall within the estimated depth range. The survey 1 model

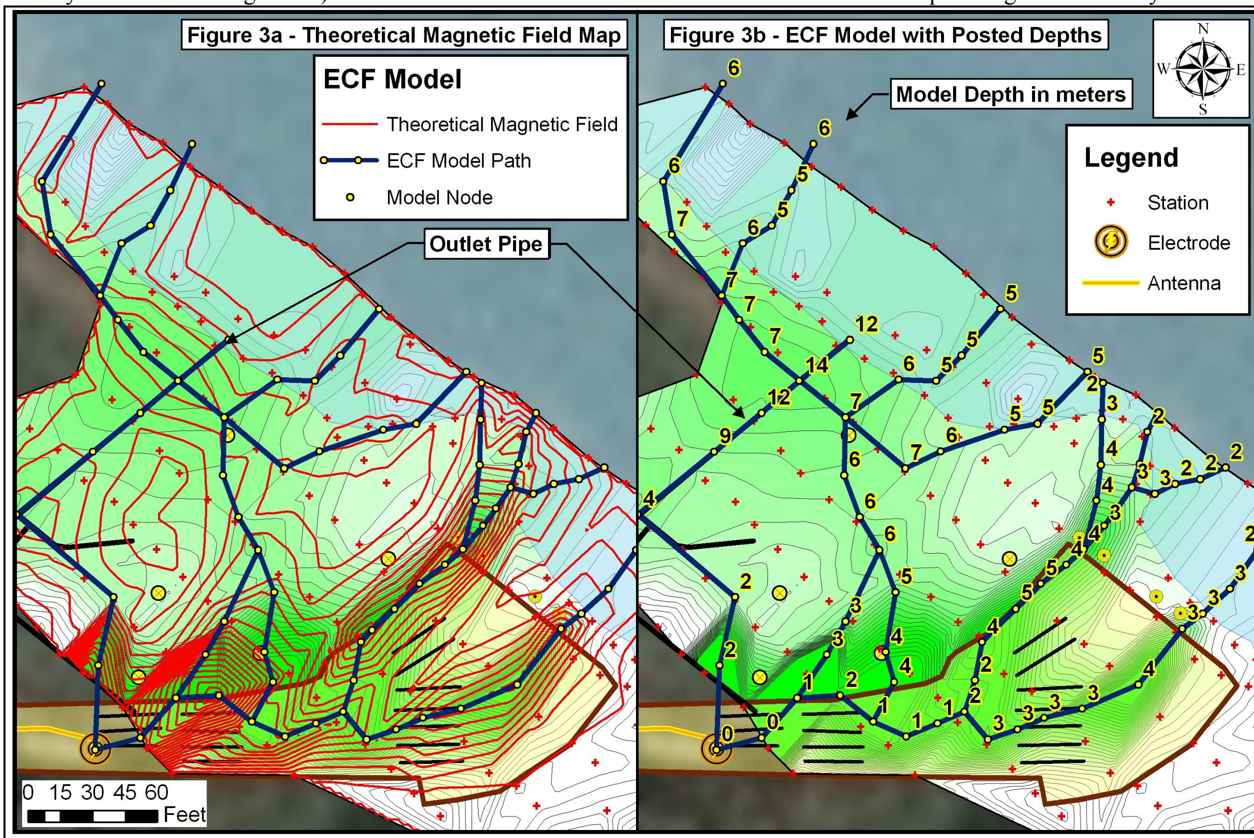

Figure 3a: Theoretical magnetic field (red contours) compared to the Magnetic Field Map
Figure 3b: ECF Model with flowpath depths below ground surface posted

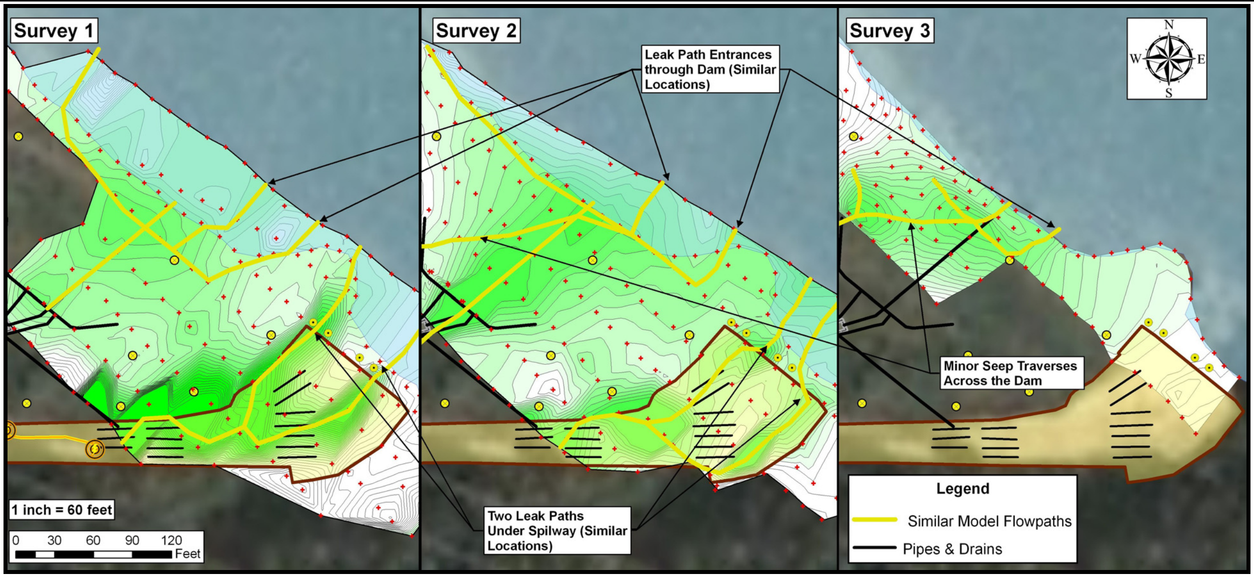

Figure 4: The three surveys correlate rather well when compared side-by-side.

indicates that there are two points where electric current flows through the subsurface underneath the spillway. Other ECF flowpaths that branch off from the spillway show that the seeps from the spillway spread out and saturate the downstream fill of the dam and probably contribute most of the water collected in the toe drains.

Figure 4 shows the results of all three surveys. Similar ECF flow paths are highlighted by the yellow lines for survey 1, 2 and 3. For example in Figure 4, two flowpaths were indentified traversing under the spillway in survey 1 and 2. A comparison of survey 3 and survey 2 shows that the minor seep in the right crotch is observed in both surveys. In survey 2 the contours extend to the west toward this seep. In all surveys high magnetic fields are observed above the central outlet pipe. This pipe did cause some interference in the center of the dam, but the main seepage flowpaths under the spillway are easily distinguished from electric current flow along the pipe because of the anomaly's shape and location.

Conclusions

There are two seepage flowpaths under the spillway that were not intercepted by the test grout holes (yellow circles at the upstream edge of the spillway). Seepage from the spillway likely spreads out and flows to the east saturating the dam's downstream face. A lot of this water is collected in the toe drains. The depth of these flowpaths is well within the weathered rock zone indicating an area of weakness. Another small seep traverses across the dam from east to west appearing in the right crotch. Electric current flowed uniformly through the rest of the dam's right abutment indicating no other obvious seepage problems.

With this information, Froehling and Robertson grouted the weathered rock under the spillway. The seepage flow rate was reduced from 500 gallons per minute (gpm) to 100 gpm. Some of the remaining water flow is attributed to springs. All in all, the entire project (grouting and characterization) came in under budget saving the state of Virginia $600,000. This project just recently won a Grand Award by the American Council of Engineering Companies of Virginia (Froehling & Robertson Inc., 2009).

Acknowledgments

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EDITED REFERENCES

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REFERENCES

Froehling & Robertson, Inc., 2009, F&R wins ACEC-VA grand award for Laurel Bed Dam project: http://www.fandr.com/newsroom_Content.asp.