Modern Technique for Leakage Detection at Dams

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SYNOPSIS. This paper describes a technique called Controlled Source Audio Frequency Domain Magnetics to track map and monitor leakage through dams. The problem most dam engineers face is that leakage can often be traced at the toe of a dam or downstream of it, and in some cases upstream within the reservoir basin, but it is usually very difficult to track the leakage through or under the dam. The 'Willowstick' technique described in this paper allows individual leakage patterns to be mapped through or under dams.

INTRODUCTION

Many dams leak, and thus unless it increases in quantity or starts to take materials with the flow, is not necessarily a problem. However, if some sort of erosion process takes place and the flow increases then failure could occur. Remedial works would normally involve comparatively expensive techniques such as grouting or a slurry trench, but obviously if the extent and location of leakages can be accurately predicted then the amount of remedial works and thus costs can be limited.

This paper describes the technique and how it was used to locate leakage and the proposed remedial works at a 200m high rockfill dam in Sri Lanka.

THE WILLOWSTICK TECHNIQUE

Controlled Source – Audio Frequency Domain Magnetics (CS-AFDM), nicknamed Willowstick, is a geophysical technique that uses a low-voltage, low-current audio frequency electrical signal to energise groundwater or seepage flows in the areas of interest. The Willowstick method works by measuring the signature magnetic field response of a controlled, alternating electric current (AC) flowing through a specifically targeted subsurface study area – i.e. the dam and its foundation.

The Willowstick magnetic field is created by a large electric circuit consisting of three parts: (1) the antenna wire connecting two or more electrodes; (2) the electrodes or points of coupling with the earth; and (3)

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the targeted subsurface study area itself, which is located between and/or around the strategically placed electrodes. The diversity of site conditions in dams often necessitates wide variations of electrode and antenna configurations and interpretive parameters.

For a leaking dam, electrodes are placed upstream and downstream of the embankment or structure. The upstream electrode is placed in the reservoir water at a sufficient distance from the dam to allow electric current to spread out in the reservoir before reaching the face of the structure. The downstream electrode is placed in strategic locations (seepages, observation wells, or other downstream locations) to facilitate contact with seepage flowing through the dam. The electrical current follows preferential pathways by concentrating in zones within the saturated subsurface that offer the least resistance through, beneath, and/or around the dam's structure. As the electrical current takes these various flow paths it generates a magnetic field characteristic of the electrical current. This unique magnetic field is identified and surveyed at the ground's surface in a grid pattern using sensitive magnetic sensors.

The horizontal and vertical magnetic field magnitudes are measured at each grid measurement station on the surface of the ground to define the electrical current's subsurface distribution and flow patterns. In nearly all cases, the paths of least resistance for electrical current to follow infer zones of higher porosity within the saturated subsurface. The locations (coordinates) of measurement stations are obtained using a Global Positioning System (GPS) unit and are recorded in a data logger along with the magnetic field data. The measured magnetic data are then processed, contoured, modelled and interpreted in conjunction with existing hydrogeologic information to enhance the characterization of groundwater beneath the area of investigation.

The overall approach to the fieldwork involves energizing the groundwater of interest with an AC electrical current with a specific signature frequency (380 or 400 hertz) between the paired electrodes. As the electrical current follows preferential flow paths in the study area between the electrodes, it generates a recognisable magnetic field that is measured by sensitive coils. Magnetic field measurements are generally taken along lines ranging from 5m to 15m apart with stations on each line also spaced at 5m to 15m intervals. These distances vary from one project to another depending upon resolution requirements and other site conditions. The grid pattern proposed for any particular investigation is designed to provide sufficient detail and resolution to adequately delineate the groundwater of interest while at the same time optimizing funds available for the investigation.

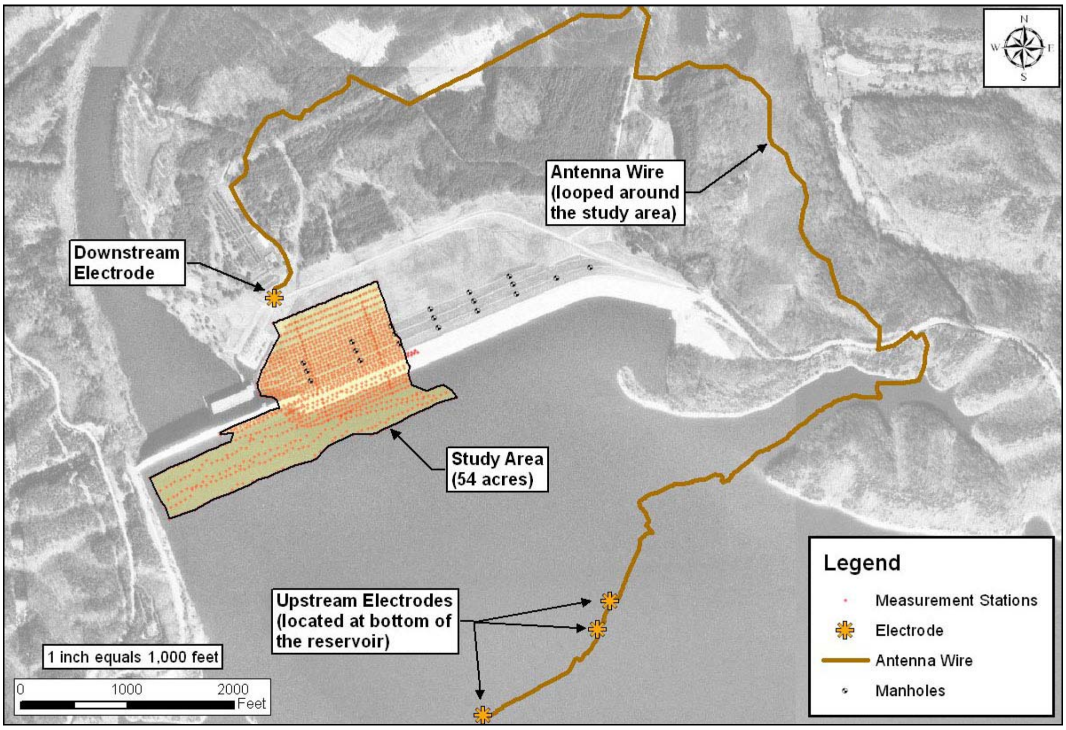

Figure 1. Typical Horizontal Dipole (Plan View)

Each measurement station's X, Y, and Z coordinates are recorded as part of the field work. The stations are designated by small red crosses or "+" signs shown in the figures. These spatial locations are critical to data processing, comparison of surveys, modelling and interpretation.

Equipment

The equipment used to measure the magnetic field induced by electrical current flowing in the groundwater of interest includes: three magnetic sensors oriented in orthogonal directions (X, Y, and Z-axes); a data logger used to collect, filter and process the sensor data; a Global Positioning System (GPS) used to spatially define the field locations; and a Windows-based handheld computer used to couple the GPS data with the magnetic field data and store it for subsequent reduction and interpretation. All of this equipment is attached to a surveyor's pole and hand carried to each field station (Figure 2).

The magnetic receiver (nicknamed the "Willowstick") filters and monitors various frequencies, amplifies the signals through noise-reduction algorithms, measures the strength of the signature magnetic field, and converts all the information into a recordable data set that is ready for subsequent processing and corrections (collectively called data reduction).

Figure 2. Willowstick Instrument

Physical Principles involved in Willowstick

The following principles used by Willowstick show how the technique can be applied to identify, map, and model electric current flow paths that infer groundwater distribution patterns through the subsurface.

- Electric current follows the path of least resistance. Groundwater is generally the best subsurface electrical conductor.

- Electrical current flowing in a conductor generates a magnetic field with characteristics that reflect the location of its source.

- Based on Maxwell's equations, an alternating electrical current in a conductor will generate an alternating magnetic field around the conductor. The converse is also true. An alternating magnetic field will generate an alternating electrical current in a conductor that is under the influence of the alternating magnetic field.

- Two coils in close proximity to each other can be coupled magnetically. A transformer is a special case of two magnetically coupled coils. The electric current in the primary coil creates a magnetic field which then induces an electric current in the secondary coil, completing the magnetic coupling. The primary coil in the Willowstick technology is created by a large primary loop that consists of the antenna wire, electrodes, and the preferential conductive pathways (groundwater) in the subsurface between the electrodes. The Willowstick technology's secondary coils are in the magnetic receiver. When the magnetic receiver is under the influence of the magnetic field emanating from the primary coil (conductive subsurface flow path), the three receiver coils sense and measure the strength of the magnetic field emanating from the primary coil.

- Conductive features will gather electrical current flowing in the ground. This is referred to as current gathering. Electric current flowing in the ground will follow long conductors or conductive zones that facilitate conduction between point A and point B (i.e. the two electrodes). The long subsurface conductors or semi-conductors can be grouped into four general classes:

1. The first class of conductors is subsurface groundwater flow paths and channels. When electric current is biased to flow through a subsurface study area, the electrical current will tend to concentrate and flow in the most conductive medium, which is the groundwater/seepage/leakage.

2. The second class of conductors is 'culture', or any long continuous conductor that is man-made. These include: communication cables, overhead and underground power lines, underground metallic pipelines, metal fences (chain link, barb wire, etc.), railway tracks, steel guardrails, and other elongated continuous conductors.

3. The third class of conductor is wet clays, which often pose a problem in DC resistivity and other electrical or electromagnetic (EM) methods. Near surface clays can act as a "shield" and cause much difficulty measuring the electrical properties of materials beneath the clay. The Willowstick method has two advantages. Firstly, it measures the magnetic field response, which is not directly affected by wet clays as are the electric field or the EM field. Secondly, by directly energizing the medium of interest, greater control can be maintained in most cases to minimise the amount of electric current straying and flowing in the wet clays. In most cases, natural subsurface waters moving through a channel will have a lower resistivity than even wet clays, so the current will tend to focus in these if the proper energising perspective is employed.

4. The fourth class of conductor to consider is any and all other geologic semi-conductors such as graphite-bearing shale, sulphide ores and iron formations. Because of their nature and distribution, these geologic materials are rarely present in significant quantities to cause a problem around Willowstick surveys.

Interpretation and Modelling

After data reduction is complete, one or more footprint maps are created to reveal the patterns of electrical current flow in the subsurface by showing contrast between areas of high and low electrical conductance.

When identifying anomalous patterns in a typical footprint map, it is important to be able to distinguish the main influences on electric current flow, as classified above. Besides the groundwater influence, the residual effects of culture and electric current bias still exist in most cases - even though the data reduction processes may have reduced these effects to some degree. These three main influences are discussed below:

1. The groundwater influence in a typical footprint map is obviously of greatest importance. As discussed, Willowstick is based on the principle that its signature electric current is strongly influenced by the presence of groundwater, or areas of higher porosity where groundwater is accumulating and/or flowing, and which are revealed in the footprint map.

2. The magnetic field may be influenced by culture (see above). 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 some of the signal coming from the subsurface. The best approach is to identify all culture before a survey is initiated and either avoid as much of it as possible by strategic survey design or remove its effects when interpreting the data.

3. The magnetic field in any given survey is always subject to electrical current bias because electric current must travel from one electrode to the other in order to complete 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 electrodes. It is always true, however, that 100% of the electric current must concentrate in and out of the points of coupling (the electrodes), and hence the magnetic field tends to grow much stronger as it nears these points.

Interpreting magnetic field contour maps could be compared to reading a topographic quadrangle map. On a topographic map, the ridge lines connecting the peaks could be thought of as the pathways offering the least resistance to traverse. In the same way, these lines in the magnetic field maps represent paths of least resistance for electrical current to follow, although it undergoes some measure of dispersal and regrouping in more complex ways than can be fully described. By identifying these high points and ridges and connecting them together through the study area, the centre position of strong preferential electric current flow can be identified (see dark blue lines in Figure 3). Note that the flow paths attributed to culture are highlighted to keep them separate from those attributed to groundwater.

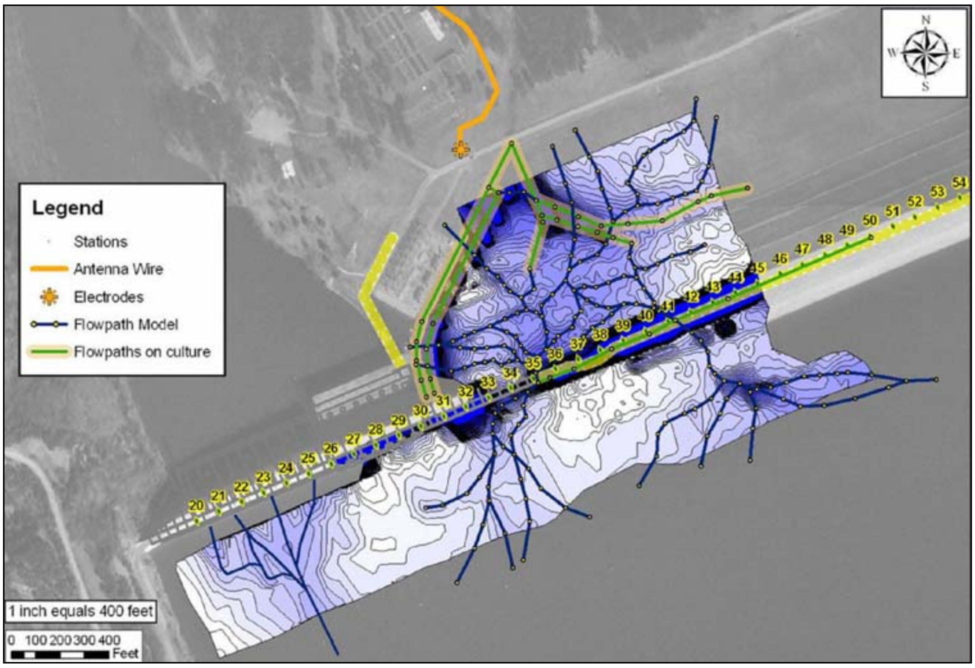

Figure 3. Electric Current Flow Path Model

In some cases electric current flow paths produce very tight and revealing anomalies that can be modelled with a fairly high degree of accuracy (depths to within 10% error). In other cases electric current flow patterns are not as distinctive and the depth and character can only be roughly estimated—in which case it is very important to have additional data to help characterize the groundwater zone of interest, such as well logs, piezometric data, or other geophysical or hydrological data. In any case, the horizontal position of electric current flow paths is generally determined with a high degree of consistency and accuracy.

The results obtained from a Willowstick geophysical investigation is to be used to make informative decisions concerning how to further confirm, monitor and possibly remediate groundwater problems through a given area of investigation.

EXAMPLE OF THE WILLOWSTICK SYSTEM IN PRACTICE

The Samanalawewa Dam is located in Sri Lanka, approximately 160km southeast of the capital city, Colombo (Figure 4).

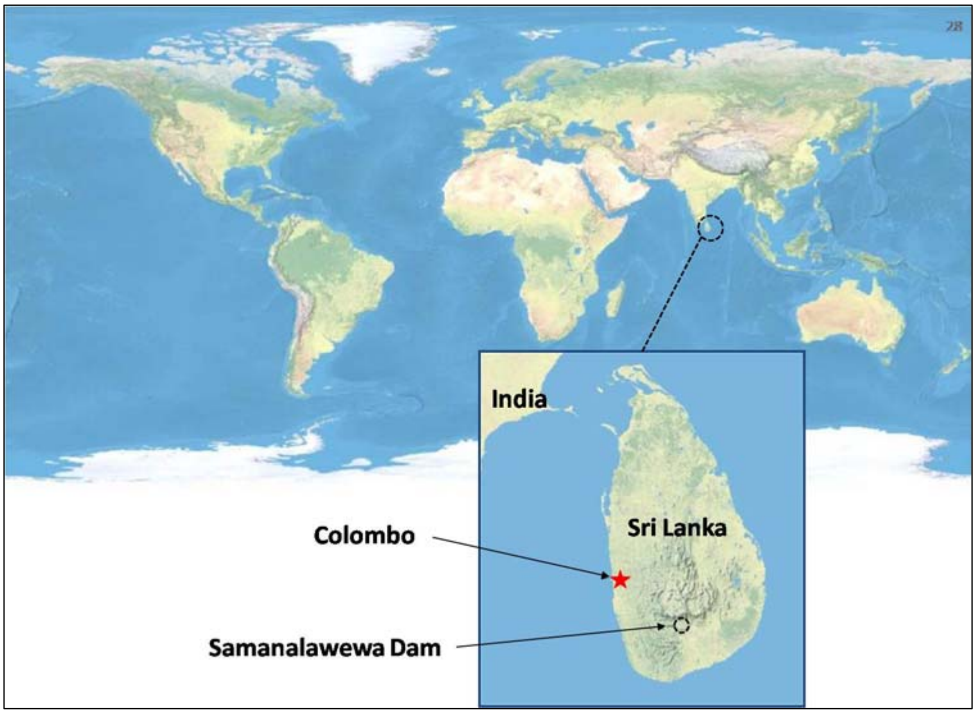

Figure 4. Samanalawewa Dam Location Map

The Samanalawewa Dam impounds the Walawe River, the 5th largest river in Sri Lanka. The Walawe River, in conjunction with another major tributary - the Belilhul Oya River - flows from the mountains of central Sri Lanka. The two rivers flow in parallel valleys in a south-eastern direction and eventually join together. The horizontal separation of the two rivers is roughly 6km while the vertical separation between the Walawe River (after joining the Belilhul Oya River) and Katupath Oya (a tributary of the Walawe) is over 300m. This difference is used as the head for power generation.

The construction of the Samanalawewa Dam started in 1986 and was completed in 1991. The dam and resultant reservoir provide one of the largest storage facilities created in recent times in Sri Lanka. The dam is a zoned rockfill embankment with clay core. It is roughly 105m high and 530m long and retains a reservoir with a capacity of $254Mm^3$ (Figure 5). The catchment area of the dam covers nearly $350km^2$. Not only is the dam important for its renewable energy resource, but it also serves as a key element for water supply, flood control, fish and wildlife and many other immeasurable benefits to the country of Sri Lanka.

Figure 5. Photograph of Samanalawewa Dam

GEOLOGICAL SETTING

The project is located within the highlands that lie in the Balangoda region of the Central highlands of Sri Lanka, and the reservoir is situated in the 'Highland Complex' with the underlying rock types comprising metamorphic rocks including granulate gneisses, charnockite, marble and dolomitic marble. These rocks are overlain by a thick weathered layer.

The dam's right abutment and right rim areas consist of karstic terrain. Karst conditions develop from the dissolution of the host rock along fractures, joints and/or bedding planes which become enlarged over time from the saturation and flow of groundwater along these features. In addition to karstic conditions, the right abutment and right rim areas have been subject to extensive folding, faulting and hydrothermal reactions, making the right abutment and right rim areas geologically complex.

During the investigation and construction phases of the reservoir it was recognised that karstic features were likely to be common in the right bank.

The right abutment rises up to a peak of elevation of 545m AOD and then descends to a low ridge which extends southwards to form the right bank of the reservoir. The topography beyond the abutment is based on saddles; with four low saddles located on a ridge within a distance of 2.9km of the dam site. These saddles occur at levels varying from 20m to 60m above the top water level of 460m AOD.

A karstic feature, a cave, was discovered during the construction phase 300m upstream of the proposed axis of the dam on the right abutment. This cave appeared to form along a minor fault, one of a number of minor, parallel faults which create the saddle features noted above. This and other signs of possible leakage through the right abutment area resulted in an extensive grouting program. Six large cavities were found and sealed with concrete during construction.

MEASURES TO LIMIT WATER LOSSES

During the construction of the dam four adits were driven along the axis of the dam. Despite the effort to cut off seepage through the right abutment area, a small spring appeared downstream of the dam upon initial filling of the reservoir (June 1991). The seepage was large enough to suspend filling the reservoir. Additionally, a flat water table was observed up to a distance of 2.5km from the dam (along the reservoir's right rim) responding to the reservoir levels. As a remedial measure, a 1,880m long tunnel was drilled beneath the right rim area. From inside the tunnel, a 100m deep by 1,600m long grout curtain was constructed.

'LEAKAGE INCIDENT' & SUBSEQUENT REMEDIATION

On 22 October 1992 water burst out of an area downstream of the right abutment of the embankment when the water had reached a level of 439.01m AOD. The water level was immediately lowered to 430m AOD over a period of three weeks ending on 11 November 1992. However, groundwater levels in the right abutment area were kept high as a result of a blockage at the downstream end of the 'karst/pipe feature'. Once this blockage had been removed the ground water level dropped by 2m to 3m in the abutment area. Nearly 25,000m³ of earth was washed away from the adjacent hillside.

The next remediation effort consisted of dumping clay from barges in an attempt to slow seepage flowing out of the reservoir into suspected ingress areas along the noted fault zones. However, after installing nearly 50,000m³ of clay, the leak was not stopped. No reduction was noted after the first phase dumping but after the second phase it was reported that the clay blanket did marginally reduce the groundwater pressure in the right abutment.

WILLOWSTICK SURVEY LAYOUT

The Willowstick investigation of the right abutment study area employed one horizontal dipole electrode configuration to energize the subsurface study area. The original scope of work was limited to only one demonstration survey.

Shortly after the fieldwork was initiated, and based on preliminary results, Willowstick suggested a second survey. This second survey was targeted to investigate possible seepage through the right rim grout curtain area. This work was limited to a minimal number of measurement stations and was done to investigate whether or not seepage was a problem through the grout curtain. The intention of the additional work was not to detail or model seepage flow paths through the right rim grout curtain, but to identify if major seepage path(s) existed through the grout curtain and if so, to determine what additional work should be performed to fully characterise seepage through or beneath the right rim's grout curtain study area.

In performing the two surveys, an injection electrode was placed in the reservoir some distance from the upstream face of the dam and right rim area. A return electrode was strategically placed in contact with seepage flowing from the hillside down-gradient of the embankment.

Figure 6 presents an interpretation of Survey 1 results. This figure shows the positions of the ECF modelled flow paths (vertical and horizontal alignment).

It appeared, based on these posted elevations, that seepage north of the tunnel was near the elevation of the reservoir level at the time of the survey (about 440m AOD). The model also suggested that seepage north of the tunnel occurred above the tunnel and found an opening in the adit's grout curtain very near the 440m AOD elevation. Seepage south of the tunnel flowed a few metres deeper at elevation 438m AOD. At the location where the two flow paths converged, east of the adit, the elevation of the preferential flow path dropped a little more rapidly as it flowed to the discharge point out of the hillside. It is important to note that all elevations as well as horizontal positions were the result of a relatively inaccurate GPS data set. Nevertheless, the data still provided a good indication of how seepage flowed past the dam.

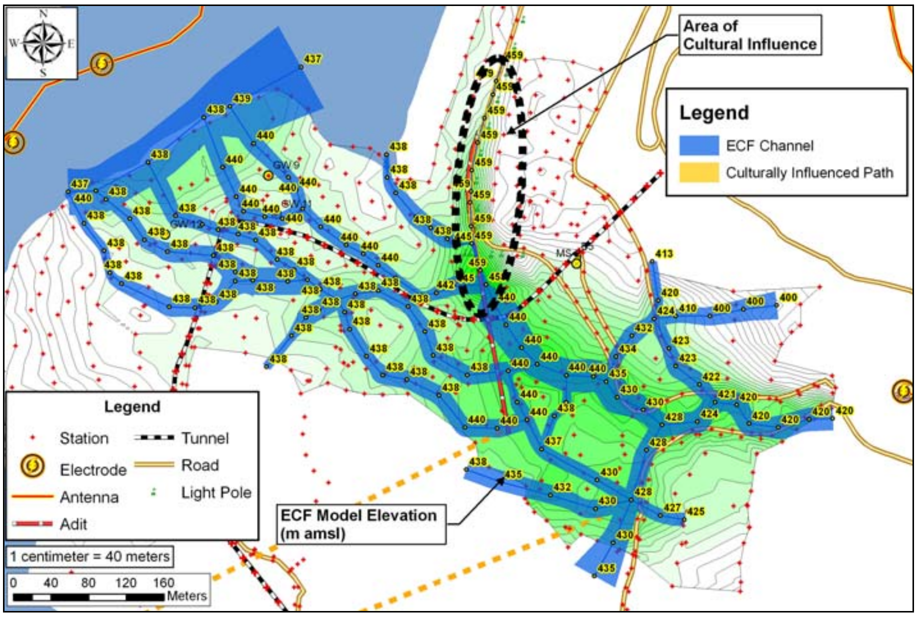

Figure 6. ECF Model with Posted Elevations

Seepage through the open gap in the tunnel's grout curtain appeared to be slightly below reservoir water level. Had the grout curtain been placed below the tunnel in the gap, seepage would still have passed through this area because the seepage flow is above the tunnel. Where the grout curtain was placed above the tunnel, just west of the adit's grout curtain, seepage was split by the upward vertical grout curtain, with some flows through the adit grout curtain and some flows south of the tunnel around the adit's grout curtain.

In conclusion the results of the investigation suggested that there was a series of braided seepage flow paths north and south of the tunnel that ran beneath the right abutment study area. Seepage appeared to concentrate around the right side of the dam rather than underneath or through the dam's earthen embankment. There was some seepage occurring along the right rim grout curtain, but not to the extent that it was flowing through the right abutment study area. It was recommended that any seepage through the karst topography needed to be carefully characterised, monitored and possibly remediated to ensure the integrity of the reservoir as well as the safety of those residing downstream of the dam.

REMEDIAL WORKS

The Willowstick survey confirmed two main areas where the cut-off is compromised – one on the bend of the tunnel and the other where the original cut-off crosses the tunnel. Having identified the location of what was believed to be the two largest sources of leakage through the right abutment area it was possible to undertake cost effective remedial works at Samanalawewa Dam to ensure its safety and integrity, and to bring the reservoir back to its proposed top water level to retain its ability to generate energy.

The work will involve measures:

1) To close 2 significant gaps in the existing supplementary grout curtain
2) To locate and fill major karstic features at approximate elevation of 438mm.

CONCLUSION

The Willowstick technique allows individual flow paths to be mapped both in plan and elevation at depths in excess of 200m to an accuracy of 0.1m. This enables remedial works to be focused on the areas of defects and enables savings of many millions of pounds to be made on large schemes, where, without this knowledge, extensive grouting or cutoff construction schemes would be necessary.