Locating the leakage route at Torside Reservoir using the Willowstick AquaTrack system.

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SYNOPSIS At the 2006 BDS conference in Durham, Val Kofoed and Jerry Montgomery of Willowstick Technologies and Keith Gardiner of United Utilities and Supervising Engineer for Torside Reservoir, introduced the AquaTrack subsurface water-mapping methodology (Kofoed et al 2006) While the technology seemed promising, at that time there was relatively little data to confirm its accuracy. Now there is a wealth of results which provide a clearer picture of this technology's reliability and capacity

This paper will analyse just such results from a seepage-diagnosis project conducted at United Utilities's Torside Dam in Derbyshire. That project investigated the source of water that was leaking into the drawoff tunnel running beneath the dam. As per the AquaTrack procedure, the reservoir was charged with a low-voltage electrical current, which emitted a magnetic signal representing the subsurface water flow. When read and analysed, that signal indicated the path of the water flow into the adit. Following the investigation, UU lowered the reservoir and found a sinkhole where the mapping procedure had predicted.

HISTORY OF PROBLEMS AT TORSIDE RESERVOIR.

Torside is the second in the chain of five reservoirs in the Longdendale valley, constructed between 1847 and 1887, to supply water to the city of Manchester. From its construction there have been problems with the dam. (Bateman, 1884 and Quayle, 2006) On first filling of the reservoir in 1851 the drawoff pipes laid through the dam at foundation level ruptured and in 1854 the Engineer, J F Bateman, reported to Manchester Corporation that the dam had "stretched itself upon its base up and down the valley carrying the pipes with it". After several attempts at repair, Bateman abandoned the drawoffs and drove a tunnel through the rock in the north abutment in which he installed two new drawoff pipes. The original drawoffs were sealed and, fearing that the stretching of the foundations could have compromised the integrity of the central clay core, in 1855 Bateman added a 1.5m to 1.8m thick clay blanket on the upstream face of the dam connected to a new clay filled cut-off trench upstream of the toe.

At the north abutment of the dam, instead of taking the original clay core into the hillside, Bateman excavated what he termed an "arm trench", at right angles to the core, at the foot of the north valley slope, to a depth varying from 9m to 12m backfilled with puddle clay. The fissured rock at the north abutment was covered with a clay blanket, between 0.6 and 1.2m thick, connected to the embankment core to the west, the arm trench to the south and terminating in a puddle-filled wing trench to the east (see Figure 1). The blanket is protected with masonry pitching laid on a thick bed of gravel. The clay blanket, laid later, on the upstream face of the dam was connected to the abutment blanket.

On first filling of the reservoir the abutment blanket was found to be leaking considerable quantities of water into the fissured rock. The first repair was made in 1851 and repeated remedial works, usually associated with the deep puddle filled arm trench, have been needed in this area up until the present day. The lining system was finally completed in 1865, having been delayed by further failures, in 1858 and 1865, that were sealed by placing concrete onto the fissured rock before restoring the clay lining.

Further, similar repairs were made in 1879, 1882 and 1897 and again in 1944, 1946, 1947 and 1949. Between 1949 and 1951 an extensive programme of grouting was carried out using 1:1 sand cement in holes at 1.5m centres up to 38m deep into the rock foundation Grout takes were in the region of 4 tonnes per hole with a maximum of 32 tonnes recorded. There was a further failure of the clay lining in 1963 but since then there had been no recorded leakages in the area until 2004

The abutment blanket and arm trench effectively prevents groundwater from the hillside entering the reservoir so, probably to prevent build up of water pressure causing damage, a deep rubble filled trench was excavated in 1861. An adit or box drain, 550mm by 350mm connects the rubble drain to the draw off tunnel. Water discharges into the tunnel through an opening formed in the masonry lining.

Recent leakage problems.

In 1997 a v-notch weir was installed on the tunnel wall at the discharge point to gauge flows from the rubble drain into the tunnel. A weir plate was also fixed across the width of the downstream tunnel near the portal where the flow could be more easily observed and measured. A rectangular slot

330mm wide and 100mm deep was cut into the plate and, initially, this easily accommodated the leakage flow.

In May 2004 the Supervising Engineer observed that the flow had exceeded the capacity of the slot and was flowing over the full 2m width of the weir plate to a depth of 20mm. This represented about a tenfold increase in the flow rate to around 30l/s. The advice of an AR Panel Engineer was sought and Dr A K Hughes carried out a Statutory Inspection, under the Reservoirs Act 1975, on 17 November 2004. He recommended that "repairs are undertaken to reduce the inflow to the tunnel to at least the levels experienced prior to May 2004" by September 2005.

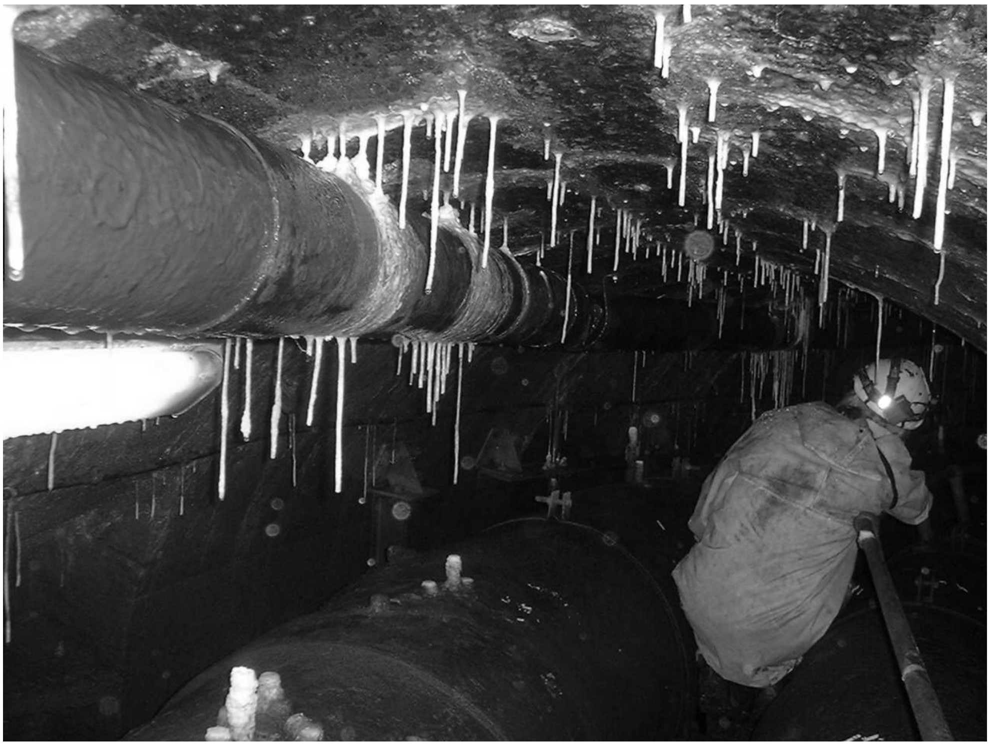

Photo 1 - Stalactites and stalagmites in the drawoff tunnel.

Prior to 2004 the leakage had been quite steady but a rapid growth of stalactites and stalagmites had been observed in the tunnel. A stalagmite 60mm long had been observed growing on a stainless steel pipe strap that had only been installed 6 months earlier. It was speculated that acid water from the reservoir was dissolving the lime from the cement in the grout injected into the rock in 1950.

It is not known whether a defect in the clay blanket or arm trench was identified when the grouting was being carried out. It is possible that grouting was considered to be a permanent solution, since the rock would now effectively be non-fissured, and that the integrity of the puddle clay ceased to be important.

The reservoir level was lowered to try to identify the level at which the leakage stopped; however this was easier planned than accomplished. The reservoir has a large catchment, only some of which can be diverted, and it is not unusual for the water level to rise by 7 or 8m up to overflow level overnight. Initially, a 3m drawdown would reduce the leakage flow significantly, and this was the case until 2005, however by 2007 a 12m drawdown was required to achieve the same result.

It became evident that the identification and repair of the defect would not be achieved before the due date so Dr Hughes was once more appointed to carry out a Statutory Inspection and made a further recommendation for a repair to be effected by July 2008. It is important to note that at no time was there any evidence of seepage through the dam.

Since lowering of the reservoir to attempt to locate a defect was problematic, Willowstick Inc were commissioned by United Utilities (UU) to carry out a survey using the AquaTrack technique in the winter of 2005. (Kofoed et al 2006) This survey concluded that there were 3 main leakage paths from the reservoir and one from the valley side to the north. However, drawdown to 12m had revealed no visible defects and the reservoir had been full at the time of the survey. Remote detection of leakage at depth though a clay blanket beneath a reservoir had not been attempted before by Willowstick inc, or anyone else, so it was decided that the area should be re-surveyed with the reservoir substantially lowered and using a different antenna configuration. This was done in December 2006 over a 6 day period. However the reservoir rose from 10m below TWL to 3.4m below during the survey and the later readings had once more to be taken by boat.

THE AQUATRACK SURVEY

The AquaTrack technology has been applied twice at the Torside Dam and Reservoir site to map and delineate preferential groundwater flowpaths into the adit and drainage tunnel located beneath the reservoir. The results of both geophysical groundwater investigations showed supportive evidence as to how groundwater was getting into the adit and tunnel. The information presented by the survey results was intended to provide UU with the necessary information to make informed decisions concerning how to accomplish the stated task of minimizing seepage into the adit and tunnel.

There were some differences in magnetic field maps between the Phase I and Phase II surveys, which were performed with different reservoir levels and utilized different antenna / electrode configurations over the same study area. Each antenna / electrode configuration induces current to flow with a particular bias, thus the differences in the relative field strength. It is possible that changes in reservoir level contribute to changes in seepage flow, which would also lead to changes in the magnetic field response from electrical current flowing in the subsurface. Despite the differences however, the technology still revealed the important anomalies in the same locations.

Details of the Phase II survey

The purpose of the Phase II investigation was to re-survey the site to further evaluate subsurface flow and determine the source of water and its path(s) into the rubble drain and the drawoff tunnel. The water level in the reservoir was at a low level exposing a significant amount of north shoreline. The antenna / electrode configuration employed for the Phase II survey allowed energy to flow in either the reservoir (similar to the Phase I investigation) or beneath the reservoir's clay liner, which is unique to the Phase II survey. As with Phase I, there were no leaks observed beneath or through the dam's earthen embankment.

The Phase II work was initiated on 5 December 2006 with the majority of the work being completed over a 6 day period. This project presented a particular challenge in mapping a water leak under a body of water and beneath a clay liner. A significant portion of the field measurements had to be taken along the exposed "wet" clay lined reservoir and/or from a boat. Measurements taken from the boat required the installation of a tie line to prevent the boat from drifting while taking readings and recording the magnetic field data. The work was slow and could only be done when weather conditions (rain and wind) were acceptable.

A horizontal dipole antenna/electrode configuration was employed to energize the leak in the adit for the purpose of conducting the AquaTrack geophysical investigation. The antenna/electrode configuration differed from the Phase I survey in the placement of the return electrode. Rather than putting the return electrode in the reservoir's water body (as was done in the Phase I survey) this investigation placed it in the north hillside in wet soils and grasses at the edge of the shoreline and east of the area of investigation.

The injection electrode was placed downstream of the dam in water discharging from the drawoff tunnel. This antenna / electrode configuration was designed to allow electrical current to concentrate and flow (between the electrodes) in and out of the adit beneath the clay liner.

An AC current, with a specific signature frequency (380 Hertz) was applied to the electrodes. The magnetic field, generated from the large electric circuit consisting of the subsurface study area, antenna wire and strategically placed electrodes, was measured and recorded from the surface of the ground. Measurements were taken along the north and west shorelines and directly over the drainage tunnel, adit, rubble drain trench and puddle arm trench from a boat in a grid pattern. The measurement pattern used in the investigation provided sufficient detail and resolution to adequately evaluate the leak and its flow paths into the adit and drainage tunnel.

The Phase II north shoreline survey consisted of 308 measurement stations. The actual number of measurements taken to fully delineate the anomalies identified required 418 measurement stations. These measurement stations were established on lines spaced roughly 5m apart with measurements taken on each line at roughly 5m intervals, resulting in a 5m by 5m grid pattern covering the entire area of investigation. The readings taken from the boat were taken at 10m intervals and the distance between the lines varied because of the tie-line method that was used to stabilize the boat.

The field data was sent to Willowstick's home office near Salt Lake City, Utah, USA for reduction and interpretation. While this was being performed, field crew members were instructed on a daily basis where to take additional readings in an effort to identify and delineate leakage and flow into the adit.

The results

The results of the Phase II investigation identified and confirmed the same locations of seepage into the adit as did the Phase I work. The Phase II work more specifically identified two main sources of seepage and their flow paths into the adit and the drainage tunnel.

The first source of water, observed to be seeping into the rubble drain, appeared to be flowing from the north hillside (see Figure 1). This water is trapped between the clay blanket liner, clay core of the dam and puddle filled arm trench. This trapped groundwater flows into the rubble drain trench and is conveyed westward via the adit into the drawoff tunnel.

The second source of water identified in the survey data appeared to be flowing from the reservoir through a breach in either the puddle filled arm trench and/or the clay blanket liner.

Point A, in Figure 1, represents the location where water is seeping into the adit. This location is confirmed in both the Phase I and Phase II investigations. Point B represents an area where groundwater from the north hillside is highly concentrated and channelised. This location is above high water level where groundwater may be intercepted from the hillside in an effort to reduce groundwater flow into and beneath the reservoir's clay bottom liner. Point C represents an area where water from the reservoir appears to have broken through the clay blanket liner and/or puddle arm trench.

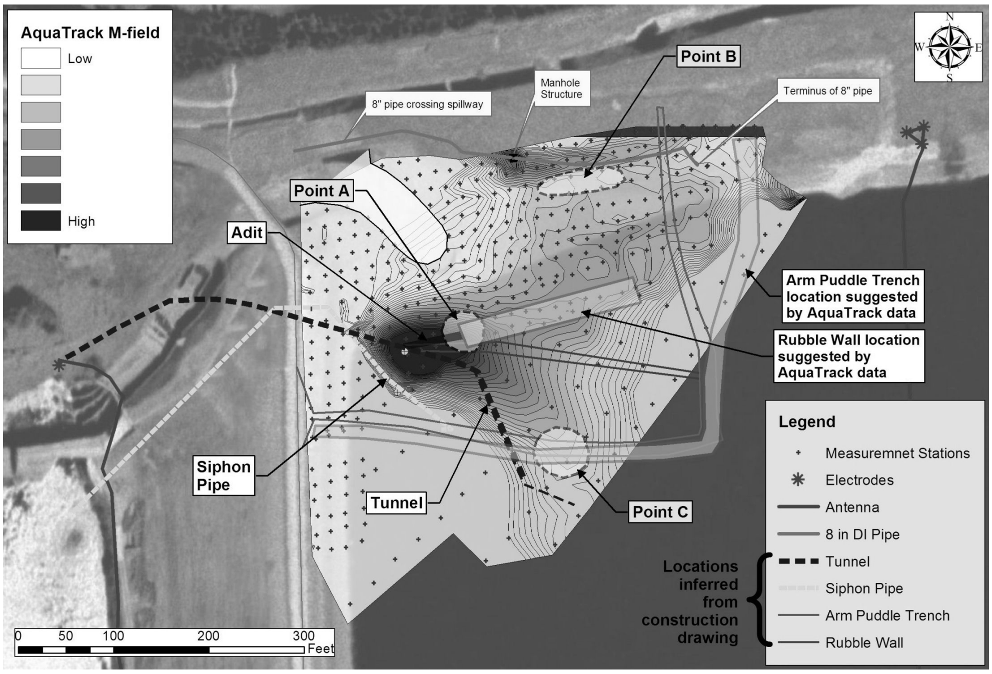

Figure 1 - Plan of the survey area with Phase II Interpretive Results

<u>Survey conclusions</u>

The Phase II AquaTrack survey results provided additional information regarding water movement beneath the reservoir's clay liner and puddle filled arm trench into the adit and a source of leakage into the drainage tunnel. The data obtained from the survey could be used to formulate the next phase of work to identify a remediation strategy to minimize the leakage flow.

The information gathered through the AquaTrack investigation suggested that the survey layout, including antenna/electrode configurations and data grid spacing, were appropriately designed and that the findings of the studies are reliable and accurate in the sense that they seemed to corroborate known information at the site. In general, the AquaTrack survey results were consistent and supported the understanding of existing features in and around the site as noted and shown in the original drawings of the dam. It is believed that the original drawings and sketches (150 years old), when georeferenced to the GPS data provide estimated,but less than entirely accurate, locations of the adit, rubble drain trench and puddle filled arm trench.

The results and final interpretation of the Phase II AquaTrack investigation represents a generalised picture of the subsurface flow. Actual subsurface flow may be more complex than shown because the magnetic field emanating from the cultural features is likely shadowing or over-powering minute groundwater flow paths (e.g., smaller, less permeable features) which may be present, especially given the dynamic conditions of the reservoir (high and low water levels, drainage from the north hillside, etc.). Also, the results are a representation of groundwater conditions observed at the time of completing the fieldwork. It should be noted that different, or additional, groundwater paths may be activated under different hydrologic conditions (e.g., increased level in reservoir, drainage runoff from hillside, dry seasons, etc.).

SITE INVESTIGATION

During the dry spring of 2007 the reservoir was progressively lowered in an attempt to find a surface feature that might indicate the position of a defect in the clay liner. On 23 April 2007 the reservoir was lowered below the 18m level to reveal a 4m diameter, 1.5m deep, hole where the pitching had collapsed. This coincided with the point where the line of the leak predicted by the AquaTrack survey crossed the line of the arm trench. However, the exceptionally wet summer of 2007 meant that it was almost impossible to hold the reservoir at this level and it was September before works to investigate and repair the hole and the defect beneath it could commence.

Draining down the reservoir to this low level had serious consequences for the water yield from the Longdendale valley and meant that the Torside Sailing Club had to abandon its 2007 programme and temporarily relocate to the nearby Winscar reservoir in Yorkshire. The AquaTrack survey provided assurance that such a substantial drawdown was necessary to find the defect giving rise to the leakage.

The physical investigation commenced on 28 September 2007 and was completed by 20 November 2007. The initial excavation exposed a sectional profile around the periphery of the hole comprising pitching overlying ballast bedding above the clay lining. The hole was extended by excavator, within a trench support box, over the plan area of the hole, down to a maximum depth of 5.7m below the surrounding pitching. The excavation quickly confirmed that the hole was located directly above the southern puddle arm trench. The construction of the puddle trench was much the same as that shown in the section taken from a record drawing of repairs carried out in 1882 (see Figure 2).

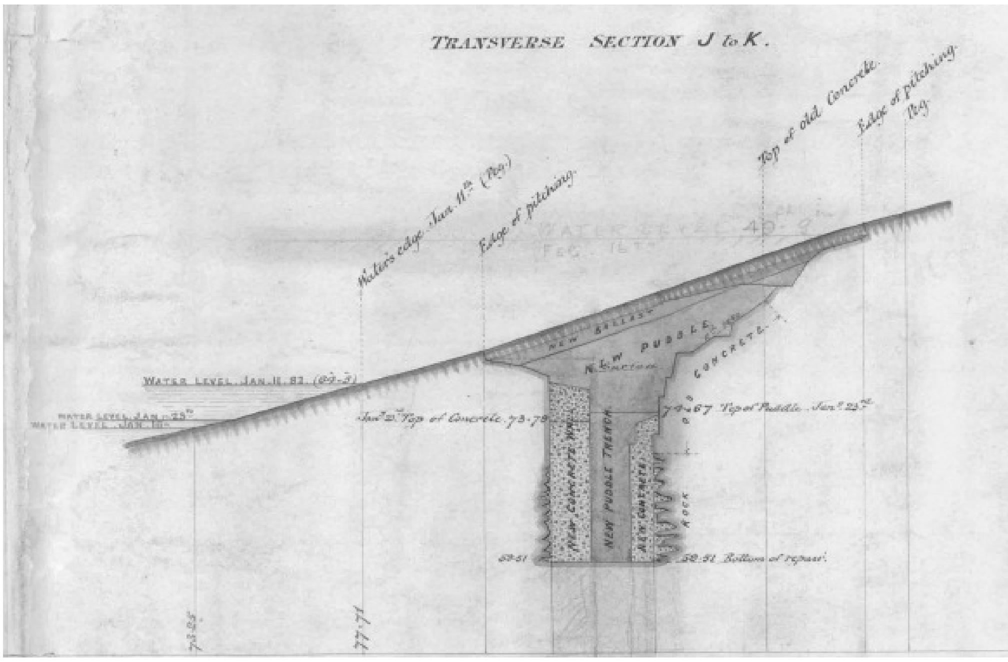

Figure 2 - Section showing the repairs to the arm trench in 1882

Concrete, thought to have been used by Bateman to seal to the rock-head, was uncovered to the northern elevation of the excavation. Exposed at the southern elevation was the top of the arm trench. The material being removed from the hole as the excavation progressed consisted predominantly of the clayey/gravely ballast bedding. This extended down into the arm trench as the construction was exposed. Early evidence indicated that the sides of the trench had been lined with a vertical face of concrete to both the northern and southern elevations.

The concrete lining the south face of the excavation was found to be intact however the north wall contained a large void. As the excavation was deepened, firm intact clay continued to be exposed in the base of the trench. However, the work was continually disrupted owing to inundation from the reservoir. After each inundation event, the contractor removed debris and silty deposits, together with clay that had become soft and slurried, from the base of the trench. On each occasion firm clay was exposed in the base with no evidence to suggest a concrete face to the bedrock on the northern elevation had ever been placed at this particular location. No concrete residue could be seen adhering to the rock nor was any found in the joints. It is probable that this void was once filled with puddle clay laid directly against the rock as part of an even earlier local repair.

The joints in the bed rock were aligned roughly vertical and were generally between 1mm-2mm wide but up to 80mm in places. Very wet, sloppy clay deposits could easily be scraped out from the wide joints by hand. Ground water observed issuing from the fractured rock was initially silty and cloudy but eventually ran clear.

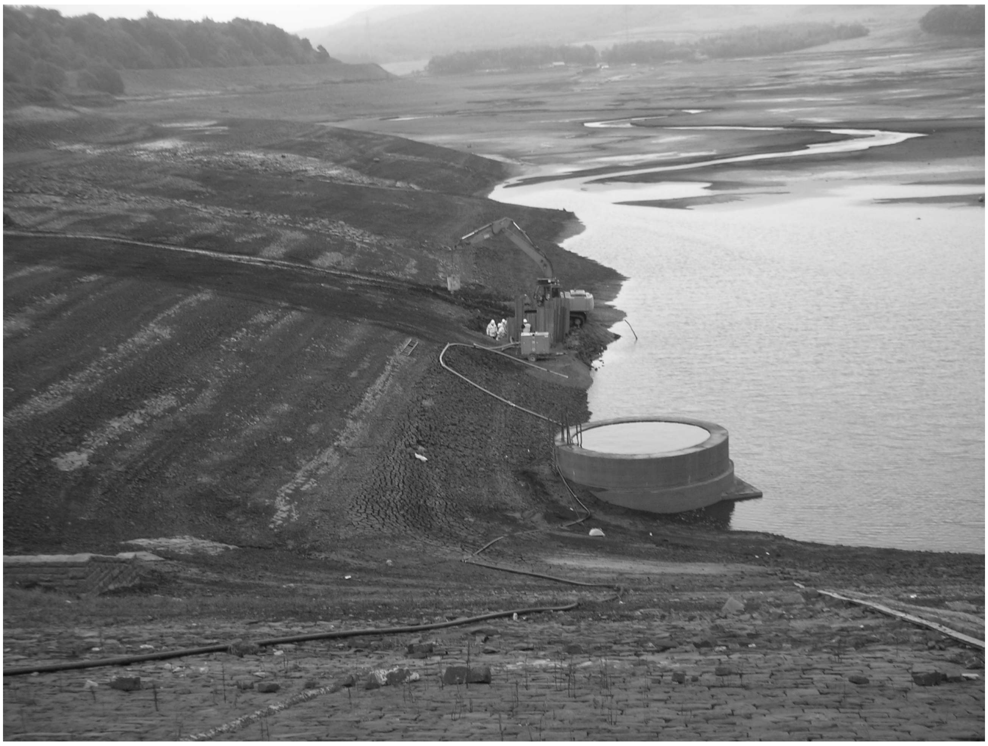

Photo 2 - Excavation at the site of the hole viewed from dam crest.
Upstream valve chamber in foreground.

Photo 3 -

View into excavation looking east showing the north face of the arm trench.

The concrete forms a cantilevered overhang below which a void had filled with ballast and clay materials.

Bedrock was encountered behind the overhang

It is postulated that, under pressure from the reservoir, clay was pushed into the fissures in the rock causing settlement and shear cracking in the deep puddle-clay filling to the arm trench. Water seeping through these cracks softened the clay and washed it further into the rock fissures causing further slumping of the clay and the eventual collapse of the masonry pitching. Eventually the flow of the acidic moorland water was sufficient to erode a path through the cement grouted rock until it eventually reached the rubble drain and the draw-off tunnel.

REMEDIATION WORKS

Owing to the continued risk of inundation disrupting the works, a decision was taken to terminate the investigation and implement remedial measures and reinstatement works.

The arm trench, including the void to the rock face behind the concrete facing, was backfilled with in-situ concrete up to the upper elevation of the vertical concrete facing. The existing clay liner, exposed around the periphery of the swallow hole, appeared to be in good condition so a new section of clay was keyed into this making the blanket continuous once more. The repair work was designed by Montgomery Watson Harza (MWH) and supervised by Mr I C Carter, an All Reservoirs Panel Engineer employed by MWH. The Contractor was Eric Wright Construction of Preston, Lancashire.

When the reservoir refilled, which it did in the space of 2 days following very heavy rainfall, the leakage flow was found to have reduced by about 75%. At the time of writing this in the spring of 2008, flow is slightly higher than that measured before May 2004. Plotting of the flow against reservoir head and rainfall may help determine if all of the flow is from the hillside or if there is still some leakage through the clay blanket.

CONCLUSION

The AquaTrack 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.

The experience at Torside, and at other reservoirs in the Longdendale chain and elsewhere, shows that clay blankets placed directly on fissured or porous foundations are likely to fail at some time. It also indicates that cementitious grouting, although in this case it lasted 50 years, can eventually fail in unfavourable environments.

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