Identifying Leakage Paths in Earthen Embankments

VAL KOFOED, Willowstick Technologies, Utah, USA
JERRY MONTGOMERY, Willowstick Technologies, Utah, USA
KEITH GARDINER, United Utilities, Warrington, UK

SYNOPSIS. The leakage of water from a dam suggests a number of possible scenarios, and none of them are good. At best, the reservoir owner is losing the power-generating potential of the escaping water. At worst, the leakage may be the precursor of dam failure. Among the technological advances that will enhance the safety and efficiency of hydropower in the future, is a remarkable breakthrough in the area of seepage diagnosis and remediation.

Researchers, working under the auspices of Willowstick Technologies, have developed a system that has been proven to reduce significantly both the time and the expense associated with seepage diagnosis. It thus represents a major step forward in dam safety.

In the new procedure, electrodes are placed strategically upstream and downstream of the dam structure, and the water between them is charged with a low voltage, low amperage, and audio-frequency electrical current. The current creates a distinctive magnetic field that represents the location and character of the water flow occurring between the electrodes. This field can be identified and surveyed from the surface using a specially tuned magnetic receiver. Through this technique and hardware, investigative teams have accurately diagnosed seepage problems in locations throughout the United States and Canada and in the United Kingdom.

INTRODUCTION

All dams leak to some extent, especially earth embankment dams. Dam owners usually know where the leak is emerging from the embankment and can easily monitor the flow over time to ensure that the leak is not getting larger or carrying fine material. However, the only way to cure a leak successfully is to find the point where the leakage path crosses the "impermeable" barrier and plug it. This is notoriously difficult to do unless there is evidence on the surface such as a depression in the pitching or a

Improvements in reservoir construction, operation and maintenance. Thomas Telford, London, 2006

vortex in the water; even then the fault in the barrier itself could be some distance away.

What is needed is a technique that will locate leakage paths through, under or around a dam at any depth, at any time of year and through all types of fill and foundation material. Ideally the technique should provide an accurate 3D map of the leak and be able to provide a reasonably degree of certainty about the origin of the leakage water, e.g. is it coming from the reservoir, a spring under the dam or from the natural hillside?

A United Utilities Engineer encountered the AquaTrack™ technique while researching water flows into water abstraction boreholes on the internet. The website also gave an account of leakage tracking through an embankment dam in the United States using the AquaTrack™ technique which appeared to cover all the requirements listed in the preceding paragraph. Contact was made with Willowstick Technologies of Draper, Utah and in November 2005, a contract was signed to trial the technique on several dams that had long standing leaks that had proved impossible to trace and where speculative grouting appeared to be the only answer.

The trial revealed some surprising and unexpected results and will enable decisions to be made about the nature and location of the remedial works with far greater certainty. The leakage maps produced will also help provide answers to two important questions: Is any remedial action required at all?, i.e. is continuing close observation and monitoring sufficient?:and What will be the effect of the proposed remedial action?, i.e. could it make matters worse?

This AquaTrack technology is also known by its technical name of Controlled Source Frequency Domain Magnetics which shall be referred to throughout the remainder of this paper as (CS-FDM).

The Willowstick crews mobilized on two different occasions throughout the winter of 2005-2006. A total of five different test sites were used to determine seepage paths. For the sake of space, only two of these test projects will be described in this paper following a brief introduction of the technology.

INTRODUCTION TO CS-FDM

Although the science behind the CS-FDM technology is rather complex, at its root it relies on a set of basic physical principles. The most important of these principles is known as “transformer theory.” Transformer theory holds that two coils, set in close proximity, can be electromagnetically coupled. When the first coil is electrically charged, it emits a magnetic field, which then induces electricity in the second coil. Countless types of electrical transformers utilize this rudimentary principle.

In essence, the CS-FDM apparatus and its associated procedure use aqueous systems to form a virtual electromagnetic transformer. The initial stage of the procedure entails the strategic placement of electrodes into the water above and below the dam structure. Connected on one side by wire and on the other by water, the electrodes form the primary coil of the hypothetical transformer. The electrodes are then charged with a low voltage, low amperage audio frequency electrical current. (This AC current is harmless to aquatic life). Per the transformer theory, the charged coil conveys a particular magnetic field to the second coil, which is formed by the CS-FDM receiver device. As the current gathers into the channel that seeps through the dam, it emits a magnetic field characteristic of that channel (Biot-Savart law). Thus, when that field is conveyed to the second coil, the receiver can analyze its unique attributes to infer the shape, location, and path of the seepage flow.

To understand further how the CS-FDM apparatus works, it is helpful to consider the strength vectors of the magnetic field produced by an electrical current. The horizontal and vertical vectors reach zero at the center of the current and approach their maximum as they move outward. Therefore, the rates of change of the magnetic field strength in both vertical and horizontal directions can be used to determine the location, width and depth of the conductor in question. Furthermore, the vector known as "the horizontal minimum" can be used to identify the conductor's orientation. With its ability to read and analyze these three components of the emitted magnetic field, the CS-FDM apparatus can offer a complete picture of subsurface channels.

INSTRUMENTATION

The apparatus used to measure the magnetic field induced by the electrical current includes three magnetic sensors oriented in orthogonal directions (x, y, and z) and a Campbell Scientific CR1000 data logger which collects, filters and processes the sensor data. A Global Positioning System (GPS) instrument spatially defines the field measurements, while a Windows-based, Allegro CE handheld computer stores and couples the GPS data with the magnetic field data. All of this equipment is mounted on a surveyor's pole and hand carried to each measuring station.

During the investigation, more than 5,000 readings are taken every 4 seconds at frequencies from 30 Hz to 720 Hz. For quality control, a base station is established within the survey area, and base measurements are taken at the beginning, midpoint and end of each field day. The base data are used to identify any changes in the background magnetic field and/or diurnal drift. The magnetic field measurements collected during the survey are then normalized to compensate for these factors.

To ensure data quality at each measurement station, the Campbell Scientific CR1000 calculates the 380 Hz magnetic field strength (after Fast Fourier Transform, statistical analysis, and stacking of sixteen separate readings) and compares the signal to the background or ambient magnetic field strength at numerous frequencies. These data are compared to pre-determined signal quality criteria and signal-to-noise ratio criteria to establish data legitimacy and repeatability.

QUALITY CONTROL

The CS-FDM procedure calls for the processing and correction of the field data to account for distance from the source electrode, to reduce the impact of antenna interference, and to remove the effects of ambient and shallow subsurface sources of electricity. The processed and corrected data are then used to generate contour maps of the induced magnetic field. Relative changes in the magnitude and/or gradient of the horizontal and vertical fields—rather than the absolute magnitude of the induced field—are used in making interpretations.

The magnetic field observed at the surface, due to subsurface electrical current flow in water, is dominated by a horizontal component; therefore, interpretations of subsurface saturation are based primarily on the horizontal magnetic field readings. Vertical magnetic field gradients can supplement the channel characterization by helping to identify structural edges that influence the hydrology. However, the vertical data also reflect near-surface features more strongly than the horizontal component (including the influence from the antenna and electrodes), so in most cases the vertical data is less constructive in the final interpretation.

Obviously, it is preferred that manmade interferences are known prior to the investigation. If unknown, however, these interferences can often be recognized by their specific signature signals in the data, especially by analyzing the vertical field data in conjunction with the horizontal data. Once recognized, these features can be accounted for, corrected, and/or removed from the final reduced data set. Some of these possible interferences include the following:

- Ground noise from 50 Hz signal (from nearby electrical generating equipment, overhead or buried power lines, any subsurface cathodic protection of pipes, etc).
- Cultural features (buried pipes, steel cased wells, etc).

- Atmospheric noise (diurnal magnetic variations, electrical storms, solar activity and related magnetosphere activity, etc).

These various features are specific to an individual site and can vary significantly.

TEST PROJECTS

The following information highlights the application of the CS-FDM technology on two dams owned by UU referred to as Dam A and Dam B.

The objective or purpose in performing the CS-FDM geophysical investigation was to characterize and delineate areas of greatest groundwater concentrations through, beneath and/or around the earthen structure. By identifying the preferential flow paths between the reservoir and downstream seeps or tailwater, the CS-FDM technology can successfully answer questions about where water, leaking from the reservoir, originates and how it moves through the earthen structure. Understanding the location and extent of seepage moving through an earthen dam is of significant value in engineering a remedy.

Mapping Seepage at Dam A

Dam A was experiencing leakage into the outlet control tunnel, which curves beneath the earthen structure. The tunnel and associated piping and valves control the reservoir levels and flow from the storage reservoir. This leakage was first recorded on a drawing dated 1883 at the same locations as found today. In his Statutory Inspection report of Sept 2003, the Inspecting Engineer recommended that the leaks be grouted up. Before doing so, United Utilities wished to find the leakage path and determine the extent of any possible defects in the embankment which may have been caused over the preceding century.

Also of interest to the client was the origin of a seep flowing from a small diameter pipe located in the downstream groin (mitre) of the left abutment.

Three horizontal dipole antenna/electrode configurations were employed to energize the earthen dam structure for the purpose of conducting the AquaTrack geophysical investigation in an effort to delineate the origin of the seeps and their flow paths through the dam. Two configurations were used to investigate saturation levels and flow paths through the overall earthen embankment. This was done by placing injection electrodes in the reservoir and then placing a return electrode in the tailwater located below the dam. A third configuration targeted the seepage in the left groin by placing an electrode in the reservoir and a return electrode in the very pipe which carried the seepage waters. In all cases, the antenna connecting the injection electrodes with the return electrodes was placed in the shape of a large horseshoe around the area of investigation.

An alternating electrical current, with a specific signature frequency (380 Hertz), was applied to the electrodes. The induced magnetic field, produced from the electrical current, was measured along a series of lines along the embankment. The measurement grid was designed to provide sufficient detail and resolution. Magnetic field readings were collected at 115 measurement stations. These measurement stations were established on lines spaced 25-50 feet apart with measurements taken on each line at roughly 25 feet intervals, resulting in a 25 by 25 foot grid pattern covering the entire earthen embankment.

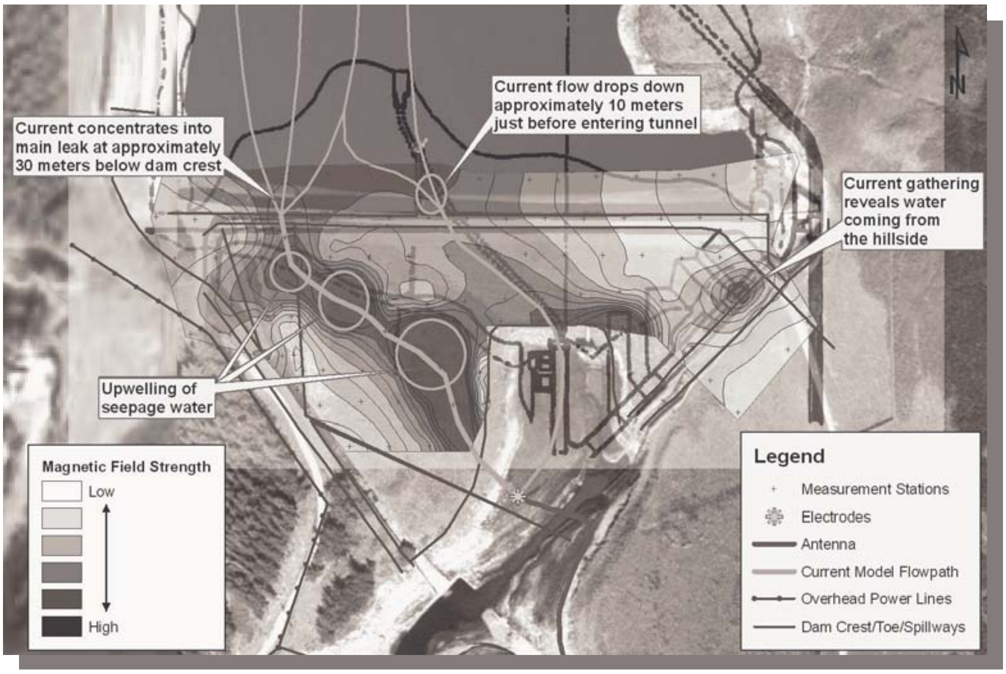

Figure 1 - Dam A Survey Map

The results revealed two seepage paths through and beneath the earthen embankment. Also, the origin of the seep in the left groin was identified. The figure below (Fig. 1 – Dam A Survey Map) provides a summary interpretation of the final results for the earthen embankment at Dam A. The dark grey shading in Figure 1 indicates conductive highs and the light grey shading indicates conductive lows beneath and/or through the dam. In the most general terms, these highs and lows can be viewed as areas of high and low groundwater saturation.

Figure 1 shows two seepage paths. The first seepage path flows around and underneath the concrete cutoff trench of the right abutment between two geologic features consisting of horizontal marine sediments and steeply dipping fractured or brecciated shale. The second identified seepage path flows along the outlet control tunnel were it intersects the clay core of the dam and it finds its way through the tunnel's concrete and stone construction and into the tunnel.

The first noted seep, previously unknown to the client, is believed to be the larger of the two seeps and appears to flow beneath the west abutment's cut-off trench through what is likely a thrust fault contact zone. This contact surface is formed between fairly impermeable horizontal marine sediments (clay and shale) and steeply dipping fractured or brecciated shale. At this interface, between the two formations, water is seeping beneath the dam. It appears that the dam's cutoff wall did not extend deep enough through the fractured or brecciated shale into the impermeable clay/shale to prevent seepage from flowing underneath the dam.

The second noted seep path, which is believed to be the lesser of the two seeps, follows the outlet control tunnel. Water flows along the interface between the exterior concrete and stone tunnel wall and the outer, more porous fill material. As water pipes along this interface and approaches the core of the dam, where earthen materials are suspected of being less porous, water is concentrated and pressured along the interface of the two earthen materials (concrete/stone and clay). Eventually, the water is forced through the tunnel wall through small cracks. These cracks are believed to have been caused by differential settlement of the rigid tunnel conduit straddling the dam's concrete cut-off trench. A previous survey using temperature probes had not detected any flow through the core itself and this finding was confirmed by AquaTrack.

The seep flowing from the small diameter pipe located in the downstream groin of the east abutment did not originate from the reservoir, but almost certainly originates from the hillside east of the dam. When placing a return electrode in this seep and an injection electrode in the reservoir, virtually no current flow through the ground could be established.

Mapping Seepage at Dam B

Dam B has a clay core linked to a clay blanket and a puddle filled arm trench which cuts off the reservoir from the porous rock in the valley side. Water flowing within the rock from the steep hillside is intercepted by a rubble drain trench and flows through a short adit into the draw off tunnel. A weir has been constructed in the drainage/drawoff tunnel at the exit from the adit to monitor the drainage flow. In recent years flow from the adit has increased considerably and it is suspected that there may be a fault in the clay blanket allowing reservoir water to add to the drainage flow. UU was desirous to identify the location of any faults in the blanket so that remedial measures could be taken. Original sketches of the dam show the approximate locations of the adit and rubble drain trench, however, the exact length and location of the adit and rubble drain trench were uncertain

A horizontal dipole antenna/electrode configuration was employed to energize the earthen dam structure. This configuration consisted of an

injection electrode in the reservoir at a point upstream from the embankment. A return electrode was located in the drainage tunnel in a weir box at the entrance to the adit in direct contact with the adit leak. An alternating electrical current was applied to the electrodes. The resultant

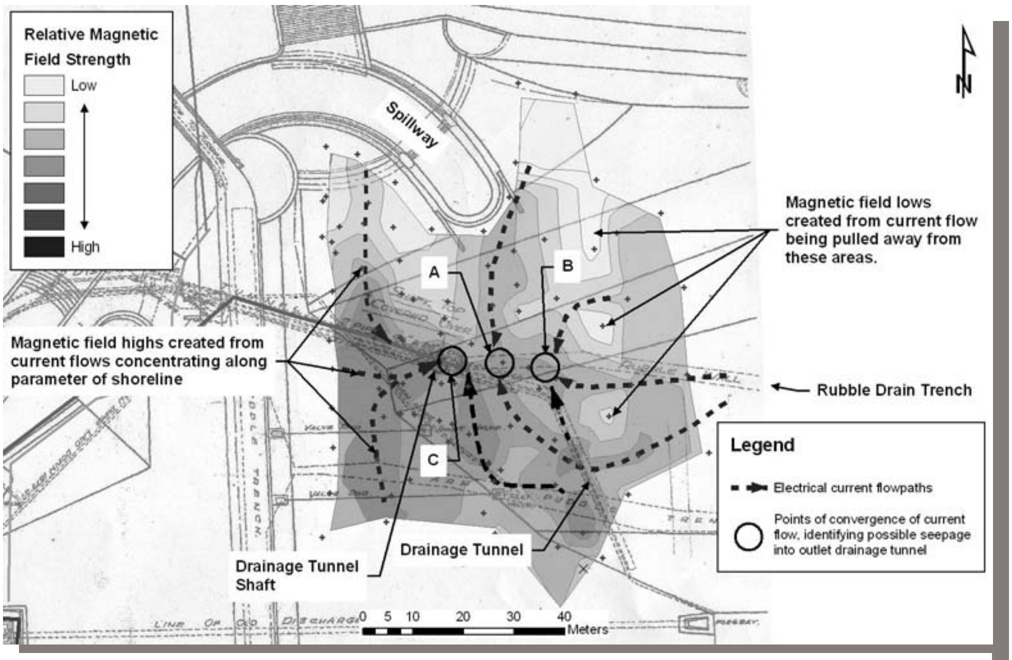

Figure 2 - Dam B Survey

magnetic field was measured and recorded at measurement stations along the embankment and in the reservoir from a boat. A total of 466 measurement stations were established on lines spaced roughly 25 feet apart with measurements taken on each line at roughly 25 foot intervals.

The results revealed the locations of the adit and rubble drain trench beneath the reservoir. The location of water leaking into the adit was also identified. Figure 2 – Dam B Survey shows the results of the adit leak investigation. The darker grey shading in Figure 2 indicates conductive highs. These conductive highs are highlighted and connected with dark grey dashed arrows forming preferential flow paths the electrical current takes as it flows from the injection electrode located in the upper reaches of the reservoir to the return electrode located in the drainage tunnel. The lighter grey shading indicates conductive lows that were observed in the magnetic field data. These high and low conductive areas are created from the signature electrical current introduced and driven through the reservoir.

Five main conductive pathways where observed in the magnetic field data. In all instances, these conductive paths appeared to be influenced by long continuous conductive features known to exist in and/or around the reservoir. These conductive features are noted in Figure 2 and include the shoreline, drainage tunnel, concrete spillway, drainage tunnel shaft and rubble drain trench and/or adit.

The survey indicated that no leakage occurs through the dam itself.

A dashed line labeled “Rubble Drain Trench” in Figure 2 shows a magnetic high following a long conductor that corresponds well with the theorized location of the adit and rubble drain trench.

The survey identified three seepage paths into the outlet drainage tunnel. These paths are noted as points “A”, “B” and “C” in Figure 2. Point “A” represents a leak in the adit and is the most dominant of the three leakage points. Point “B” represents a second leak in the adit or possibly the location of where the rubble drain trench connects to the adit. The survey data was not able to determine from the data where the adit ends and the rubble drain trench begins. In either case, current flow is concentrating on two points along the suspected alignment of the adit and rubble drain trench. Therefore, leakage points “A” and “B” are the locations from which water from the reservoir is leaking into the adit and through the weir box into the outlet drainage tunnel. Point “C” represents leakage into a capped shaft, used to construct the tunnel, which co-mingles with the leakage from the adit and is conveyed into the drainage tunnel.

The adit leak investigation was a unique survey. Never before had Willowstick Technologies performed a survey where a water leak was mapped beneath a body of water, in this case the reservoir itself. Theoretic ruminations regarding the ability of CS-FDM to perform this task were proven correct during this survey.

CONCLUSION

The CS-FDM technology provided critical insight as to how seepage was affecting Dams A and B. The client now possesses valuable information that will allow him to improve and optimize repairs, monitoring and management of these important facilities. Willowstick Technologies does not specialize in earthen dam remediation, engineering and construction, rather they focus their expertise on groundwater characterization, mapping and modeling.

The information provided by the CS-FDM survey should also be compared with known information of the site to further characterize and substantiate subsurface conditions impacting the earthen embankment. Willowstick remains committed to assisting United Utilities with whatever effort is required to fully understand the information provided.

The diagnostic investigations which took place at Dams A & B provide substantial evidence regarding the efficacy of this new water-mapping technology. CS-FDM's particular utilization of basic scientific principles—including transformer theory, current gathering and Biot-Savart law—has resulted in an elegant and efficient method for identifying seepage points in earthen dam structures.