The British Dam Society

Managing risk at Victoria Service Reservoir

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SYNOPSIS Victoria Reservoir is a reinforced concrete service reservoir located in the heart of Bristol. Constructed in 1914, it is one of the oldest reservoirs of its type in the UK. It was constructed on the site of an earlier open service reservoir. During the second world war, the reservoir was damaged and repaired on account of bombs being dropped on it during the Bristol Blitz. In more recent decades, a series of investigations and repairs have been carried out to assess and maintain its structural condition and operational performance. This paper will describe and discuss the various challenges faced by the operator in managing the safety and operational risks associated with a very old reinforced concrete service reservoir.

INTRODUCTION

The design and construction of service reservoirs in the UK has greatly changed over the last 150 years with an ever-increasing focus on maintaining the quality of the stored potable water. Victoria Reservoir in Bristol is one of the UK's oldest active service reservoirs. This paper looks back over its history and discusses the present-day challenges in continuing its operation and ensuring its compliance with safety and water quality regulations.

HISTORY

The reservoir is believed to date from 1848. Plans from 1877 show that Victoria Reservoir started its life as a rectangular open reservoir formed with a lining of puddle clay and masonry. Figure 1 shows the original reservoir. The reservoir received water from Barrow Treatment Works to the south of Bristol and pumped it to the original Durdham Down Reservoir near Clifton. Victoria Reservoir was converted to a covered twin-cell concrete service reservoir in 1914. The total capacity was and remains approximately 30,000m^3. The design followed the Mouchel-Hennebrique system of ferrocement, an early form of reinforced concrete. This utilised a cement mortar matrix and layers of small diameter wire mesh in combination with more traditional steel reinforcement bars. The construction was monolithic and the walls were constructed encastre with the roof slab. Elements of the original reservoir construction were retained including the overflow/washout shaft and the underdrain system. The original overflow shaft can be seen in Figure 2. The side walls are relatively thin at 150mm, supported internally by counterforts. The side walls were backed with puddle clay but there is no back-of-wall drainage system.

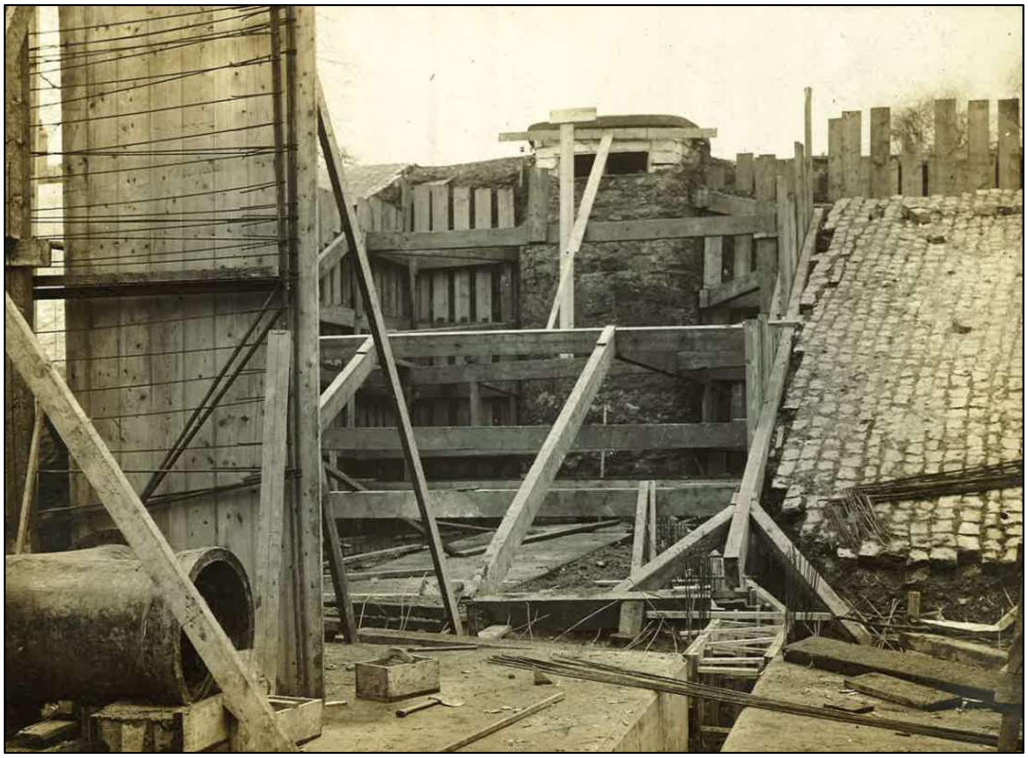

Figure 1. Original open service reservoir with the Engine House and Boiler House in the background.

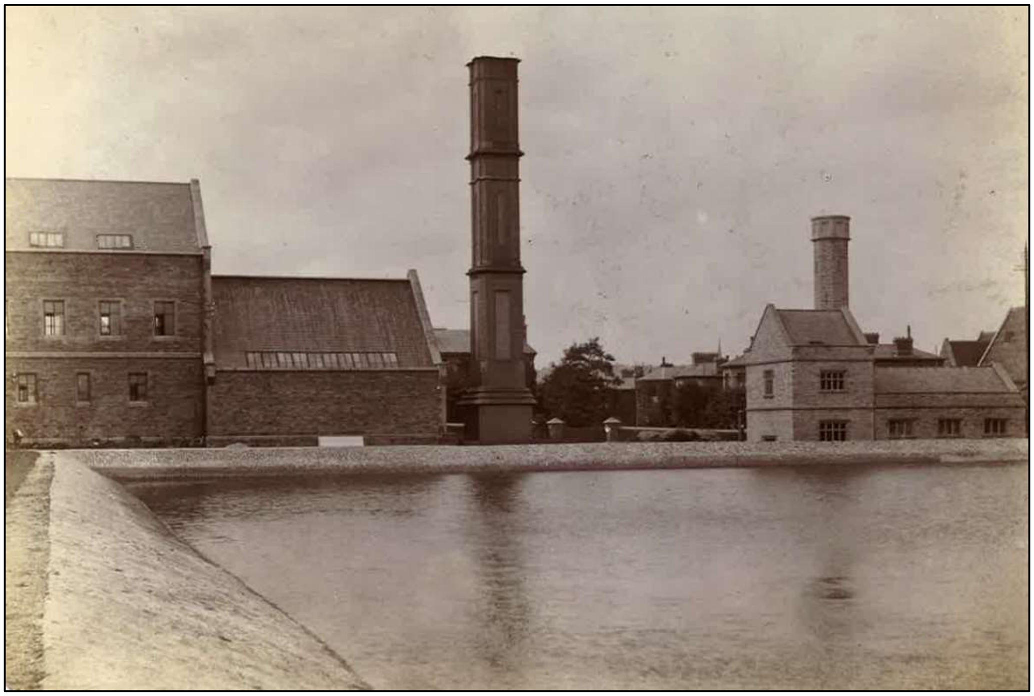

Figure 2. Reservoir conversion works in progress showing the original overflow shaft and reservoir lining.

The reservoir was damaged during the Second World War. During the Bristol Blitz (1940-41), bombs damaged both compartments although the extent of the damage was not significant and the reservoir was repaired. One area of damage was sustained in the northern compartment and two areas of damage were sustained in the southern compartment. Drawings from 1949 indicate that the adjoining pumping station was reconstructed following the war.

Some remedial and improvement works have been carried out, particularly over the last 50 years. A bitumen liner was applied to the roof slab to reduce infiltration. Roof vents were removed to reduce contamination risk. Concerns raised regarding the structural condition of various concrete elements in the late 1980s led to investigations. Major repairs were carried out in the mid-late 1990s to some of the concrete roof beams and columns. The southern compartment floor slab was thought to be leaking at this time. The internal concrete walls, floor and column surfaces were treated with Flexcrete Cementitious Coating 851 to reduce leakage and to help arrest concrete deterioration.

The reservoir is in a highly urbanised part of Bristol and presents a high hazard to local residents. It is a statutory reservoir regulated under the provisions of the Reservoirs Act 1975.

CONCRETE DETERIORATION

In parallel with a statutory inspection of the reservoir in 2013, an investigation of the roof structure of the northern chamber was carried out. The roof slab soffit displays numerous cracks, most of which have 'healed' through calcite deposition. Cover meter readings to the roof beam reinforcement gave mean values between 17-36mm. Schmidt hammer testing of the original concrete indicated compressive strength values in excess of 40 N/mm^2 but much lower values for some areas that had been repaired. The risks of concrete deterioration through carbonation, chloride-induced corrosion, sulphate or chemical attack or freeze-thaw actions causing degradation in the form of cracking, spalling, delamination and surface softening or erosion were evaluated. Carbonation was considered the primary mechanism of deterioration, but the rate of deterioration will likely have been arrested by the high moisture conditions within the reservoir. Cracks in the roof slab were primarily attributed to thermal movement. Local areas of spalled concrete on roof beams were attributed to a loss of the protective passivation layer on the steel reinforcement through carbonation. This protective film is formed as a result of the high alkalinity in the cement paste but becomes unstable when the pH decreases or the film is destroyed through contact with chlorides. Chlorides can be present in concrete as calcium chloride was a common accelerating admixture during cold weather concreting from the end of the 19th century until the 1970s. The investigation concluded that with an appropriate proactive maintenance regime, the residual operational life of the reservoir roof should exceed 50 years (to c.2060), giving a projected overall service life of approximately 150 years or more.

Figure 3 shows an image of the inlet pipework and concrete from the time of construction and a similar image taken in 2023. It can be noted that the concrete elements generally remain in very good condition after more than 100 years in use.

Figure 3. Southern wall and inlet pipework in 1915 (above) and 2023 (below)

CRACK MONITORING

Crack monitoring within the reservoir is difficult given that access is infrequent, typically every 2-3 years, time-limited as there is pressure to return the reservoir to service quickly, and carried out in low light conditions.

Formal recording of cracking patterns on the internal walls, floors, roof slabs and beams started in 1995 and was undertaken manually by sketching the extents of larger cracks onto hard copies of printed drawings. This process was improved from 2007 with the manually sketched cracking on site later transferred to CAD record drawings when back in the office. A different colour of CAD layer was used for each survey so change could be detected over time. Differences in the personnel, the viewing locations and the lighting during these infrequent inspections meant the results were indicative only, but it allowed the undertaker to track the behaviour of the larger cracks.

In 2019, improvements in technology allowed trialling of 3D laser scanning of the interior. This has several benefits in that it is rapid, covers all areas (floors, walls, roof) in one go and does not rely on good lighting for results. It is also repeatably consistent and produces a large amount of digital data that can be interrogated later. The remaining issue is that manual review of the data and logging of the cracks is still the most reliable way of recording the results. Investigations into the use of an artificial intelligence (AI) engine is being explored at present for the automatic interpretation of the scan data and subsequent change detection when comparing to previous scans.

THERMAL EXPANSION OF THE ROOF

Inspection of the northern compartment in 2013 revealed fresh horizontal cracks through some of the internal buttresses. It was speculated that exceptionally hot weather in Bristol in 2006 may have instigated the cracking through thermal expansion of the roof slab. The roof slab has a surface layer of 100mm of gravel and 75mm of grassed topsoil above the bitumen membrane. Instrumentation of the compartment was recommended in the interests of safety to better understand how the cracking may have occurred and whether the crack widths are increasing over time. In 2017, a number of tilt beams and strain gauges were installed (Figure 4).

Unfortunately, many of the instruments failed to perform well on account of the conditions within the reservoir affecting the electronics, particularly the high humidity levels and chlorine off gas above the water level. Data sets were obtained over a four-year period to 2021 before the instruments had to be abandoned.

As would be expected with roof expansion forces being transmitted into side walls, greater strain values were detected towards the top of the wall buttresses than at cracks lower down the buttresses. Tilt beam readings were also greater near the roof. Actual deflections across the cracks were however quite modest with the greatest values being less than 0.5mm and more generally the readings were less than 0.2mm. The variations in strain did not correlate well with changes in reservoir water level, indicating that thermal gain is the primary driver for the wall cracking. The investigation results, reviewed as part of the 2023 statutory inspection, gave no immediate concern for the safety of the reservoir although some form of roof insulation may be considered by the operator going forward, especially in light of climate change.

Figure 4. Strain gauge installations across two new horizontal cracks extending partly through an internal wall counterfort.

SEEPAGE MONITORING

Seepage monitoring at the reservoir is restricted by the original design provisions. There is a single underfloor drain serving each of the two compartments. These drain to the base of the overflow shaft so combined flow readings are monitored except when one compartment has been emptied. Mean annual underdrainage flows increased nine-fold between 1999 and 2010 but the trend did not continue and has since partially reversed. The increase was most likely attributable to leakage past the washout valves into the base of the overflow shaft where all drainage is directed, including roof drainage. This highlights the challenges associated with monitoring reservoir performance where there are not separate monitoring provisions for each drainage system. The reservoir features no back-of-wall drainage system. Seepage into the surrounding embankments would likely be limited by the puddle clay backing to the walls. The stability of the surrounding embankments is generally managed through regular surveillance for any wet spots at the toe.

There is a system of perimeter drains which do not specifically serve as toe drains but could receive flow in the event of reservoir leakage. These date from the original construction. They are difficult to survey but some information on connectivity has been gained through flow testing.

PRESERVING WATER QUALITY

Whilst creating a covered water retaining structure was a huge step forward for water quality, the new (1914) covered structure used Gatic covers which were neither weather or insect resistant. Air vents were installed, again without insect mesh along both walls. Material access covers of concrete planks were weather-proofed with lead sheet under a soil covering. Water sampling was not even considered.

Over the years the following measures have been added and improved through Technical Guidance Notes by the Drinking Water Inspectorate (DWI) and Public Health England (now UK Health Security Agency), Security and Emergency Measures Direction Policy and good industry practice:

- Covers have changed from Gatic to GRP, to now double skinned tamper-monitored covers in sight of CCTV.
- The pump station changed from steam powered to electric in 1956, requiring installation of a deeper outlet sump and new outlet main.
- Bristol Water opened a laboratory for water samples in 1963.
- The roof was stripped of topsoil, the seal on the material access covers improved and the whole roof covered with Bituthene membrane in 1977; the heaviest item of plant allowed on the 75mm thick roof slab being a wheel barrow.
- A level recorder house was added and removed, to make way for a level control kiosk and sampling kiosks.
- In 1989, the DWI was formed and weekly water sampling from Potable Water Structures was enforced.
- Air vents were removed, covers changed to galvanised steel with ventilation apertures with improved seals and insect mesh.
- In 2002, the Bristol Water laboratory closed and water sample testing was contracted out.
- Overflow weirs were covered with hinged flaps and insect mesh.

CONCLUSIONS

Victoria Reservoir is an example of a very old reinforced concrete reservoir formed on the site of an even older open reservoir which has provided potable service storage for over one hundred years and is likely to do so for at least another 50 years. Like many such reservoirs, it is located within a community so the safety of the reservoir is of paramount importance. The age of the reservoir presents numerous challenges in maintaining the quality of the stored water and in monitoring the structural condition. Modern technologies have been deployed to better understand the nature and magnitude of movement in the side walls and in monitoring any new indications of structural deterioration. The structures are now inspected using a risk-based approach, with both the structural and water quality conditions assessed, with these criteria setting the internal inspection frequency to two, four or six years with allowance made for Section 12 and 10 safety inspections to occur within these drain-down periods. Over its remaining service life, the condition of the structure will demand a more proactive approach to maintenance. The reservoir has survived the impact of time, a bombing and increased regulatory standards. In modern times, climate change appears to have caused some minor deterioration of the structure. Nevertheless, with an appropriate maintenance regime the reservoir appears set to provide many more decades of service to the people of Bristol.