Roadford Dam - 20 years of monitoring

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SYNOPSIS Roadford dam, located in the south west of England, is one of only six dams in the UK that have upstream asphaltic concrete membranes. The embankment is constructed of a low grade rockfill. The dam was extensively instrumented during construction and many of these instruments are still being monitored 20 years after installation. The paper discusses the instrumentation and geochemical monitoring, and the value of the observations in assessing dam performance. Monitoring has indicated the chemistry of the drainage waters has remained within acceptable limits and is related to rainfall and water level, and varies over wide ranges. These unique long term measurements demonstrate the value of a well designed system and conscientious monitoring on the part of the owner.

INTRODUCTION

Roadford Dam forms a reservoir on the River Wolf, a tributary of the River Tamar, to supply water to Plymouth, south west and north Devon. The dam is an embankment, 41 m high and 430 m long, formed from 1,000,000 m^3 of low-grade rockfill obtained from a borrow quarry within the reservoir basin[1]. The waterproofing element consists of an asphaltic concrete membrane on the upstream face, the most recent of six dams in the United Kingdom with this form of construction[2]. A public road runs on the crest of the dam. The reservoir impounds 37,000 Ml of water. Impoundment commenced in October 1989.

EMBANKMENT

The membrane consists of two layers of bituminous material laid over a drainage blanket placed on the embankment fill. The membrane connects into the concrete inspection gallery and cut-off at the upstream toe[3].

The embankment is predominantly made up of compacted rockfill from the quarry – a mixture of rock types ranging from sandstone and siltstone to mudstone and shale, from the Crackington Formation, part of the Culm

Measures of upper Carboniferous age. The embankment fill was placed by mixing the various strata with a ratio of 50:50 mudstone:sandstone.

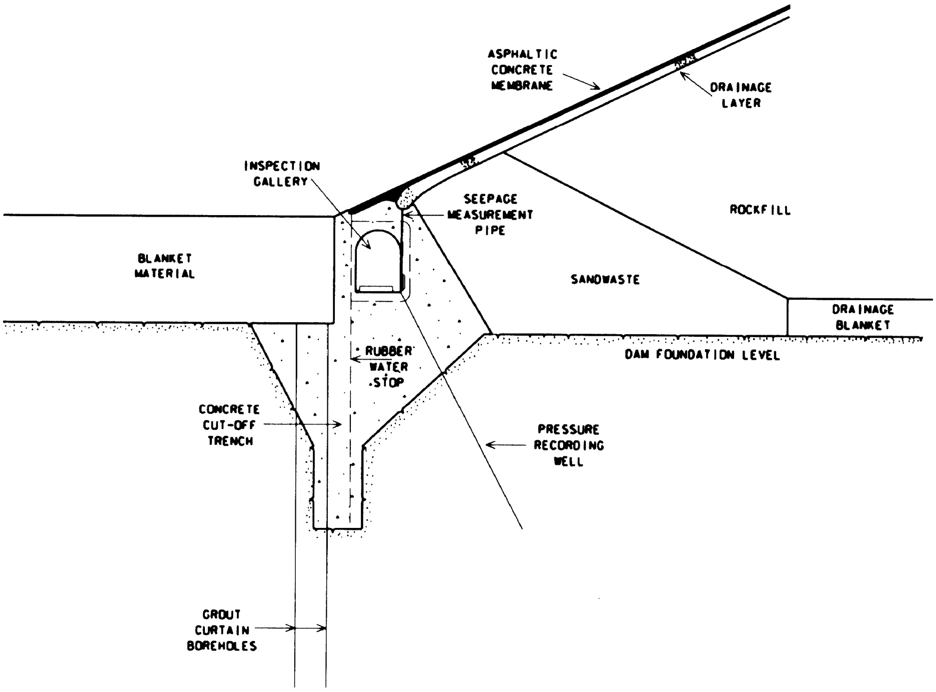

Figure 1. Upstream toe detail

China clay sandwaste was used downstream of the concrete cut off to minimise differential settlement under the asphalt concrete membrane. Downstream of the sandwaste zone the bank is underlain by a foundation blanket resting on the bed-rock.

<u>Chemical Degradation</u>

The rockfill, in particularly the mudstone, contains minerals which are prone to degradation by chemical weathering. The principal mineral components consist of clay minerals and quartz with minor amounts of iron sulphide (pyrite), iron bearing carbonate (siderite) and organic carbon. Samples from the fill indicated an average pyrite content of 1.12% although values up to 2.4% were recorded in fresh mudstone. The fill was markedly acidic; pH values ranged from 3.1 to 6.4 with most samples in the range 4.0 to 4.5[5].

Degradation may affect the properties of the dam fill material and make the water draining from the dam unsuitable for discharge to the river. The degradation is due to oxidation of pyrite when the material is excavated and exposed to air and water as embankment fill. This results in the generation of acidic drainage water with high sulphate and metal content, which could attack clay minerals and soluble carbonates in the fill and cause pollution of downstream watercourses. An allowance for long term degradation of the fill materials due to geochemical weathering was made in the selection of the design parameters for the embankment[1].

The embankment fill is protected by the upstream membrane, the crest road and the soiling, grassing and drainage of the downstream face. This was intended to limit ingress of air and water to minimise the rate of chemical degradation by the oxidation of pyrites.

The design of the embankment utilises the foundation blanket to keep the embankment from becoming saturated. The foundation blanket material was an altered dolerite, which was found to have a significant content of calcite. There was concern that acidic drainage from the embankment fill would react with calcite in the foundation blanket, leading to precipitation of gypsum (calcium sulphate) and ochre (hydrous iron oxides) which could clog the blanket and prevent it functioning, leading to a build up of pore pressure in the embankment fill. There could also be settlement due to leaching of material in drainage water. Investigations carried out during construction[5] indicated that the scale of the reactions was unlikely to significantly affect the performance of the foundation blanket or the embankment as a whole.

Differences of opinion existed between various advisors on the composition of the rock fill from the Crackington Formation, and the chemistry and rate of the degradation processes likely to affect the fill[4]. Monitoring of the chemistry of drainage waters from the embankment was therefore instigated[6], both to assess the implications for stability and functioning of the dam (in conjunction with other monitoring such as pore pressures and settlement).

Monitoring of the drainage water chemistry was also required to enable the treatment needs to be assessed. The River Wolf downstream of the dam is a high quality watercourse and agreement had to be reached with the regulatory authorities (at the time of construction this was the South West Water Rivers Unit, now the Environment Agency) on what measures were required to ensure the drainage waters did not damage the water quality. Particular concern was expressed about iron, manganese and lack of dissolved oxygen in the embankment drainage[5]. These contaminants are derived from weathering of pyrite in the embankment fill. A woodland irrigation system was developed, which proved to be effective at removing the iron and manganese and reoxygenating the water[5,6]. A dedicated treatment system using settlement lagoons and cascade discharge through limestone rock filled channels has subsequently been installed. Continued monitoring of the drainage water was required in case the composition of the drainage changed and the system would no longer be able to cope.

INSTRUMENTATION

An extensive range of geotechnical instruments were built into the embankment to monitor its performance. These include piezometers in the foundation and the embankment, vertical settlement and horizontal extensometers and electrolevels to measure settlement in the asphalt membrane[7].

Pore pressures are currently measured fortnightly in hydraulic piezometers at three cross-sections through the dam within the foundation, rockfill and sandwaste. Inspection gallery pressure recording wells, with taps closed, are monitored weekly.

Drainage flows are recorded weekly from meters M4 and E5, pressure relief wells and membrane drains. Monthly readings are taken at vee-notches in manholes W3 and E4, drainage adit and individual pressure relief wells.

Settlement is monitored monthly at embankment magnetic plate gauges at the three cross-sections. Membrane electrolevels are currently recorded monthly, although many of these have now failed or become unreliable. These are to be abandoned. Levels are taken on the embankment crest and downstream slope, and crest wall copings six-monthly.

Displacements are measured annually on horizontal extensometers in the embankment and joint movement tell-tales in the access galley.

DRAINAGE

Any seepage through the membrane is collected in the underlying drainage layer and discharged into the inspection gallery where the flow can be monitored[7]. A series of pressure recording wells can act as shallow drains for the foundation immediately downstream of the cut-off.

From small flows observed from the membrane drains shortly after impounding, during the first winter in 1989/90 membrane drain flows increased significantly in line with rising water level. Flows virtually ceased during the next summer. During the next winter, when the reservoir approached full, flows increased significantly, with flows the following summer again virtually ceasing. This trend has continued although winter drainage flow peaks have generally been on a gradually reducing trend with some correlation with water level. Water temperatures vary between approximately 20°C in summer, corresponding to minimal flow in the membrane drains, to 5°C in winter when flows are at a maximum. The majority of the membrane flow originates from the area between the access tunnel and the centre of the dam.

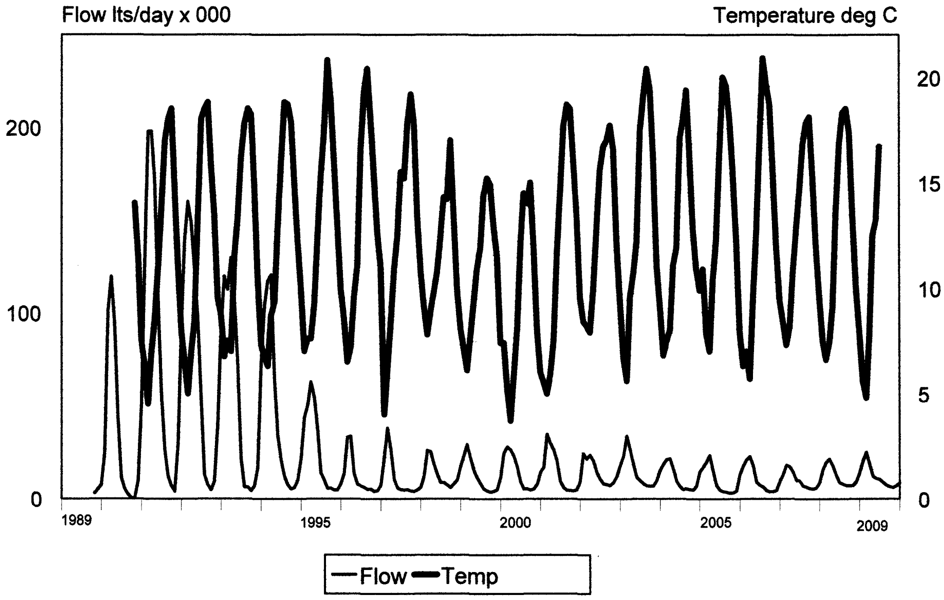

Figure 2. Membrane drainage flows

It has been suggested[9] that the leakage may be a function of the thermal expansion/contraction of the asphaltic concrete when local imperfections open during cold weather with a corresponding increase in leakage. The gradual decline in maximum membrane leakage rates suggests that these local imperfections self-seal with time. A crack along a vertical day joint in Panel D47 about 5m to 8m below the crest has been observed. This is in the area of membrane flows into the gallery.

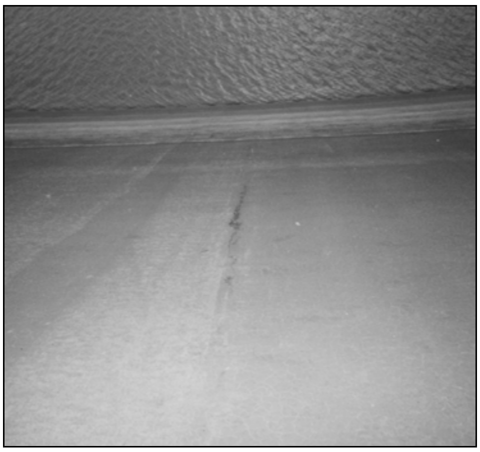

Figure 3. Day joint in Panel D47

The total embankment flow from west of the culvert shows a seasonal response with increases following heavy rain being evident. There is some influence from reservoir level. Flows in recent years have been in the range 0.37 Ml/d to 0.85 Ml/d.

Underdrainage from east of the culvert and the downstream pressure relief wells respond to rainfall with a base flow that is dependant on reservoir level and groundwater level. Flows have generally declined from first filling. The highest flow in recent years has been 40,000 l/d.

PRESSURE
As would be expected, the foundation piezometers upstream of the cut-off respond to water level. There is also some response of the downstream piezometers but the pressure differential between the two sets shows that the cut-off is effective. Piezometric pressures in the foundation downstream of the cut-off generally remain within the drainage blanket.

Pressures recorded by the instruments in the sandwaste are fairly stable, with most levels being close to the tip installation level.

Piezometer readings have been stable in all three of the monitored zones of the embankment fill. Two piezometers in Zone B, which are in the same area as gallery segments 25 and 26 where the main drain flows are recorded in winter and early spring, also show similar seasonal trends.

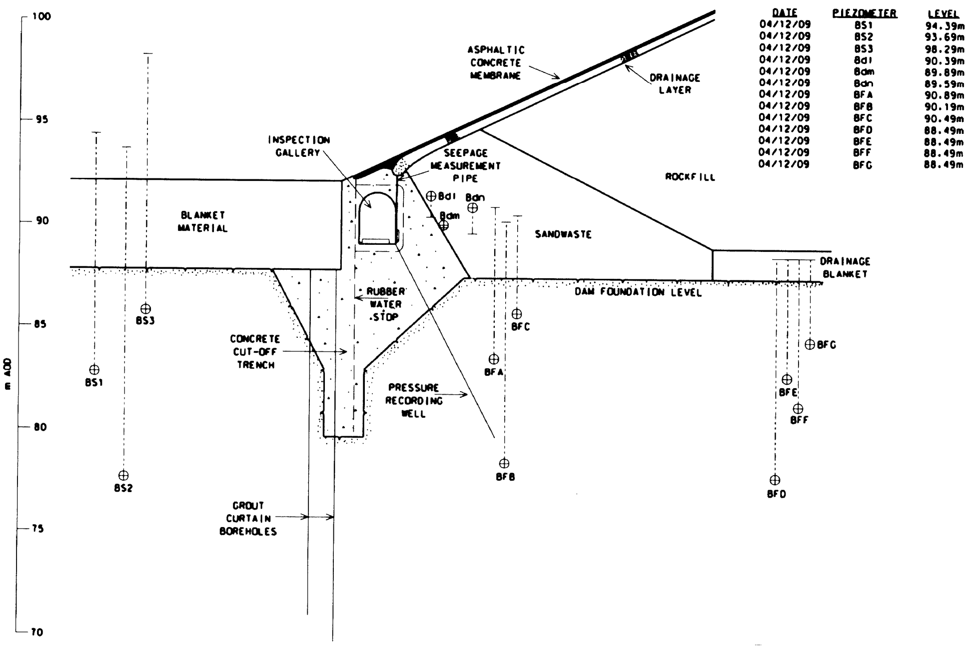

Figure 4. Piezometric Profile

SETTLEMENT

Crest coping levels have indicated a reducing settlement trend with time. Maximum settlement at the crest copings since impoundment in October 1989 has been 447mm. This is well within the freeboard design allowance of 981mm. Similar measurements have been recorded by the vertical magnet settlement gauges for the same period. An additional 110mm settlement was measured by the settlement gauge prior to impounding.

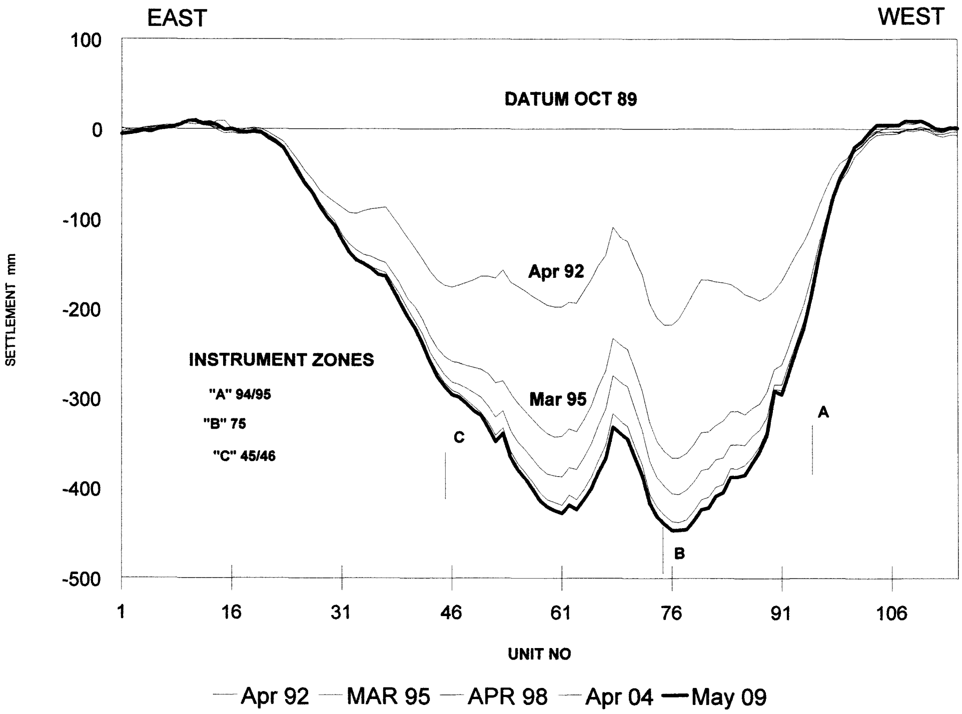

Figure 5. Crest settlement

The twin settlement troughs either side of the centre of the valley, clearly identifiable in Figure 5, are visible in the parapet wall. It is believed these are an indication of collapse compression coincident with higher water content of the fill. Zones of higher settlement are coincident with areas of membrane drain flows. See Figure 6.

Roadford has shown considerably more settlement than Brianne, Megget, Scammonden and Winscar dams which have also been monitored for long periods[8]. The data is plotted in Figure 7 as vertical strain. Maximum settlement since end of construction corresponds to a vertical strain of 1.32%.

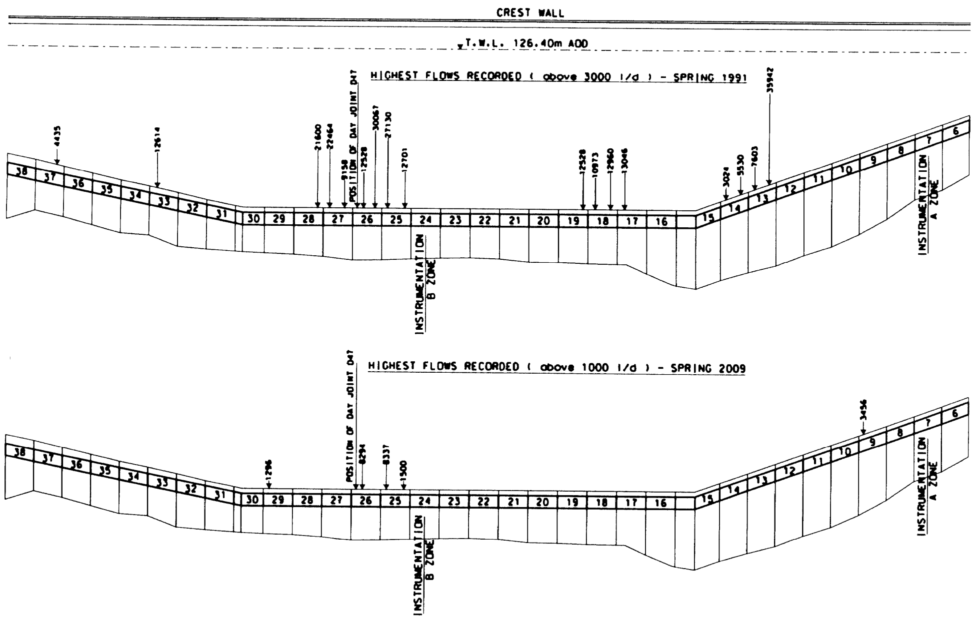

Figure 6. Position of membrane drain flows

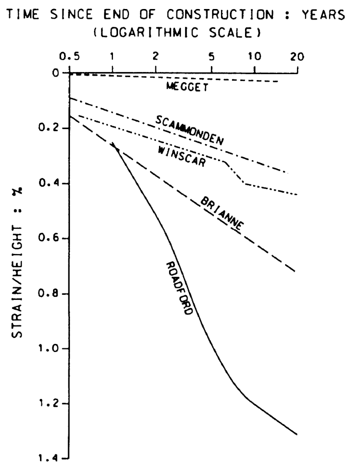

Figure 7. Post construction long-term settlement of crests (after Charles[8])

To monitor deflection at the sand waste transition zone at the toe, an electro-level system was installed immediately under the membrane at the three instrumented sections along the dam[7]. Details of the system and observations for the first five years are described by Tedd et al[10,11]. The deflections of the membrane normal to the slope and relative to the toe of the dam are shown in Figure 8 for different times after impounding. The largest deflections occurred between the toe and 1m up the slope (17mm per m) and at the sand waste/rockfill interface (12.5mm per m). There has been very little differential deformation over the area where the sand waste was placed. Figure 8 also shows a simple prediction of the membrane deflections based on the compressibility of the sand waste from 1m oedometer tests.

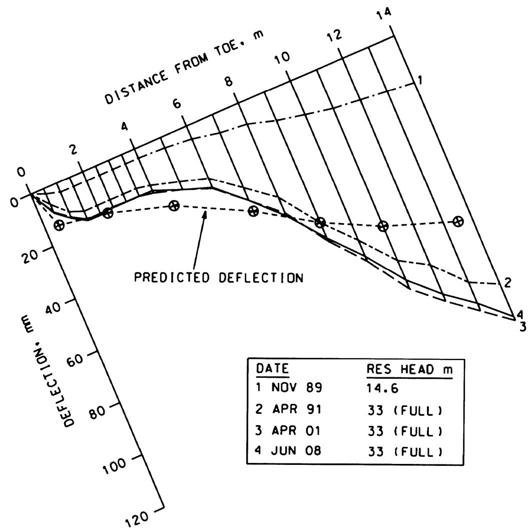

Figure 8. Deflection of the asphaltic membrane

CHEMICAL MONITORING

Initially a wide range of chemical parameters was measured on weekly samples of drainage from the east and west sides of the embankment in manholes E5 and W6 respectively. The chemistry of underseepage, local groundwater and a drainage adit was also measured to obtain information on the background concentrations of the various parameters. For assessment of the effects of chemical weathering, the key parameters were pH value, sulphate and calcium concentrations. For treatment of the drainage waters, iron, manganese and suspended solids were the key parameters.

The embankment drainage consists of a mixture of underseepage, which is dilute and has a pH value of between 6.5 and 7.0, and drainage from the embankment. Measurements of drainage from trial embankments of rockfill during the site investigation for the dam indicated that this would be acidic, with a pH potentially less than 4.0, with high concentrations of sulphate, metals and other ions[5]. This would be modified by reaction with calcite in the foundation blanket.

Compared to groundwater and underseepage, the embankment drainage water has much higher concentrations of sulphate, bicarbonate (alkalinity), calcium, magnesium and manganese. It also has a higher pH value, but lower concentration of iron. These differences can be attributed to chemical reactions within the embankment.

A clear seasonal trend was apparent in the embankment drainage from the start, with much higher concentrations of sulphate, calcium, magnesium and manganese in winter than summer. This reflects greater percolation of rainwater through the rockfill during the winter months.

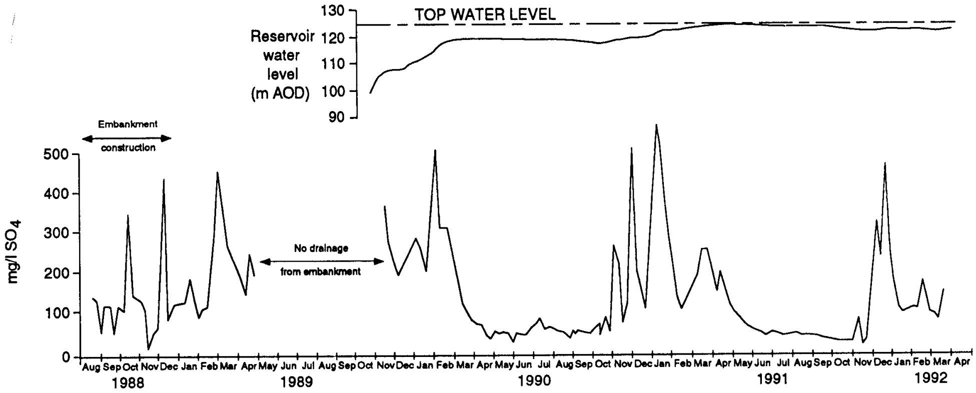

Figure 9. Sulphate content of embankment drainage (after Davies[5])

This seasonal trend has been maintained ever since, with concentrations of most parameters remaining in broadly the same range. It had been expected that with time the rate of chemical reaction in the embankment would decrease. During the construction phase the entire embankment was open to the atmosphere, whereas after construction there would be decreased percolation of rainwater due to the presence of the upstream asphaltic membrane, crest road and topsoil and vegetation on the downstream face. However, the seasonal pattern has continued and appears to be related principally to rainfall.

Monitoring of pore pressures has confirmed that there is no build up of water within the embankment and the dam is still functioning as designed. See Figure 4.

As there has been no change in the pattern for 20 years now, it is likely that the present range of drainage water chemistry will persist indefinitely. The embankment drainage will therefore continue to need treatment.

The pH value shows an inverse relation to sulphate (see Figure 10), dropping when sulphate is high and rising when it is low. Calcium shows much less variation, indicating that the drainage water is saturated with calcium carbonate due to dissolution of calcite from the foundation blanket. Estimates of the amount of pyrite and calcite removed by weathering are calculated from the calcium and sulphate concentrations and the drainage flows on a quarterly basis. The rate of loss of material has remained roughly constant on an annual basis, though the amount in any quarter or year is affected by the rainfall.

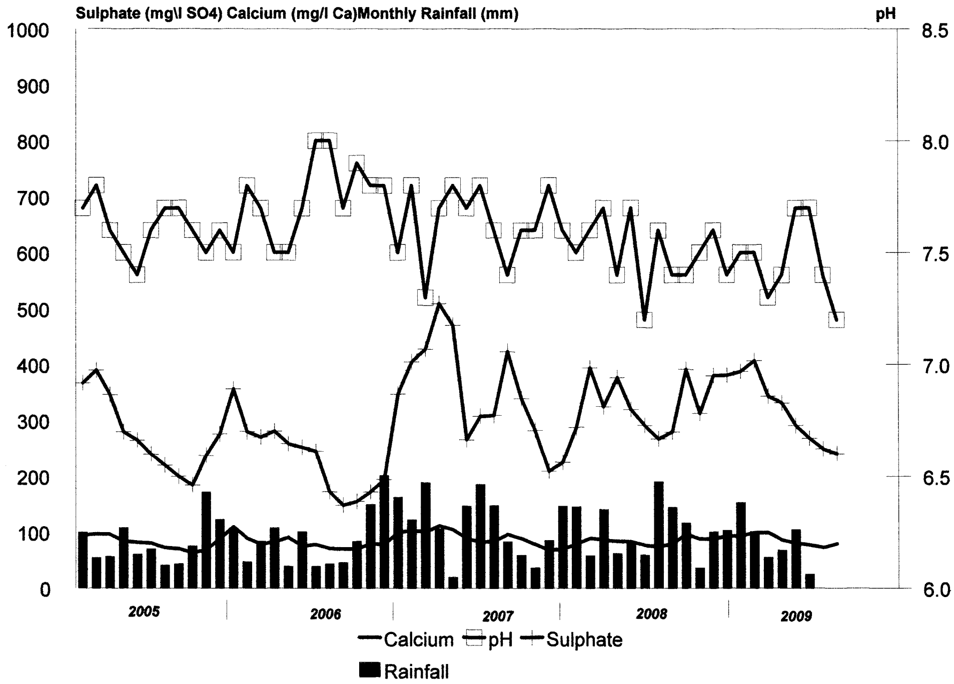

Figure 10. Manhole W6 sulphate, calcium and pH 2005-2009

The calculations suggest that in the 20 years to the end of June 2009, 2.7% of the pyrite and 4.7% of the calcite has been consumed by chemical reactions. The figures should be regarded as estimates, but help to indicate the scale of the reactions. The figure for calcite is of greatest concern as if the readily available calcite was used up, there would be a rapid drop in the pH of the drainage and a rise in sulphate and metal concentrations, with implications for the treatment of the drainage waters before release to the River Wolf. The figures indicate that this is unlikely to occur in the medium term, but could occur when the dam approaches 200 years in use.

Over the 20 years since impounding started, the dam has experienced a wide range of weather conditions, from very wet years in 2000/01 to extended droughts. Geochemically, the greatest concern is during sustained wet periods as the rate of leaching of weathering products could exceed the ability of the foundation blanket to neutralise them. This would be shown by a rapid drop in pH and rise in sulphate and metal concentrations. During the very wet period of 2000/01, the pH values of the embankment drainage dropped below 7.0 (neutral) for a period, though they subsequently recovered when the rainfall decreased.

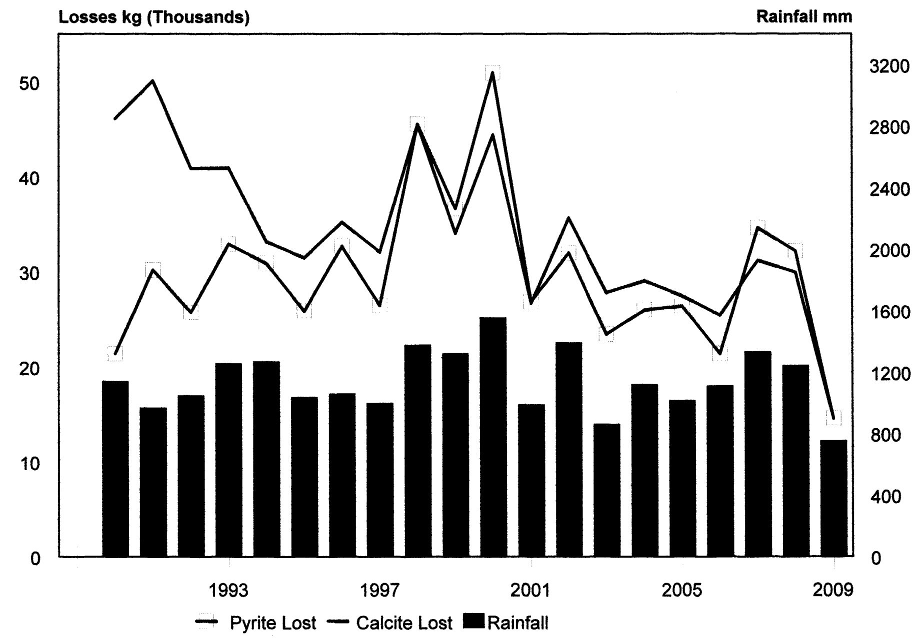

Figure 11. Annual loss of pyrite and calcite

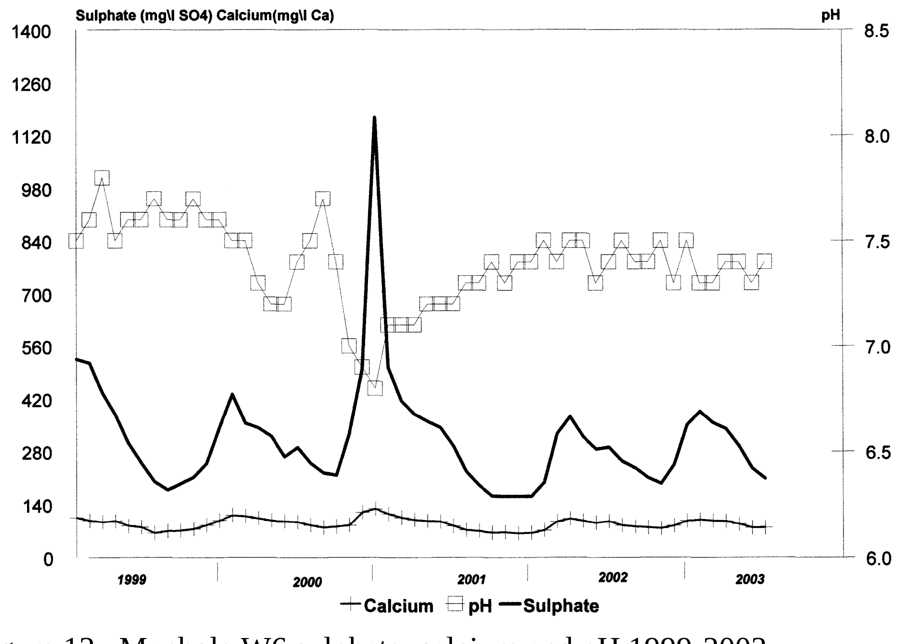

Figure 12. Manhole W6 sulphate, calcium and pH 1999-2003

In order to guard against this possibility, chemical monitoring of drainage waters is continuing. However, the extent of this has been decreased considerably over the years as knowledge of the variation of the chemistry has increased. For some years now, limiting values have been set for two key parameters; pH value and conductivity (this relates directly to sulphate and is easier and quicker to measure). If the pH value of monthly samples falls below 7.0 or if the conductivity exceeds 1500 µS/cm, monitoring of the full suite of parameters will be resumed and the situation reviewed. These parameters were breached in 2000/01, but have not been exceeded since.

CONCLUSIONS

The extensive instrumentation of the dam and the continued maintenance of many of these instruments over the past 20 years have shown that the dam continues to perform much as anticipated. Foundation pore pressures remain generally within the drainage blanket. Drainage flows remain within acceptable limits and are generally reducing with time. Settlements, whilst being fairly high, have significantly reduced with time and remain within acceptable limits.

The particular geochemical reactions arising from the use of local low grade rockfill containing pyrite, and the interaction of this with calcite in the foundation blanket, has meant that the chemistry and mineralogy of the construction materials had to be investigated and assessed during construction. The chemistry of the drainage waters has been monitored to ensure that the assumptions made during construction have not been exceeded, both in terms of the performance of the dam and the treatment requirements for the drainage waters. This has led to accumulation of a large amount of data on the long term geochemical performance of the dam, as well as on engineering parameters such as pore pressures, drainage flows and settlement.

The geochemical monitoring has confirmed that the chemical reactions predicted during construction continue to operate and remain within predicted bounds. The reactions do not show any indication of decreasing with time, but there does not appear to be any threat to the stability of the dam. There will be an ongoing requirement to treat the drainage water, however, to avoid pollution of the River Wolf.

Over the last 20 years the dam has experienced severe drought and the wettest year on record. The buffering capacity of the system has coped with these extremes successfully giving confidence for the dam’s future. Chemical monitoring will continue on a reduced scale for the key parameters pH value and conductivity so that any significant changes can be picked up and the impact assessed. These unique long term measurements demonstrate the value of a well designed system and conscientious monitoring on the part of the owner.

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