The use of Leakage Detection Techniques to Improve Dam Safety and in Asset Management Studies

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Introduction

Leakage and leakage detection is one of the most important means of surveillance and monitoring of dams to try to ensure safety. Often we know where leakage exits from the face of the dam but we have no idea where the flow is taking place; i.e. whether it is through the dam, through the foundation etc.

In addition when carrying out risk assessment exercises one of the probabilities one has to assess is that associated with piping. Often when one carries out that assessment one has to assume whether leakage could or is happening and this probability forms the major part of the total probability of failure which put on an f-n chart results in the reservoir plotting in the intolerable range.

This paper describes leakage detection methods used to successfully track individual paths in plan and elevation. A number of case histories will describe the surveys undertaken, the results obtained, the targeted remedial works designed and the many millions of pounds saved.

In addition the results of asset management studies will be provided which shows how the survey results have been used to reduce the overall probability of failure assumed thereby allowing resources to be diverted to more wanting projects.

1. Background

Piping is one of the most likely modes of failure associated with dams. In the case of embankment dams piping usually occurs through the dam, through the foundation, or through both. In the case of a concrete gravity dam piping can take place through the foundation or the abutments. If one can detect leakage and prevent or stop it then the dam must be safer.

Most dams leak to an extent – if steady state conditions exist and remain whilst the dam is in service it is not necessarily a problem and the situation is just monitored for the quantity and “quality” of leaks. However, if leakage suddenly appears or increases in any way that the dam could be at risk, or the economic value of the leaking water is large, then often investigation and remedial works are required. Dams on karst foundations can be particularly susceptible to deterioration of conditions which could lead to failure. This investigation often has to be carried out rapidly without knowing the path of the leakage and the remedial works can be very expensive. Individual boreholes or even suites of boreholes are unlikely to intersect or identify individual leakage paths.

In most cases, although not all, the exit path of leakage can be found, and in some cases by slowly lowering the water level one can find the point at which water leaves the reservoir. What usually cannot be traced is the exact route of leakage water through or under the dam – until recently.

2. The Willowstick Technique

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 – ie the dam and its foundation. The technique was first used in contaminated land but is now used extensively in the field of dam engineering.
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) 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 variations of electrode and circuit wire configurations and interpretive parameters.

For a leaking dam survey, electrodes are placed upstream and downstream of the embankment or structure. The upstream electrode is placed in the reservoir water at 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 electric 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. In most cases, the paths of least resistance for electrical current are those which follow zones of higher interconnected porosity within the saturated subsurface. As the electrical current takes various preferential flow paths through, beneath and/or around the dam, 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 highly 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. The locations (coordinates) of measurement stations are obtained using Differential Global Positioning System (DGPS) 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 characterisation of groundwater beneath the area of investigation.

![Fig. 1. Typical horizontal dipole (plan view)](image)

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. Magnetic field measurements are generally taken along lines ranging from 5 to 15 metres apart with stations on each line spaced at 5 to 15-metre 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. The process can be used on and around embankment dams, in the area downstream of concrete dams, and even on boat over the reservoir when necessary.

3. **The Use of ‘Willowstick’**
The case histories cited below illustrate the Willowstick process can be used in three different ways associated with the management of dams.
Fig. 2. The Willowstick process

Obviously reacting to a new leak is a reactive process, requiring often a rapid response, rapid analysis and then actions, perhaps including reservoir drawdown to bring about a safe reservoir via some targeted remedial works.

The most common situation is the proactive approach whereby an owner is aware of a leak which might be getting progressively worse or starts to change in character in terms of the quantity and ‘quality’ (turbid flow or deposition of fines), or the owner starts to become uncomfortable with the condition of the dam (minor indications/reed growth/wet patches) and wants to find out what the source of the leakage is and to be able to decide whether a potentially dangerous situation is developing.

Once this has been done a decision can be made whether the leakage is reservoir safety related or not, whether in fact it is reservoir water or ground water, whether remedial works are necessary or not, and if required then a target remedial response can be designed.

The significant advantages that the Willowstick process gives to an owner and a dam engineer is the fact that it enables individual leakage paths to be identified both in plan and in elevation. Remedial works can then be ‘targeted’ on those positions, for example grouting or piling/diaphragm walling techniques need only be actioned in the areas of the known leakage. Knowledge relating to the depth of the leakage feature enables the most appropriate construction technique and plan to be chosen and the overall result for the owner is significant cost savings over solutions which are based on incomplete or assumed knowledge necessitating an extended area to be repaired, but it also leads to an improved level of confidence in the safety of the structure as a result of knowing that a leakage path has been sealed. Surveys can be undertaken before and after any remedial works to check on the impact of the repairs.

The effectiveness of grouting ‘repairs’ to dams can reduce with time – either because seepage paths have not been totally filled or perhaps because the grout type was not chosen correctly and reservoir water is causing the grout to be eroded, or a number of other causes including the solution of karst features. Recently the Willowstick survey process has been repeated on a dam 4 years after remedial works were carried out and this identified a marked reduction in the performance of the structure since the time of the remedial works.

Asset management by an owner of one dam or a portfolio of many dams is another way in which the Willowstick system is being used. Surveys are carried out on the dam or the portfolio at say 5 or 10 year intervals perhaps just before any planned independent safety inspection and in this way it can be seen whether there has been any change in condition and therefore performance over the period. This information can be used in a number of ways; it can be used to try to estimate rates of deterioration of a potential type of dam construction in a particular setting and under a particular operating regime, or it can and has been used successfully in portfolio risk assessment (PRA) – or risk assessment of individual dams. If one is able to say with certainty that there is little or no leakage through a dam, then the probability of failure associated with piping can be significantly reduced or perhaps even removed. Which
when capital programmes and remedial works are being developed and prioritised on the basis of perceived risk, this can have a significant effect and benefit. This is a useful input to a PRA exercise or individual risk assessment.

If dams plot in the intolerable region unless one can reduce the population at risk the only way of moving the dam into the ALARP region or tolerable area is to reduce the probability of failure. Often when one looks at the total of the probability of failure it is built up of components due to flood risk, internal erosion/piping and stability. Clearly if one can reduce the degree of uncertainty and so there is no leakage paths then that element can be taken out of the total probability. Thus, the risk profile changes dramatically and resources can be directed at the more appropriate sites when the investment would be better placed.

Some dams sit on foundations which do not promote the observation of leakage downstream of the dam. For example many of the dams in the River Thames valley basin sit on 30 to 40 metres of alluvium into which any leakage through the clay core of the dams would pass – giving no indication of any leakage on the surface. Greenbooth near Rochdale, UK, suffered from severe problems associated with piping and internal erosion in the 1980’s, which eventually manifested itself as depressions which formed in the crest. Even though the failure process had progressed significantly, no flows were measured in the drainage system and no leakages were noted downstream because the geology at the site dipped steeply downstream. If the Willowstick survey system had been available and used in a proactive/asset management role then the incident would have been avoided.

4. Examples

4.1 Dolwen Reservoir, North Wales
This embankment had leakage problems which manifested itself as wet areas on the toe of the embankment, adjacent to and in the spillway channel, and there was a suggestion that minor undulations in the downstream face were signs that the leakage was the cause of some instability.

The independent Inspecting Engineer, upon review of the performance of the dam, recommended that the reservoir level be kept down by about 2 metres, because this was where seepage/leakage seem to stop. This resulted in a significant loss of water resource for the owner.
The stability issues were thought to be deep seated and there were worries about piping failure occurring.

In the past remedial works had included a slight raising of the dam and an incorporation of a concrete diaphragm wall and its associated concrete foundation. Willowstick was asked to do a survey under the direction of an Atkins Panel Engineer.

The reservoir was filled by the owner to top water level and soon afterwards a Willowstick survey was undertaken. The survey showed three seepage paths; one either side of the drawoff shaft in the centre of the embankment and one under the weir of the overflow. The flow paths were shallow; just under the foundation of the diaphragm wall and just under the spillway slab, indicating that deep sealed slips were unlikely, that it was likely that the new ‘diaphragm wall’ had not been properly ‘connected’ to the original dam core in places, and that there was a seepage path beneath the slab of the spillway. All useful information on which to judge the safety of the structure was assembled and the leakages were seen to be very small in character and not linked to the wet areas either on the toe or in the spillway described by the owner. It was suggested to the owner that steady state seepage conditions may not have become established because the reservoir had been kept low for so long, and knowing that there were no significant leaks feeding deep seated slip places that the reservoir should be kept full for some time and the survey be repeated.

This was done and the water kept high for a number of weeks on site. An area on the toe had become wet and there were now flows in the spillway. The Willowstick survey was repeated and the same three leakage paths were identified but with an important difference. Upon analysis the two leaks either side of the drawoff shaft had not changed – they were rather small, insignificant, and shallow – just under the diaphragm wall. The leak under the spillway however, was more significant and water was being driven not only into the spillway channel but parallel to it down to the toe to feed the wet patch at the toe, all of which became clear in the comparison of the repeat survey to the original. The Atkins advice to the owner was that the underside of the spillway should be grouted or a shallow cutoff be provided and that the action would stop most of the leakage. The advice was that the leakage either side of the drawoff was minor and could be left to a later phase of their capital programme if the owner wished because the flows were small and shallow and that deep seated slips were unlikely. Most importantly the reservoir could be full to top water level and be operated safely with the peace of mind there was no ‘insidious’ piping/seepage process taking place.

4.2 Samanalawewa Dam, Sri Lanka
The Samanalawewa Dam is located in the island country of Sri Lanka just off the southern tip of India. The dam is located approximately 160km southeast of the capital city, Colombo (see Fig. 5).
The Samanalawewa Dam impounds the Walawe River, the 5th largest river in Sri Lanka. The Walawe River, in conjunction with another major tributary—the Belihul Oya River—flows from the mountains of central Sri Lanka. The two rivers flow in parallel valleys in a southeastern 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 Belihul Oya River) and Katupath Oya (a tributary of the Walawe) is over 300 metres. This difference is used as the head for Power Generation.

The construction of the Samanalawewa Dam was started in 1986 and completed in 1991. The dam and resultant reservoir are one of the largest storage facilities created in recent times in Sri Lanka. The dam is a zoned rockfill embankment with clay core. The dam is roughly 105 metres high and 530 metres long and retains a reservoir with a capacity of 254 Mm3. The catchment area of the dam covers nearly 350km2. 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 (see Fig. 6).
**Geological setting**

The project is located in the Balangoda region of the Central highlands of Sri Lanka. 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. During the investigation and construction phases of the reservoir it was recognised that karstic features were likely to be common in the right bank. A karstic feature, a cave, was discovered during the construction phase 300 metres 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 routed on site.

**Measures to limit water losses**

During the construction of the dam, four adits were driven along the axis of the dam and used for a grouting exercise.

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 responding to the reservoir levels up to a distance of 2.5km from the dam (along the reservoir’s right rim). 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 the 22nd October 1992 water burst out of an area downstream of the right abutment of the embankment when the water had reached a level of 439.01 metres AOD. The water level was immediately lowered to 430 metres AOD over a period of 3 weeks ending on the 11th 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 2-3 metres in the abutment area. Nearly 25000m³ 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 from 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 help reduce marginally the groundwater pressure in the right abutment.

Some £58M had been spent on remedial works up to the time of the Willowstick survey.

**Willowstick survey layout**

The Willowstick investigation of the right abutment study area employed two horizontal dipole electrode configurations to energize the subsurface 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).
Seepage is concentrated beneath the dam’s right abutment rather than underneath or through the earthen embankment. It follows a series of braided paths both north and south of the tunnel. Based on modelling and posted elevations shown, seepage north of the tunnel is near the elevation of the reservoir level at the time of the survey (about 440m). The model also suggests that seepage north of the tunnel occurs above the tunnel and finds an opening in the adit’s grout curtain very near the 440m elevation. Seepage south of the tunnel flows a few metres deeper at elevation 438m. At the location where the two flow paths converge, east of the adit, the elevation of the preferential flow path drops a little more rapidly as it flows to the discharge point out of the hillside. There is some seepage occurring along the right rim grout curtain, but not to the extent that it is flowing through the right abutment study area. It was recommended that any seepage through karst topography be carefully monitored and remediated to insure the integrity of the structure and safety of those residing downstream.

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

The work will involve measures:-

- to close 2 significant gaps in the existing supplementary grout curtain
- to locate and fill major karstic features at approximate elevation of 438M which would cost about £2M

4.3 King George V - UK
A third example involved a non-impounding reservoir with a crest length of some 7 kilometres. Suddenly a leak appeared about half way up the downstream shoulder. Water levels were reduced until water level was about 1 metre below top water level.
Most in the owner’s organisation assumed that desiccation had occurred in the upper part of the core but the reservoir safety manager was concerned and asked for a Willowstick survey. The construction of the dam was a thin central clay core with gravel shoulders sitting on gravel foundation. With a thin clay cut-off, there were concerns that leakage and erosion could go unnoticed.

A coarse survey of the whole perimeter was carried out to show the owner whether there were any other leaks through the embankment. No other leakages were noted. In the area of known leakage the survey showed that the leak passed through the core at the interface within the original ground.

Remedial works involved a targeted section of core replacement using a slurry wall technique. Research into historical records showed that the defect had appeared on the line of the original river channel.

5. Conclusion
Ensuring dam safety involves using a toolbox of techniques and approaches. Willowstick is a powerful tool not only to trace leaks and to target remedial works but now as an asset management tool to reduce uncertainty and assist in the qualification of risk.

Development of the equipment in terms of weight reduction, speed of response and accuracy is continuing. Improvements are also being made to reduce the cost of the surveys and improve the way information is analysed, transferred and presented. The next phase may well be real time monitoring.

Owners have benefitted in a number of ways including:

- Greater knowledge
- Greater certainty and comfort in the preference of their structures
- Significant savings in remedial works.

The Authors
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hydraulic engineer and hydrologist and has written a large number of technical papers and research documents. He has managed groups of individuals and professionals, departments and firms to the benefit of each organisation. Dr Hughes is advisor to the UK’s Environment Agency with respect to the Reservoirs Act 1975, emergencies, incidents and accidents. He is also a member of the UK Register of Expert Witnesses, has acted as Expert Witness in a number of high profile cases with respect to dams and reservoir legislation and is advisor to the British Government on Reservoir Safety.

V. GARDNER has been with Willowstick since 2008 working to help clients find detailed answers to their frustrating subsurface water seepage issues. Mr. Gardner started with Willowstick focused on the mining industry where Willowstick had few clients. He has developed mining into one of Willowstick’s strengths with clients in gold, silver, copper, lead, zinc, phosphates, trona, salt, coal and aggregates. Since 2013 he has been focused on all of Willowstick’s core industries including hydro dams, mining, oil & gas as well as environmental remediation. His current geographic focus is on Europe, Africa and India. He has seen clients progress from using Willowstick only reactively, when they had unexplained seepage; to proactively, when they wanted to gain more insight; to now as tool to help them manage their water-related assets.