Remedial grouting works at Upper Rivington Reservoir

P. J. RIGBY, United Utilities Engineering, Warrington, UK
K. D. GARDINER, United Utilities, Warrington, UK

SYNOPSIS In January 2002 a serious leak into the culvert below the Yarrow embankment of Upper Rivington led to a rapid drawdown of the reservoir being required. Subsequently a grouting programme was undertaken during which a defect in the puddle clay core was identified. A geophysical survey was undertaken which revealed that the grout curtain had successfully sealed the original leak but that other seepage paths existed around the curtain and beneath the dam.

A weighted filter was identified as the most likely solution and contract documents were prepared. However, before tenders were invited an event tree analysis was carried out to identify the most likely failure modes. This was done using the "Toolbox" methodology developed by the United States Bureau of Reclamation, the US Army Corps of Engineers, The University of New South Wales and URS. This process showed that the most likely mode of failure was erosion of the puddle clay in the base of the shallow cut-off trench by water flowing in the fissured rock beneath. Failure by seepage through the dam was shown not to have a sufficiently high probability to justify the planned remedial works and the tender was not issued. Instead a contract was awarded to grout the fissured rock at its interface with the core.

INTRODUCTION

Upper Rivington Reservoir is situated approximately 2km north west of Horwich, near Bolton and 4km south east of Chorley. The reservoir is one of a cascade of five reservoirs that supply Rivington WTW (Table 1).

The Yarrow embankment of Upper Rivington is located on the west side of the reservoir to the north of the Horrobin embankment, which separates the Upper and Lower Rivington impounding reservoirs. The embankment has an overflow weir at its southern end and the spillway runs down the mitre and discharges into the River Yarrow. Twin valved scour mains discharge into a culvert passing under the embankment and into the watercourse at the foot of the spillway. The dam is a Pennine type earth embankment dam, constructed from locally sourced materials with a central puddle clay core and a cut-off extending approximately 2m into the underlying rock

(Figure 1). The founding material across the embankment comprises a variable mix of Alluvial deposits, Glacial Deposits and Rock, reflecting its location within an existing river valley.

Table 1 Embankment Details

Design Engineer	Thomas Hawksley
Date of completion of construction	1857
Type of Construction	Earth Embankment with central puddle clay core and core trench
Maximum Height	12.2m
Downstream slope	1:2
Upstream Slope	1:3
Embankment Crest Length	300m
Crest Width (at centre)	5.0m
Upstream protection	Stone pitching
Crest Level	131.35mOD
Reservoir Capacity	1092 Ml
Top Water Level	129.28mOD

Alluvial material was located towards the centre of the dam during investigations, along the line of the previous course of the River Yarrow, and is described as a soft grey Clay with peat inclusions. These deposits proved to be of the order of 1.5m in thickness.

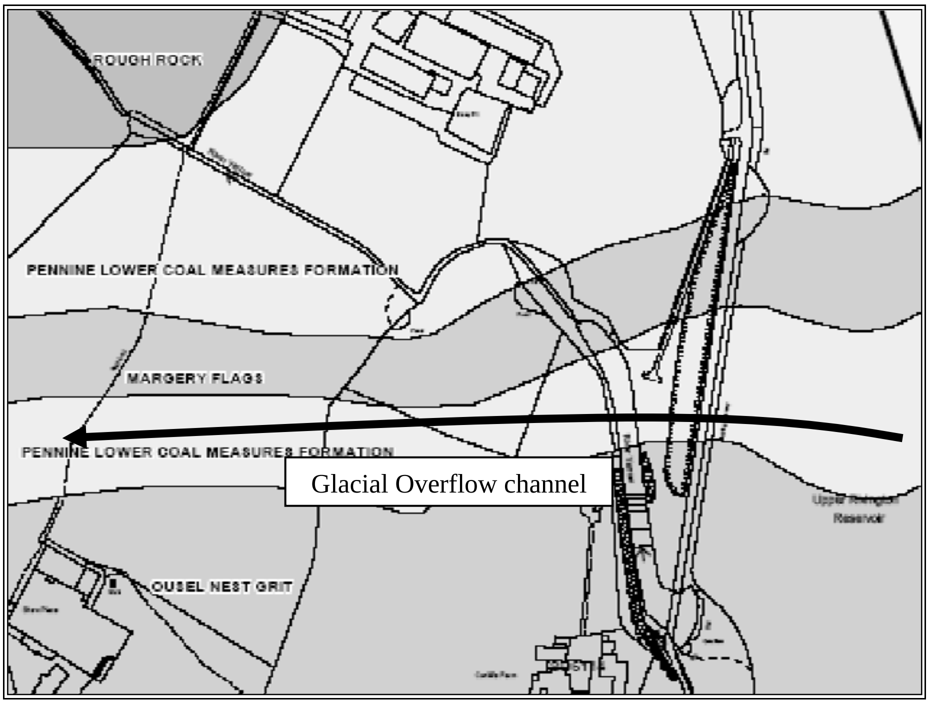

Figure 1. Plan showing solid geology and line of Glacial Overflow channel

Glacial Deposits are encountered underlying the Alluvial material towards the centre of the dam and directly underlying the embankment fill material towards the outer shoulders. This material typically comprises firm to stiff sandy Clays with occasional gravel and organic inclusions and is described as partially laminated interbedded with medium dense grey brown sandy Gravels/gravelly Sands.

Rock at the site comprises Lower Coal Measures Strata, typically coarse-grained yellow Sandstone (Ousel Nest Grit), underlain by mudstone, shales and occasional flagstones. Rock outcrops within the spillway channel and is evident on the adjacent valley sides. A review of the drawings and borehole information suggests that this is a small rock cliff forming a bench feature extending to the line of the drawoff culvert before dipping steeply towards the former stream levels at the centre of the dam, approximately 24m below embankment crest level. The geological maps for the area show a glacial overflow channel which is aligned approximately north to south, through Anglezarke, Upper and Lower Rivington Reservoirs, typically following the line of a north west/south east trending fault (Figure 1).

Major leak 2002

In January 2002 a major leakage event occurred when the flow of compensation water coming from the downstream end of the culvert was noticed to have increased and to be brown in colour (Ref 7). Inside the culvert, a jet of water was issuing at full bore from one of the half-brick weephole openings in the wall and was hitting the opposite wall. The water was discoloured and depositing material in the invert of the culvert.

This flow had not been there when the drain flows in the culvert had been measured the day before. The leak was downstream of the core and vertically below the downstream edge of the dam crest. The reservoir was overflowing by 50mm at the time of the incident. The reservoir water level was reduced during the incident, by a combination of full flow discharge from the scour mains and pumping, to approximately 7m below top water level. The leak stopped at approximately 5m below top water level.

The reservoir level was maintained at 7m below TWL during the grouting exercise carried out during the summer of 2002. A grout curtain was formed using tube-a-manchettes (TAM), both upstream and downstream of the clay core, centred over the drainage culvert and extending about 16m on either side. The clay core itself was then grouted in the same manner. A fan of grout holes was also drilled from the inside of the culvert to join the grouted core. During the grouting upstream of the core, grout was found to have followed the original seepage path and filled the weephole in the culvert wall. Also it was found that there was relatively little grout take in the embankment but the rock beneath the core needed extensive grouting.

On re-filling the reservoir it was noted that the seepage measured in the culvert increased about four-fold when the reservoir level was above 1m below TWL so the reservoir level has been maintained at 1m below from then until now pending remedial works.

Piezometers

Following grouting, standpipe piezometers were installed in the embankment. Four piezometers were installed in the dam crest, two upstream and two downstream of the clay core, just north of the grouted area. The readings show that the downstream piezometer levels follow changes in reservoir level closely and with very little time lag. The downstream piezometer in the sandstone foundation was consistently about 4.5m lower than reservoir level and the piezometer in the dam shoulder was 5.7m lower. This seemed to indicate that water was flowing in the sandstone beneath the dam. Other piezometers installed at the south end of the dam near the spillway, where the rock is quite shallow, only reacted when the reservoir level was higher than 1m below TWL. The spillway is cut into the rock and is generally unlined.

Willowstick

In January 2006, as one of five trial sites for United Utilities (UU), a survey was undertaken to characterise and delineate potential seepage paths through the dam using AquaTrack, a patented geophysical technique from Willowstick Technologies (Ref 5 and 6). The aim of the survey was to understand the location and extent of seepage paths and areas of saturation through, beneath and/or around the dam at various reservoir levels.

The survey identified high and low conductivity areas relating to five small seepages across the embankment. Two major flow paths were identified (Figure 2), one located on the southern part of the dam centred over the drainage culvert with a second coinciding with the alignment of the original stream channel. These flows were noted to act independently of each other and were highly influenced by an increase in reservoir level resulting in increased flows. The footprint of these flows beneath the dam indicates that they are fairly wide, suggesting sheet flows rather than concentrated flows. The remaining seepages were reported to be minor, again influenced by raised reservoir levels and focused around the southern abutments at elevated levels within the embankment. This was in line with the piezometer readings. The survey also indicated that the previous grouting works undertaken in 2002 had been successful with seepages shown to flow around this grouted zone.

A Statutory Inspection was carried out by Dr A K Hughes on 17 August 2005 and the findings of the AquaTrack investigation were made available to him for inclusion in his report. His recommendation “In The Interest of

Safety" (ITIOS) was to: "Continue studies and then remedial work to be designed/actioned to reduce the level of "leakage" to an acceptable level, determined by an All Reservoirs Panel Engineer."

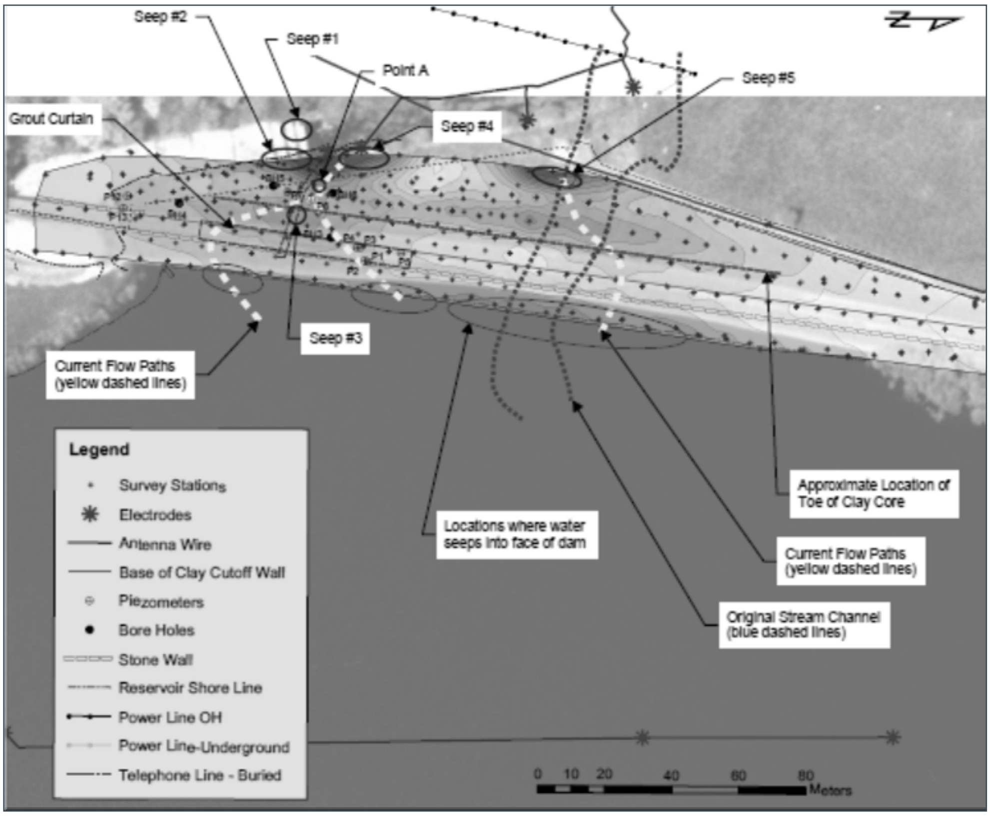

Figure 2: Willowstick interpretation of potential flow paths

UU determined, in conjunction with Dr Hughes, that the ITIOS recommendations would be satisfied by the construction of a weighted granular filter on the downstream face of the embankment together with a filter collar around the outlet pipe and systems for measuring the rate of seepage through the filters. The aim of the filters was to control and monitor seepages through the dam and prevent removal of fines.

The proposed filter design comprised a sandwich arrangement of a 300mm thick layer of sand/gravel/sand overlain by additional berm material and was designed as a critical filter. The sand would provide a filter for both the embankment and berm material. The berm material was designed to replicate the embankment shoulder material adopting a 6F1 material as per the Highways Specification. These measures were also justified by the risk assessment carried out for Upper Rivington under UU's Portfolio Risk Assessment (PRA) programme. (Ref 8).

However, it was recognised that, although the solution for Upper Rivington would prevent the potential for further loss of material from the dam and provide a measurable system for determining flow levels, the degree of risk reduction likely to be achieved by these works could not be ascertained at Portfolio level. UU in conjunction with MWH had, since 2008, been reviewing a methodology based on event tree analysis entitled "A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping" or "The Toolbox", developed by the US Corps of Engineers and the Bureau of Reclamation in association with Consultants URS in the States and the University of New South Wales (Ref 4). The process used is discussed in detail in Eddleston et al 2010 (Refs 1, 2 and 3).

It was decided to trial the Toolbox approach on the Yarrow embankment to ensure that the most appropriate solution was being considered and that a risk reduction could be determined based on the remedial measures, which would then feed back into the PRA. In order to facilitate this approach and in discussion with Dr Hughes, the dam was re-inspected and the ITIOS recommendations, made in May 2009, tailored to reflect the intended study works. These ITIOS recommendations are listed below and were to be undertaken under the direction of an AR Panel Engineer:

i) Studies and investigations be continued to assess and evaluate the current level of leakage and within that study an acceptable level of leakage be agreed with the AR Panel Engineer.

ii) The Engineer will identify and implement measures, if necessary, to reduce the level of the existing leakage to an acceptable level

iii) Studies be continued to complete the risk analysis and undertake any further investigation in order to identify possible remedial measures to reduce the risk of failure to the dam from further seepage

iv) Design and implement appropriate measures identified during the studies, if considered necessary, to reduce the risk of failure to the dam from further seepage.

<u>Toolbox</u>

The toolbox approach looks at potential seepage paths which could occur through the embankment and founding materials and evaluates these using event tree analyses. The following stages are considered:-

a) an initiating mechanism which could cause a flaw to occur

b) the potential for the mechanism to continue to develop the flaw

c) the potential for the mechanism to progress, developing a flow path through which seepages can occur

d) The potential for intervention to be effective prior to a breach of the dam occurring.

A systematic review of the embankment was undertaken by the assessment panel or Risk Estimating Team (RET) comprising an AR Panel Engineer, UU Reservoir Safety Manager, the Supervising Engineer and a Geotechnical Engineer, using the Toolbox approach to assess potential seepage paths likely to impact the integrity of the embankment and underlying foundations. This assessment considered 13 initiation mechanisms (Tables 2 and 3). Based on the HSE Framework for Tolerability of Risk, two mechanisms within the embankment had probabilities lying within the ALARP (As Low As Reasonably Practicable) region, ($>1 \times 10^{-6}$ and $<1 \times 10^{-4}$) one associated with the existing drainage culvert, whilst three failure modes within the rock foundation had probabilities in the Intolerable Region ($>1 \times 10^{-4}$).

Table 2. Summary of Failure Mechanism - through the embankment

Failure Mode	Summary Description	Probability of Failure
Through the upper parts of the embankment (cracking)	Cross valley differential settlement over the bench in the foundation	7.46E-06 ALARP Region
Through the upper parts of the embankment (cracking)	Cross valley differential settlement due to embankment staging during construction	Negligible Tolerable Region
Through the upper parts of the embankment (cracking)	Earthquake loading	5.41E-08 Tolerable Region
Through the middle and lower parts of the embankment (cracking)	Cross valley differential settlement over the bench in the foundation	1.52E-06 ALARP Region
Through the middle and lower parts of the embankment (cracking)	Arching of the core onto the shoulders of the embankment	Negligible Tolerable Region
Through the embankment (poorly compacted / high permeability zone)	Poorly compacted or high permeability layer in the core	1.02E-05 ALARP Region
Through the embankment (poorly compacted / high permeability zone)	Poorly compacted or high permeability layer around and along the conduit with flow through the downstream shoulder	9E-05 ALARP Region
Through the embankment (poorly compacted / high permeability zone)	Poorly compacted or high permeability layer around and along the conduit with flow into the conduit through a crack or open joint	1.42E-06 ALARP Region

Based on an assessment of the mechanisms and resultant probabilities, it was proposed to implement remedial works to reduce the seepage/flows passing through flaws in the core trench and/or at its base which could give rise to erosion and consequent material movements potentially affecting the integrity of the dam. The two areas to be targeted are:

- The base level of the core trench at its contact with rock
- The full depth range of the core trench within the rock

The event tree mechanisms were reassessed assuming that grouting would be undertaken to seal the area of the core trench within the rock (as per Figure 3). This resulted in revised probabilities of failure within the ALARP region (Table 3) which was considered acceptable by the RET.

Table 3. Failure Mechanism and proposed fixes - in the foundation

Failure Mode	Summary Description	Probability of Failure	Proposed Works	Probability of Failure (After fix)
Foundation Initiation Mechanisms				
Through a rock foundation	Through stress relief effects in the valley sides	3.36E-03 Intolerable Region	Complete grouting works to the bridge adjacent to spillway	8.38E-06 single grouted row ALARP region
Through a rock foundation	Through stress relief effects in the valley floor	3.36E-04 Intolerable Region	Grouting extending from rock head to below the base of core trench	1.31E-05 ALARP Region
Internal erosion of the embankment at or into a rock foundation	Backward erosion or suffusion of core cut-off trench material where it lies adjacent to an open joint in the rock foundation	Negligible Tolerable Region	None Required	
Internal erosion of the embankment at or into a rock foundation	Erosion at the base of the core cut-off trench where it abuts open joints in the rock foundation	5.34E-03 Intolerable Region	Grouting extending from rock head to below the base of core trench	5.51E-05 ALARP Region
Internal erosion of the embankment at or into a rock foundation	Erosion of a crack or hydraulic fracture across the core cut-off trench material where it lies adjacent to an open joint in the rock foundation	6.12E-06 ALARP Region	None Required	

The proposed solution to meet the ITIOS requirement was to form two grout curtains, upstream and downstream of the core, extending from a minimum of 0.5m above rock head to 0.5m below the base of the core trench.

The works were planned to extend from the 2002 grouted area towards the spillway and extend approximately 100m eastward past the line of the original stream channel. Probe holes were undertaken to prove the rock head profile and the base of the core trench which was understood to be socketed 2m into the rock. It was agreed that the grouting would only be needed where the core trench was founded within Sandstone. This material was considered to have no potential to self-heal and therefore fines could be washed away through the rock joints.

Within Mudstone, whilst the initiation mechanism still existed and there was an opportunity for a flaw to develop within the core trench, it was considered that the joints could effectively self-heal, halting the progression part of the mechanism and therefore preventing removal of material.

Site Works

The site works commenced pre-Christmas 2011 with the initial investigations to determine rock head profile and to install the Tube-a-Manchettes (TAM) within the rock. The TAM technique was selected to ensure that there was control of the grout placement within the defined zones required by the design. The grout holes were placed at 1m centres inclined at 1:12 to vertical, parallel to the slope of the core, with TAMs at 0.33m intervals.

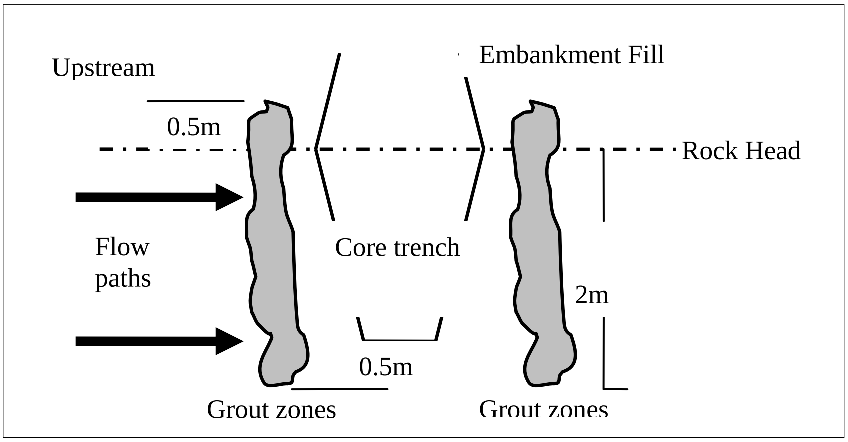

Figure 3. Proposed grouting works within the foundations.

A number of standpipe piezometers were installed downstream of the core and proposed grout holes and were sealed at a level consistent with the zone of rock to be grouted. These are being monitored daily and it is hoped that water levels within these holes will show some reduction in level once grouting works are completed. Settlement monitoring pins were installed along the crest and monitored twice daily to ensure that surface movements could be assessed and appropriate measures taken should movements exceeding 4mm occur. It has proved difficult to ensure that these remain intact given the site constraints imposed by the restricted working area on the narrow crest. The lack of working space is also proving challenging for rig movements between Area 1 and Area 2 with TAM installation and injections being carried out at both locations to meet the required timescales. From the initial holes undertaken in both Area 1 (adjacent to spillway - Figure 4) and Area 2 (central part of the embankment - Figure 5) it was noted that the rock at its upper surface was highly fractured and broken.

This has lead to problems with the initial sleeve grouting of the TAMs which have taken significant quantities of grout, locally in excess of 5000 litres, indicating some infilling of the rock fractures. Significantly lower takes, typically 300 litres, were recorded on the downstream rows of Area 1 following upstream grouting works, which supports the theory that sleeve grout, has migrated through the fractures from the upstream TAMS to the downstream face.

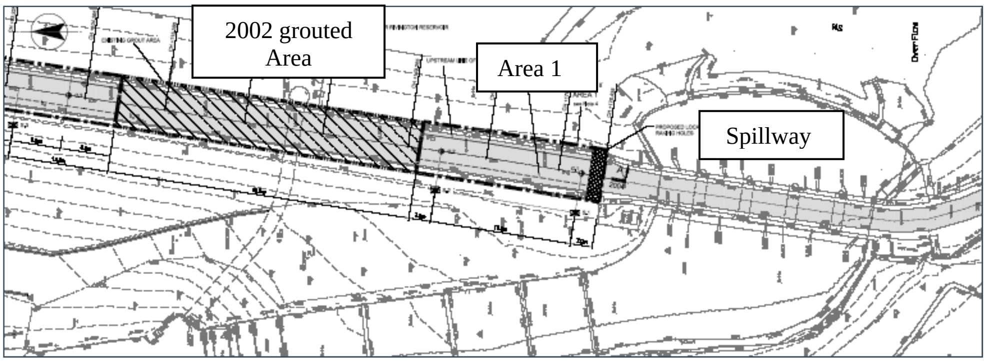

Figure 4. Area 1 grouting between 2002 grouted area and Spillway

Rock head in Area 2 lies at approximately 24m below embankment crest level and has proved to be highly fractured with significant sleeve grout takes recorded which supports the interpretation of sheet flows rather than concentrated flows beneath the dam.

Two adjacent downstream TAM holes, spaced at 1m centres, encountered a 5m difference in rock head level, possibly along the line of the glacial overflow channel in the locality. Further investigations, to ensure that the core trench within the adjacent core extended into the rock across this rock step, proved a 2m deep void 0.5m below the base of core trench level. This lies in the vicinity of the major flow path identified in the initial Willowstick survey (Figures 2 and 5) north of the previous stream channel. The extent of the void is currently being investigated and method statements developed to infill this area with grout incorporating both vertical and inclined holes.

Currently all the TAMs have been installed within Area 1 and initial injections have recorded only limited grout takes within the rock at this locality. Works to install the TAMs in Area 2 are progressing although given the ongoing high sleeve grout takes alternative options, such as single packer grouting are being considered subject to approval by the AR Panel Engineer.

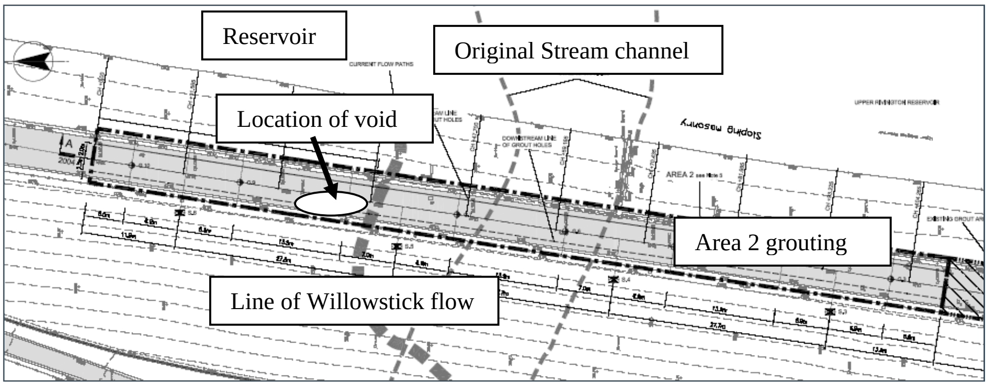

Figure 5. Area 2 grouting showing line of original stream and Willowstick flow path

CONCLUSION

The findings from the grouting exercise so far indicate that the “Toolbox” evaluation identified a likely mode of failure and justifies the decision to grout the rock. The findings are also consistent with the assessments of sheet flows beneath the embankment by Willowstick.

REFERENCES

1. M. Eddleston, P. Rigby, R. Margrett, P. Mason, K. Gardiner and J. Cyganiewicz (2011) “*Application of a unified method for estimating probabilities of failure of embankment dams by internal erosion and piping - A UK perspective*” USSD Conference San Diego

2. M. Eddleston, R Margrett, J Cyganiewicz, P Mason, P Rigby and K Gardiner (2011) “Developments in the use of event tree methods to estimate the probability of failure of embankment dams by internal erosion and to evaluate the effectiveness of potential risk reduction measures” *8th ICOLD European Club Symposium, Dam Safety - Sustainability in a Changing Environmen*t, Innsbruck.

3. Eddleston M, Cyganiewicz J, Gardiner K D. (2010) “The use of the “Unified Method of Risk Analysis” on a United Utilities Pennine type dam” *Managing Dams: Challenges in a time of change - Proceedings of the 16th British Dam Society Conference, Strathclyde*. Thomas Telford, London

4. Fell, R., Foster, M., Davidson, R., Cyganiewicz, J., Sills, G. and Vroman, N. (2008) *A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping.* UNICIV Report R 446, The School of Civil and Environmental Engineering, the University of New South Wales, Sydney, Australia 2052.ISBN:85841 413 9

5. Kofoed V O, Montgomery J and Gardiner K D (2006) "Identifying Leakage Paths in Earthen Embankments". *Improvements in Reservoir Construction, Operation and Maintenance - Proceedings of the British Dam Society Conference, Durham*. Thomas Telford, London

6. Willowstick Technologies (2006) *Upper Rivington Dam Report*

7. Gardiner K D, Hughes A K, Brown A J (2004) "Lessons From a Near Miss at a UK Reservoir", *Dams and Reservoirs* Vol 14 No 2

8. Hughes A K and Gardiner K D (2004) "Portfolio risk assessment in the UK: a perspective". *Long-term benefits and performance of dams - Proceedings of the 13th British Dam Society Conference, Canterbury*. Thomas Telford, London

9. Foster, M.A., Fell, R. (2001). Assessing Embankment Dam Filters that do not satisfy Design Criteria. *J. of Geotech. and Geoenv. Engrg,* Vol. 127, no. 4, May, pp. 398-407.