

Barrow Compensation Reservoir Grouting Works

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SYNOPSIS. Barrow Compensation Reservoir has a long history of leakage and remedial works. The 12m high embankment dam, constructed in 1863, was eventually emptied in 1882 after many attempts to stem leakage. The reservoir has normally remained empty since this time, but the reservoir can substantially fill under flood conditions. Some doubts that were raised in relation to dam safety under flood conditions led to the development of a comprehensive grouting programme to seal both the puddle clay core of the dam and its rock foundation in 2004-2005. The paper summarises the history of remedial measures at the dam, and describes the site investigation works carried out to scope and measure the effectiveness of the remedial measures. The paper discusses the effectiveness and limitations of the remedial works carried out and the implications for the future monitoring.

INTRODUCTION

The great majority of the UK's reservoirs are viewed as an asset by their owners. This paper concerns recent remedial work to a reservoir which falls in the minority group. Barrow Compensation Reservoir, owned by Bristol Water, is situated south-west of Bristol. The other three Barrow reservoirs serve important water supply functions for the city, but the Compensation reservoir has served no function for the owner for well over a hundred years.

Built in 1863, the reservoir served to provide a regulated water supply to mill owners on the River Land Yeo. The dam comprises a 160m long embankment, up to 12m high with a central, narrow puddle clay core wall and cut-off trench. Problems are documented both with the stability of the 1:2 upstream face and with leakage. The history of the problems and early remedial works to the dam are described have previously been researched in detail (Watson Hawksley, 1982). In 1870, the core wall was completely removed and replaced with fresh puddle clay. The width of the core was

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widened to 5 feet at the foundation level and the depth of the cutoff trench increased. However, problems with leakage continued and attempts to maintain the reservoir full were finally abandoned, leading to the enabling act of Parliament being repealed in 1882. From that time to the present day, the reservoir has normally been almost empty. However, the reservoir can substantially fill during extreme storm events over the Mendips, as occurred in 1968. The only practical function that the reservoir now serves is flood protection for the villages downstream. There is a drawoff weir at elevation +81m leading to a concrete-lined drawoff tunnel and an 18-inch drawoff pipe that passes through the dam. Flow can be controlled by a valve located in a tower on the line of the core wall. The spillway crest is set at +86.9m and the dam crest is at about +89.5m. A clay blanket was placed over the upstream face of the dam in 1982 in an attempt to reduce leakage but this appears to have been unsuccessful. In 2000, localised grouting around the perimeter of the drawoff tunnel and below the valve tower also failed to significantly reduce leakage.

A ground temperature survey of leakage patterns through the core of the dam in 2002 confirmed that leakage was present near the line of the 18-inch drawoff pipeline and valve tower. In addition, dye tests indicated very rapid passage of water from the reservoir area to the drainage basin located near the downstream toe, suggesting the presence of open joints or fissures within the dam body or through the foundation.

A statutory inspection of the reservoir in 2003 recommended that either the dam watertightness should be improved to improve the stability of the downstream shoulder during flood events, or that the reservoir should be discontinued.

Studies were carried out by Bristol Water and Halcrow to compare the costs of 'notching through' the embankment (discontinuance) with the cost of remedial works. The studies concluded that the most economic solution was to improve the watertightness of the dam and foundation by grouting. In particular, the costs associated with flood protection measures for the downstream villages and environmental protection measures were prohibitive. Grouting had already proven successful in sealing leakage at Barrow 3 Reservoir in 1996 (St John, Nicholls and Senior, 1998).

GROUND INVESTIGATIONS

A comprehensive site investigation was carried out in 2004. The scope of the investigation, excluding laboratory tests, is summarised in Table 1 below.

Table 1: Scope of Site Investigation

Item	Purpose	Number/Notes
Cable tool and rotary boreholes	Drilling through core wall, shoulder material and rock foundation for installation of piezometers, soil sampling and in-situ testing.	21 no. boreholes
Standpipe piezometers within the core	For critical pressure tests to determine the susceptibility of the core to hydraulic fracture	3 standpipe piezometers installed.
Vibrating wire piezometers and common datalogger	To provide accurate measurements of pore water pressure before and during the impoundment testing.	15 vibrating wire piezometers were installed, seven of which with de-airing facilities.
In situ permeability tests	To determine the permeability of the core and embankment fill before and after grouting works.	Lugeon tests were carried out at six locations within the rock foundation.

Vibrating wire piezometers were favoured for this embankment as they have a fast response time appropriate for the rapid rise in reservoir level during floods, and would not malfunction if grouted during the remedial works.

The uppermost part of the shoulders was found to comprise a firm to stiff orange brown gravelly clay. The lower part of the shoulders is formed of softer blue grey clay. It was noted that the boundary between the blue and orange clay closely matched the piezometric profile, suggesting possible oxidation of the uppermost clay.

The foundation of the dam was found to comprise (in descending order) the following beds, with a shallow dip to the north-east:

- Interbedded limestones and mudstone, weathered to clay in places (the Wilmcote Limestone);
- A thin (<10cm) band of orange gritty calcareous sandstone;
- A white silty limestone, approximately 2m thick, with thin mudstone bands (the Langport Limestone); and
- A dark grey mudstone, weathered to clay (Cotham mudstone).

The initial lugeon tests in the rock foundation yielded values consistently over 100. In some cases it was not possible to attain sufficient water pressure to provide a result due to very high ground permeability. The band of white limestone, in particular, was suspected of contributing to this high

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foundation permeability. A geological plan of the dam area is shown in Figure 1 and a geological section through the dam and the foundation is shown in Figure 2.

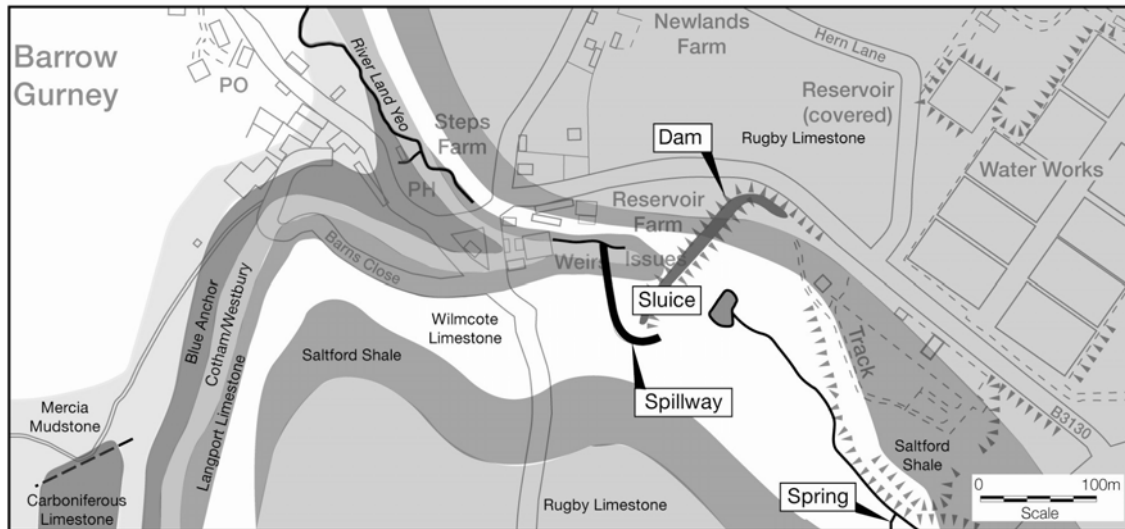


Figure 1: Geological plan of the dam area

The ground investigation found that the puddle clay core had a permeability value in the order of 10^{-6} to 10^{-7} m/s. This indicated the likely presence of open fissures within the core wall as one would normally expect a permeability in the order of 10^{-9} m/s or lower for puddle clay.

The phreatic surface was found to be significantly higher in the downstream shoulder than in the upstream shoulder (see figure 2), particularly adjacent to the left abutment. This was believed to be a result of groundwater inflow from the valley side and was clearly detrimental to stability of the downstream shoulder.

DESIGN OF REMEDIAL WORKS

Remedial works were designed to enhance the stability of the downstream shoulder during flood events by:

- significantly reducing leakage through the foundation by grouting works;
- significantly reducing the leakage through the dam core wall by grouting works;
- reducing the permeability of the clay fill upstream of the core wall by grouting to effectively widen the core (Vaughan, 1987) and reduce the risk of hydraulic fracture re-occurring in the future.

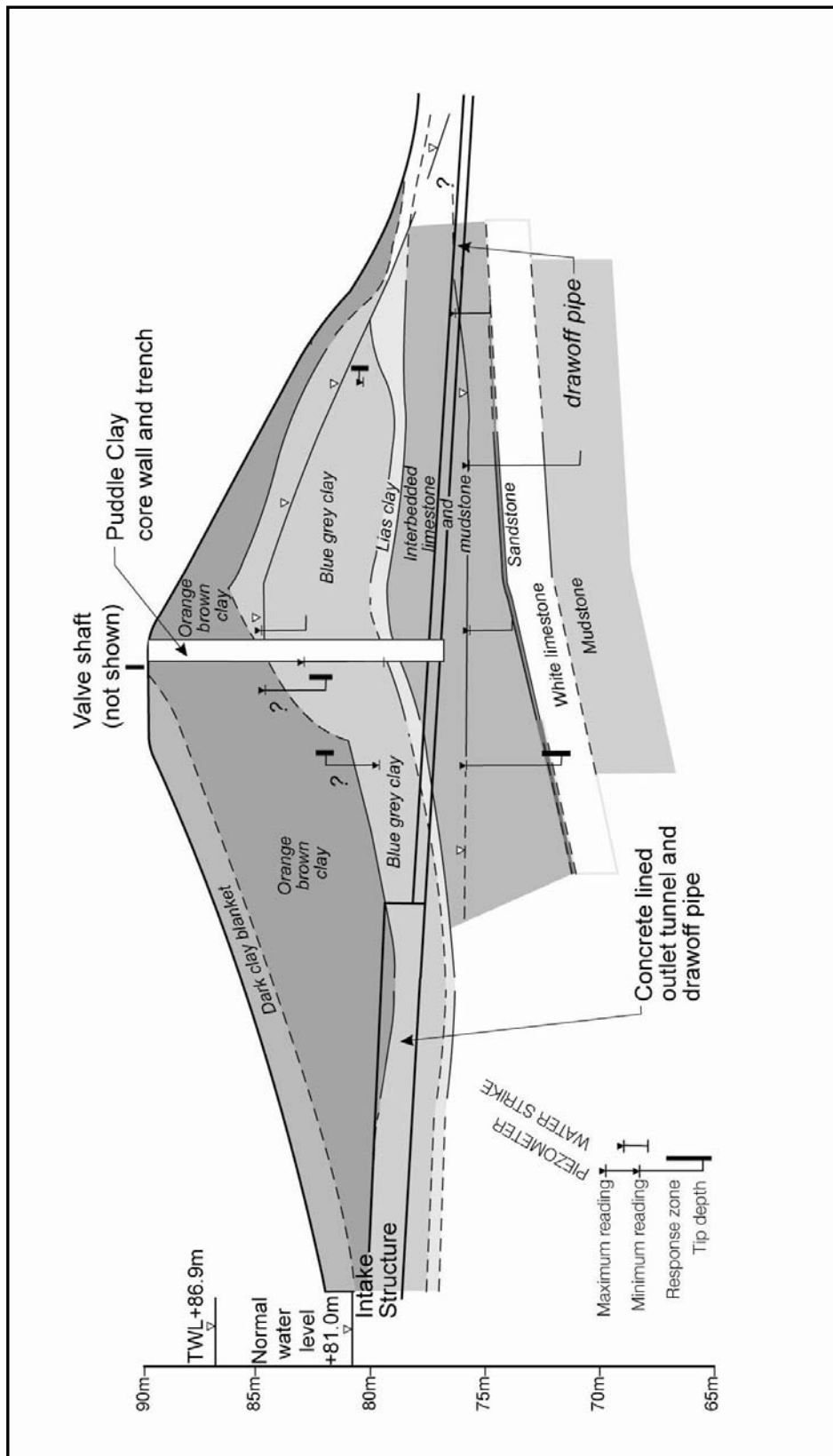


Figure 2: Geological section through dam embankment and foundation on the line of the drawoff works.

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- providing a deep French drain in natural ground adjacent to the downstream shoulder on the left abutment to assist in draining the downstream shoulder and to intercept groundwater flowing towards the embankment.

Grouting of the core wall and foundation was deemed necessary over the full length of the embankment. Tube-à-manchette (TAM) grouting was proposed for the core wall – this technique had previously been applied successfully at Barrow 3 reservoir and a general description of the equipment and technique is described by St John *et al*, 1998. Additional TAM tubes were proposed for the periphery of the valve tower to reduce water ingress.

Further rows of grout holes were proposed upstream of the core wall, extending through the clay fill and into the rock to a varying depth below the foundation level approximately equal to the height of the embankment (to as low as elevation +67m over the central section of the dam). These were aimed at sealing fissures in the clay fill and rock joints.

IMPLEMENTATION OF REMEDIAL MEASURES

Before the grouting works commenced, the drawoff valve was closed to allow the reservoir level to rise by 3m to elevation +84m and the reservoir was held at this elevation for two weeks. This provided a baseline performance in terms of seepage and piezometric response which would serve to evaluate the performance of the remedial works.

The detailed design of the grouting works was developed in consultation with the proposed grouting contractor, Norwest Holst Soil Engineering (NWH).

TAM sleeve tubes were proposed at 1.5m longitudinal centres on the centerline of the core wall. Grouting ports were proposed to have 0.5m vertical centres with the tubes extending over the full height of the core wall/trench.

Two grouting techniques were considered for the line of grouting upstream of the core wall. With either method it was proposed to use two rows of grouting holes, located 1.25m and 2.25m upstream of the centerline of the core wall, with the holes staggered at 2m spacings.

1. Pressure grouting of the foundation below packers and subsequent TAM grouting of the clay fill upstream of the core wall.

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2. A simpler 'open hole' approach whereby grout would be injected into sacrificial tubes extending into the foundation with perforations in the tubes over the length within the rock foundation. With this method, grout would also travel up the annulus between a slotted plastic casing (used to support the hole) and the clay fill, thereby filling voids within the clay fill.

The first method was favored technically, as grouting of the rock foundation could be completed using higher grout pressure. TAM grouting of the clay fill would also provide a greater degree of control in the grouting process, provide a detailed record of grout takes, and the grout mix could be varied to suit.

The advantages of the second method were in terms of cost and programme. This would arise from the shorter amount of time that critical equipment would spend at each hole in supporting the packers. With this method, which was proposed by the contractor, the grouting pressure is limited to the hydrostatic pressure available from the dam crest elevation.

It was agreed that the second method should be trialled and lugeon tests conducted to check for the effectiveness in sealing the foundation and reducing the permeability of the clay fill immediately upstream of the core wall/trench. This trial resulted in two foundation permeability results of zero lugeons in the foundation and therefore the 'open hole' method was adopted for the remainder of the work.

The grout mix used for the TAM grouting used bentonite and OPC in equal measure by weight and a water:cement ratio of 10:1. This mixture was designed to have a shear strength (when fully set) similar to and less than that of the clay core.

Following initial trials for the foundation grouting to determine the optimum ratio of water to OPC, a 3:2 water:cement (by weight) mix was selected. This mix was used for all of the foundation grouting except in cases of limited acceptance where a 3:1 (by weight) mix was used.

Grouting Performance

Falling head permeability tests in the clay fill and water pressure tests in the rock foundation were carried out to assess the effectiveness of the grouting works. The results are summarized in Table 2.

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Table 2: Grouting Results

Location	Permeability prior to grouting	Permeability after grouting
Puddle clay core wall	1E-06 m/s based on three tests.	2.5E-07m/s based on five test results
Clay fill on plane immediately upstream of core wall	1.2E-05 m/s based on two tests. Taking into account tests on the downstream shoulder fill, the fill permeability is typically in the range of 1.0E-05 to 1.0E-06 m/s.	1.9E-06 m/s based on six test results.
Rock foundation	Five borehole water pressure tests: two results of >100 lugeons; unable to obtain sufficient water pressure in the other three boreholes.	Result (lugeon)/Formation 60/ Wilmcote 40/ Wilmcote/Langport >100/ Langport 0 / Langport 0 / Langport 70 / Wilmcote.

The reduction in permeability in the core wall/trench and the clay fill upstream of the core wall was considered a success. The foundation results were disappointing, given the promising trial results (the two results of zero lugeons). However, overall the results indicated that the permeability of the foundation had been significantly reduced, if not to the standards normally associated with new dams. Discussions with the inspecting engineer concluded that the improvement was sufficient to warrant a trial impoundment of the reservoir to assess the effectiveness of the remedial works. The option to pressure grout sections of the dam foundations remained available at this time, but it was decided to reserve this option in the event that the impoundment trials indicated that the works had been ineffective.

The cost of the grouting works completed at the dam was approximately £400k.

Trials

To test the effectiveness of the remedial works, a programme for raising the reservoir level to top water level and monitoring the response of the

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embankment was prepared. The reservoir level can be raised simply by closing the 18-inch drawoff valve. The timing of the test impoundment was dictated by the requirements of a badger license and inundation of the sets in the reservoir area could not commence until the summer months. A further constraint was the proximity of an adjacent storage area owned by the Undertaker which is inundated at reservoir top water level. This area had to be cleared of equipment before the test could commence.

The strategy for testing the remedial works was as follows:

1. Close the drawoff valve and slowly raise the reservoir level to +84m and hold at this level for two weeks with the valve cracked open.
2. Compare the results with the partial raising completed before the remedial works. Assess the level of seepage flows and the piezometric response.
3. Close the drawoff valve and slowly increase the reservoir level from +84m to +86.9m, continuously monitoring seepage and piezometric pressures. This phase was implemented over a period of over three weeks.
4. Hold the reservoir at top water level for a period of at least 2 weeks and assess the results.
5. Crack open the valve and slowly draw the reservoir level down. The reservoir was drawn down at a rate not exceeding 300mm/week to guard against instability of the upstream face.

In November 2005, after the reservoir had been maintained full for nearly three weeks with no problems arising, the remedial work was declared successful. In practice, the reservoir would be full for a shorter period of time in the event of an severe flood.

It was observed that the seepage rate from the reservoir when full (+86.9m) was significantly less than had been observed prior to the grouting works when the reservoir was empty (+81m).

The piezometric responses were generally in line with expectations. The piezometers located upstream of the core responded more markedly after the remedial works in response to the partial raising, indicating reduced permeability of the core. The piezometers in the foundation beneath the downstream shoulder and in the downstream shoulder material itself generally displayed a more subdued response to the impoundment.

FUTURE MONITORING

The performance of the dam will continue to be monitored using both the vibrating wire piezometers and an improved seepage monitoring weir in the

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tailbay channel immediately downstream of the dam. These provisions will enable the Undertaker and the Supervising Engineer to effectively monitor any deterioration in the performance of the remedial works.

CONCLUDING REMARKS

This project describes the latest and most successful attempt to reduce seepage and improve the safety of Barrow Compensation Reservoir; a dam which has proved troublesome ever since its construction in 1863 due largely to a highly permeable foundation.

It is an example of where expensive remedial works have been completed for the purposes of reservoir safety despite the reservoir having no useful function for the owner.

In practical terms the project provides a further example of how puddle clay cores can be improved using TAM grouting. Despite the relatively crude approach adopted for the foundation grouting, a significant reduction in permeability was achieved.

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