The British Dam Society

Managing risks associated with the infilling of the adit at Tunstall Reservoir

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SYNOPSIS Significant leakage was observed on the left flank of Tunstall Dam upon first filling of the reservoir. A concrete-filled cut-off wall was extended into the abutment in 1879, which significantly reduced the flow but did not resolve the problem. In a further attempt to manage leakage, the adit and shaft that had been used to form the cut-off wall was repurposed and extended with additional drifts cut into the hillside to capture and transfer leakage flow.

Several measures in the interests of Safety (MIOS) arose out of a Section 10 inspection in 2021, one of which recommended *"fill the tunnel (i.e. adit) whilst providing some drainage"* in response to a concern about its structural integrity and the potential risk to the embankment dam and spillway in the event of a collapse. The remedy comprised filling the adit passing beneath the dam and appurtenant works with expanding geopolymer introduced via a series of injection holes drilled from the surface. Due to the depth, there was a significant risk that the drillholes would miss their target and that drilling might damage the existing 18-inch diameter cast iron pipe conveying leakage flows beyond the dam structure.

This paper describes how risks were managed and mitigated, the key aspects of the investigations and design process, and the works that took place to satisfy this MIOS measure.

OVERVIEW

Description of the site

Tunstall Reservoir is located 5km to the north of Wolsingham in Durham. It previously fed a treatment works below the dam, which has since been decommissioned. The reservoir is now used for river flow compensation and amenity purposes. It is impounded behind an earthfill embankment with a central puddle clay core. The dam is about 25m high and 300m long.

Dam construction began in 1873. Significant leakage was observed through the left abutment during first filling. A 1.8m wide, 27m deep concrete cut-off wall was extended some 82m into the abutment in 1879 and it significantly reduced, but did not eliminate, the leakage. In addition, a wedge of open jointed rock between the end of the existing puddle clay-filled trench and the concrete-filled extension was carefully removed and replaced with brickwork, with cement grouting upstream to reduce the leakage passing beneath the brickwork.

The formation of the brickwork wedge necessitated the driving of tunnels and shafts. The main drive from the dam toe was known as the Drift By-pass Tunnel, which henceforth will be referred to as *the adit*. The failure of the cut-off wall extensions to stem the leakage prompted further tunnelling to intercept flow and carry it away downstream via an 18-inch pipe laid along the adit.

Description of the adit

Some 120m of the 200m long adit lies below the footprint of the dam and spillway, with the rest lying within the hillside. Water passing through the left flank is intercepted by the tunnels and flows into the adit, where a low brick wall transfers the water into an 18-inch cast-iron pipe. Figure 1 illustrates the layout of the adit and associated features.

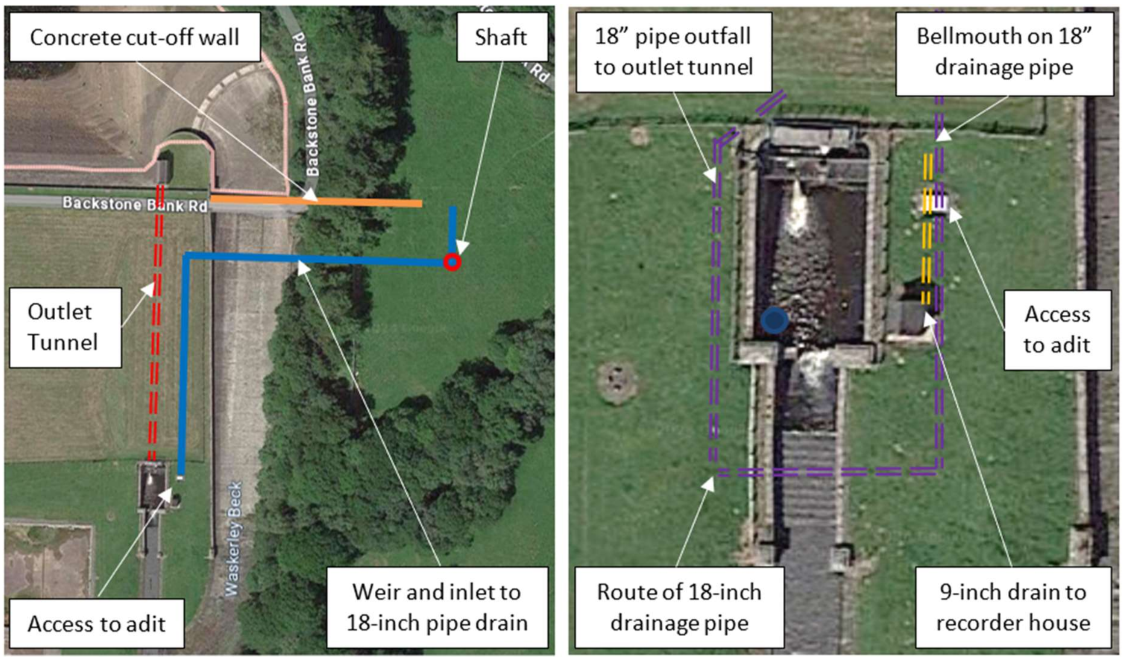

Figure 1. Extent of the adit and key features (Google Maps).

The initial 9m long brick arch section at the adit entrance is unlined and unsupported as far as the 90° bend, apart from occasional steel beams in the soffit (Figure 3). The section between the bend and the inlet to the 18-inch diameter drainage pipe is also brick lined, but thereafter the tunnel is unlined. The adit dimensions vary but are generally about 1.7m high by 1.4m wide. The maximum cover to ground level below the dam is 16m but increases up to 40m as the adit extends into the hillside. A forced air ventilation system (Figure 3) was installed in 2001 but the Undertaker has restricted entry to essential works since 2016.

The 18-inch diameter adit pipe conveyed leakage and groundwater to the treatment works but was also provided with an outfall to the outlet tunnel. A weir near the tunnel portal enables that flow to be measured. A bellmouth overflow on the pipe some 12m upstream of the downstream end of the adit allowed excess flow to discharge onto the adit floor and drain away via a 9-inch collector drain to the recorder house where the flows are measured over a V-notch weir before discharging into the outlet basin downstream of the outlet tunnel portal.

Figure 2. View of pipe inlet and weir. Note standing water on the invert of the adit.

Figure 3. View in the unlined section of the adit. Notice the beams across the soffit.

Initial Surveys

A previous recommendation under Section 11 of the Act had been made to measure and record drainage/seepage flows against rainfall and reservoir level. Several surveys were undertaken in 2020/21 to inform the upcoming Section 10 inspection including:

- A photographic record of the adit condition (including Figures 2 and 3).
- A 3D laser scan and topographical survey to confirm location, extent, and dimensions.
- A magnetometric resistivity survey (by *Willowstick*) to identify leakage flow paths in the left abutment, which suggested that flow was also passing through the cut-off wall.

RECOMMENDATIONS IN THE INTEREST OF SAFETY

Dr Andrew Hughes carried out the Section 10 inspection in February 2021 and the above-mentioned surveys and monitoring data helped inform the Inspecting Engineer regarding the long-term condition of the adit, the potential for a future collapse and implications of a total blockage on the safety of the dam. Amongst other matters, the Inspecting Engineer recommended the following MIOS to be implemented by 23 February 2024:

iii: *Works are carried out to stem the leakage over the core (cut-off wall) as identified by the Willowstick survey.*

iv: *Once the majority of flow into the shaft and tunnel is stemmed that the tunnel (i.e. adit) and shaft be filled with, say, foamed concrete whilst still providing some drainage*.

Northumbrian Water Ltd (NWL), the asset owner, appointed Esh-Stantec initially to deliver a *Concept & Definition* (C&D) contract to assess options, identify a preferred option, and subsequently to deliver the approved solution under the *Design & Construction* (D&C) phase of the project. Work commenced in July 2023 with Esh-Stantec as both Principal Designer and Principal Contractor and with Ian Carter acting as Qualified Civil Engineer (QCE).

SCOPE OF WORKS

MIOS 3 – Stemming the leakage over the core

A ground investigation (GI) was undertaken in late 2022 to investigate the cut-off wall condition and identified flow paths. Details of that study lie beyond the scope of this paper.

The findings from the GI, together with a review of reservoir levels / flows in both the 18-inch pipe and 9-inch collector drain in the adit, were presented to the QCE. No evidence of flow through the cut-off wall was found. The physical evidence confirmed the concrete-filled cut-off wall extension was in good condition, and that leakage generally passes around this wall, rather than through it. Clay was found directly above the concrete beneath the hillside and this material was used to seal the uppermost part of the access tunnel once concreting had been completed.

Figure 4 shows the leakage entering the adit predominantly through the shaft near its eastern end. Flows in the adit are closely related to reservoir water level. They decrease significantly when the water level falls 6m below the top water level (TWL). Figure 5 shows the correlation between reservoir levels and recorded flows in both the 18-inch drainage pipe and the 9-inch perforated collector drain, collecting flows from the bellmouth overflow.

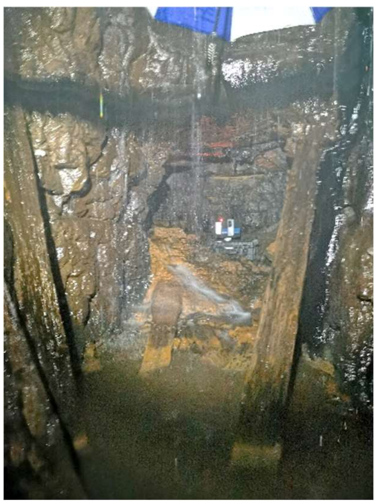

Figure 4. View of flow cascading down the shaft.

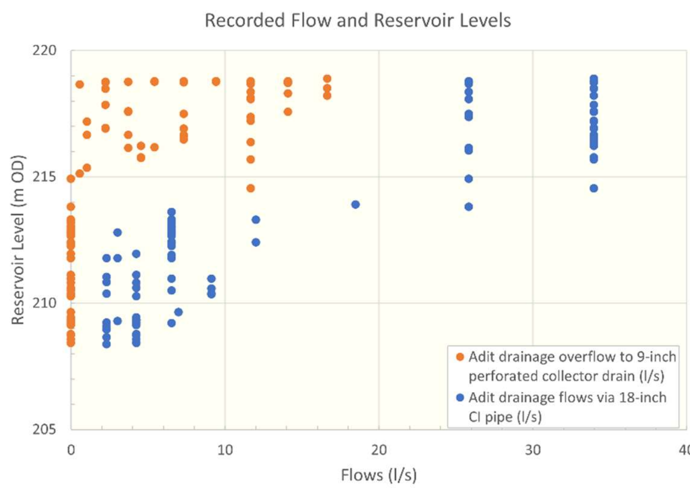

Figure 5. Relationship between reservoir level and flows recorded in both pipes systems.

Regular readings of flows both in the 18-inch and 9-inch pipes began in October 2019. Prior to the works, the maximum recorded leakage flow was 51 l/s with the reservoir water level standing at TWL for a prolonged spell. Leakage flows have historically dropped to 2 l/s with the water level 10m below TWL. It was therefore decided that flow into the adit should be stemmed during the construction phase by lowering the reservoir level and maintaining it around 6m below TWL. In view of the nature of the cut-off wall and its very good condition, no additional works were required to improve its watertightness.

MIOS 4 – Adit infill works

Concept Stage

Various options were considered during the *Concept* phase to address the Inspecting Engineer's requirements. These considered the extent of the adit to be filled, the different materials that could be used to achieve this purpose, and how they might be implemented.

Filling the entire extent of the adit was considered but was not the preferred solution due to the significant constraints associated with that option. These constraints included difficult access, required confined space activities, land ownership issues, the presence of a SSSI, and an ever-increasing depth of cover above the adit, amongst other things. It was decided that adit filling beneath the dam and spillway would be sufficient to eliminate the risk to the reservoir.

Three possible infill materials were considered:

a) Cement grout was discounted due to potential pollution concerns, given that the material might mix with groundwater and leak out through the bedrock, causing an incident.

b) Foamed concrete was discounted because of the adit length and in consideration of concerns linked to the remote location and timely delivery of concrete.

c) Expanding geopolymer foam was selected as the preferred material. It had been used successfully elsewhere and was easier to place, more economic and had a lower carbon footprint than the other options.

Definition and Detailed Design Stage

The agreed concept solution was developed during the *Definition* phase and detailed during the *Design & Build* stage of the project. Additional surveys of the adit and both drainage pipes were carried out at the start of the construction phase, and the information fed back into the final scope of works, which is summarised below:

- Part filling of the adit, i.e. the 120m section of adit below the dam and spillway, since a collapse of the adit in the abutment would not compromise the dam safety.
- Relocation of the 18-inch overflow bellmouth to facilitate future maintenance.
- The brick lined section immediately upstream of the entry point would remain unfilled, so as to retain future access to the 9-inch perforated pipe.
- The infill to be expanding geopolymer foam with a minimum compressive strength of 100kPa. *Geobear Ltd* to be appointed as the specialist supplier and subcontractor.
- Foam to be injected into the adit via injection points drilled from the ground surface and spaced at 10m intervals. The injection holes would be lined with plastic casing, which would be left in place.

Risks associated with undertaking of the works to satisfy the solution agreed with the QCE can be broadly divided into two categories, *Dam Safety risks* and *Health & Safety risks.* The next sections of this paper set out these risks, mitigations put in place, and remaining residual risks.

RECOGNITION OF RISKS

For the development of the concept design and supporting risk register the project team referred to the information provided by previous surveys. Undertaking additional surveys in the adit was only deemed possible during the design and construct phase, once the water level was drawn down 6m below TWL, and an inspection had been completed by *MRS Training & Rescue* using a team trained and equipped to enter similar unknown and uncontrolled environments.

Managing Risks for Dams and Reservoirs

The dam safety risks associated with the concept design were therefore based on several assumptions, which were verified as the works progressed. Table 1 summarises the dam safety risks, the assumptions made and the identified mitigation.

Table 1. Dam Safety Risks, Assumptions & Mitigation

Ref	Risk	Assumption	Mitigation	Residual Risk
1	High water levels in the reservoir.	• Water levels in the adit pipe are directly related to levels in the reservoir.	• Established flow/water level relationship. • Management plan for water level in place. • Regular coordination meetings.	• Storms during the works. • Inability to control water level.
2	Drilling of injection holes miss the adit.	• Previous survey coordinates are sufficiently accurate.	• Setting out data verified on site. • Injection coordinates provided to adit centre based on survey. • Slope climbing rig to be used for drilling. • Drilling to start from downstream end where cover is less. • Drilling programme extended to allow for “misses”.	• Multiple attempts to find adit with the drilling of the injection holes. • Programme extended. • Higher project cost.
3	Geopolymer enters and fills drainage pipe.	• 18-inch drainage adit pipe in good condition with no major cracks or holes.	• Formwork at downstream end to prevent expanding geopolymer from blocking the pipes. • Overflow bellmouth capped and replicated in an alternative location. • Surveys undertaken to identify potential defects in the pipe. • Flow monitored in the pipe to check for change in flow regime during geopolymer filling.	• Surveys miss identifying potential geopolymer entry points into the drainage pipes.
4	Drilling damages pipe inside adit.	• CI pipe can tolerate small impacts. • Adit would remain stable during the drilling.	• Pre-drilling entry to visually inspect the pipe. • Post-drilling surveys using drones and high- definition cameras. • CCTV surveys of the pipework attempted.	• Damage missed by pre-injection survey.

Ref	Risk	Assumption	Mitigation	Residual Risk
5	Waxcap fungi constrain surface works.	• Waxcap mitigation strategy in place before site works.	• Ecological mitigation to mitigate any impact on waxcap habitat. • Track mats provided to minimise topsoil damage by the drilling rig.	• Drilling Programme extends into Waxcap season.
6	Spacing between injection points insufficient.	• Anticipated performance and behaviour of chosen geopolymer	• Liaison with specialist subcontractor to confirm required spacing. • Polymer injection and expansion rate verified at start of site works. • Videos and photos taken to verify completeness of the injection works.	• Additional drilling required during the project.
7	Potential pollution.	• Polymer Geopolymer material is low viscosity (does not flow freely through open jointed rock).	• Fill material is non-hazardous and expands quickly, minimising loss through jointed bedrock • Watching brief for signs of geopolymer in drainage flows.	• Pollution to watercourse.
8	Drone survey unfeasible beyond the 90° bend	• Signal unlikely to travel beyond bend	• Antenna inserted through injection point to provide signal beyond the bend.	• Drone fails during survey.
9	Selected fill material unsuitable	N/A	• Minimum shear strength specified for expanding geopolymer. • Samples taken on site for Q&A testing.	• Safety of dam embankment compromised.
10	Collapse of the drillholes	N/A	• Holes cased	N/A

RECOGNITION OF HEALTH & SAFETY RISKS

Designers under the Construction (Design and Management) Regulations 2015 are required to apply the general principles of prevention in preparing their design to minimise risks to health, safety and well-being during the construction, operation and demolition phases of a project or asset. For this reason, the proposed solution aimed to minimise time working within the adit given the risks associated with working in this type of confined space. Expanding geopolymer was chosen as the preferred material as it helps mitigate the risks. Table 2 summarises the risks identified in the Hazard Identification Checklist (HIC) and Significant Risk Log (SRL) developed during the project.

Managing Risks for Dams and Reservoirs

Table 2. Significant Risks to health, safety and wellbeing, Mitigation and Residual Risks

Ref	Hazard	Activity affected by risk	Mitigation	Residual Risks
1	Live Reservoir	• Person-entry inside the adit. • Geopolymer injection	• Water management plan in place to reduce leakage flows into the adit.	• Storms during the works. • Management of the water level.
2a	Confined space / low oxygen	• Inspections in the adit. • Installing formwork at upstream and downstream ends of the section to be infilled.	• Geopolymer injection from surface to avoid man entry. • Pea gravel stop end provided at upstream end installed from ground level to avoid formwork upstream. • Ventilation pipe present but uncertain efficiency. • A single >10m entry went beyond the lined section of the adit. • Specialist sub-contractor appointed to carry out person-entry survey. • No person-entry post hole drilling permitted.	• Effectiveness of filling operation was only visible by remote monitoring means.
2b	Confined space / unknown structural condition			
3	Steep slope	• Drilling of injection points	• Slope climbing rig used for drilling, using appropriate anchors. • Temporary platform created on the spillway to create level surface. • Water Management Plan for dry access to spillway	• Working on a steep slope

MANAGEMENT AND MITIGATION OF THE HEALTH AND SAFETY RISKS

The site works started towards the end of August 2023. Establishing and actioning the water management regime was the priority action for the project team. As noted in Table 1, a reservoir level of TWL-6m was required for the duration of the works, and it was perceived that this might eliminate inspection of the adit during the Design and Build stage to a single person-entry exercise to establish the present-day condition of the adit and its pipework.

Furthermore, it was essential that the spillway did not operate while the injection holes in the spillway were drilled, and that water did not spill down them into the adit while the injection holes were open. Also, minimisation of “excess water” in the adit was desirable to ensure the that the geopolymer resin reaction was uninhibited and successful.

The water level management plan was agreed between contractor and client, who remained responsible for the management of the reservoir throughout the works. Roles and responsibilities were set out, as well as contingency plans to be implemented if control of the water level was lost, or under threat. The plan was tested on several occasions in late 2023 due to 'named' storms, at which time mitigating action was required.

Following the single entry, a Design Safety Review (DSR) took place, and the project team was challenged to amend the design to eliminate the need for any further confined space entry and work. The concept design had allowed for the installation of a plywood shutter close to the inlet of the 18-inch diameter pipe, to prevent the geopolymer from entering and blocking it. It also made provision for pipe protection at the injection points to minimise the risk of pipe damage. This proposal was also re-assessed and discounted given the visual observation that the pipe was in a good condition with walls about one inch thick.

A practical and acceptable alternative was found: the injection points were re-positioned, and the two points closest to the internal adit weir were re-purposed. One point was used to convey stone to create a pea gravel barrier, while the adjacent point became an observation point. Pea gravel was introduced via a tremie pipe to form a mound within the adit to stop the advance of the expanding geopolymer upstream (Figure 6). A basic CCTV camera was introduced into the inspection point to monitor the progress of the geopolymer foam.

It was critical that the drainage pipe remained free-draining and unobstructed. Given the limited quality offered by basic cameras, the project team monitored the foam advance using high resolution cameras with improved lighting. The improved imagery confirmed that there was a gap between the pea gravel mound and the soffit which would have allowed the foam to overtop the barrier. Fortunately, the high-resolution cameras allowed the advancing front of polymer foam to be closely monitored, and infilling to be stopped before it reached the window in the barrier, as illustrated in Figure 7.

Figure 6. View of the pea gravel mound.

Figure 7. Post injection view of the mound with foam just visible beyond the gap.

Entry to the most upstream portion of the adit was eliminated by the creation of the pea gravel stop end, however strict adherence to the no entry policy did mean that the opportunity to check for hitherto unforeseen defects was lost, as well as the opportunity to mitigate the associated financial impact.

A few entries were required at the downstream end to relocate the bellmouth overflow, but these activities were deemed to be lower risk, due to the proximity to the entry point and the brick-lining in that section. The activities were nevertheless supported by forced air ventilation and confined space rescue teams.

MANAGEMENT AND MITIGATION OF DAM SAFETY RISKS DURING THE SITE WORKS

The drilling of the twelve injection and verification holes took place after the initial person-entry survey had taken place. Initially, the preferred position for the holes was thought to be close to the adit sidewall and away from the drainage pipe. However, given the risk that the drill holes would deviate off-line, either due to drill set-up, ground conditions or survey error (arising from transfer of control below ground), the location was changed to the centreline to maximise the chances of hitting the target.

Drilling commenced from the downstream end of the adit, where the cover was smaller, and the first six holes were drilled successfully. However, as the holes became deeper, the risk of missing the adit increased, and the injection hole at the 90° bend had to be attempted three times before it could be successfully completed. The inspection point at the far end broke through close to the side wall and the pea gravel injection hole was off centre, allowing a window in the mound, as can be seen in Figures 6 and 7.

The injection of the geopolymer only began once the drilling was completed and the QCE was satisfied that there was an effective strategy in place to prevent the polymer foam from extending beyond the pea gravel mound and entering the upstream end of the 18-inch pipe. The risk associated with that outcome was considered high due to the likely difficulty of removing hardened geopolymer from the pipe and the possible build-up of water pressure elsewhere. The pre-injection condition survey of the pipe was intended to mitigate this risk and identify any potential points of ingress. However, as it was carried out by confined spaced specialists, the survey missed some of the details that would have been captured by well-trained, professional reservoir engineers. The need for a better survey specification and more effective communication with survey specialists was a lesson learnt by the design team.

Given the reticence of the Contractor, Designer and Undertaker to authorise a further confined space entry into the adit, the QCE sought evidence that drilling operations had not damaged the pipe. Drone surveys were attempted but met with mixed success due to the limited space and obstructions therein, not to mention signal communication in the underground environment. However, insofar as could be determined visually, the survey confirmed that the downstream section of the pipe was in good condition with no obvious defects. In addition, high-resolution cameras were inserted at each injection point to inspect the pipe at spot locations. Figures 8 and 9 show examples of pre- and post-drilling surveys.

Adit infilling progressed at about 10m/day. Given its nature, once injection of the expanding geopolymer starts, then it needs to continue until the next injection point is reached. A downhole camera was used to confirm the position of the geopolymer foam front and to stop the injection before blocking the next injection point. Quality assurance was made more challenging by the steam generated by the geopolymer expansion process and the poor light. The expertise of the subcontractor in this matter was key to a successful outcome. Figure 10 shows a view of the geopolymer advancing through the adit.

Figure 8. Adit view before start of drilling.

Figure 9. Minor roof fall after drilling of hole.

Figure 10. Expanding geopolymer foam in the adit

A watching brief was put in place for potential signs of resin ingress into the 18-inch drainage pipe. The injection process progressed steadily from the downstream end, but traces of resin were observed in the drainage pipe at the 90° bend and the operation was stopped while an investigation was carried out.

Upon review, the most likely explanation was that the geopolymer foam entered via a gap between the chamber at the bend and its cover slab. The foam mixed with water therein and was carried along the drainage pipe before it had the opportunity to expand and cure. If the injection point had been slightly further away from the chamber, or had the adit been drier at the time of injection, then this might have been avoided.

It seems likely that the failed attempts to drill the injection hole at this location probably contributed to the damage to that chamber. Either way, a post-drilling inspection by a trained reservoir professional would almost certainly have spotted the defect and raised concerns. While remote inspection technology has advanced in leaps and bounds in recent years, there are still occasions where it has not outpaced the "Mark 1 Eyeball".

Managing Risks for Dams and Reservoirs

Geopolymer injection was suspended temporarily in response to the incident. Fortunately, the material properties of foam are such that removal by high-pressure jetting is possible and far less problematic than the alternatives considered at Concept stage (i.e. grout or foamed concrete). Insofar as was possible, the hardened foam was cleared from the drainage pipe. Some foam remains beyond the bend, but it does not appear to be restricting flow.

The injection sequence was modified following the stoppage because injection terminated before reaching the target injection point. Injection recommenced once an alternative approach had been agreed with the QCE. Injection resumed from the last injection point to maximise the chance of a successful outcome at the pea gravel mound, with the gap between the two geopolymer foam fronts being filled in the last phase. There was no opportunity to obtain visual confirmation that the foam filled the entirety of that void, but the increase in backpressure at the injection lance suggests that there is no residual void at that location.

CONCLUSION

The location of the adit at Tunstall reservoir and the nature of the required remedial works presented several challenges to the project team (including Client, Designer, Contractor, and Sub-contractors) beyond the normal management of risks to dam safety.

The priority of the project team was to complete the required works without compromising health and safety and to minimise confined space entry into the adit. The project objectives were achieved by risk management throughout the various stages of the project via a combination of:

a) early identification of risks and appropriate mitigation measures,

b) effective collaboration between the Client's operations and capital delivery teams,

c) use of technology to allow remote inspection of the adit and the filling process, and,

d) selection of appropriate fill material and installation techniques.

Without doubt, health and safety risks were managed effectively and no near misses or incidents were registered on site during the adit infill works. However, rigid adherence to the no-entry policy did result in missed opportunities to detect and avoid problems, which ultimately introduced significant additional cost to the project.