The British Dam Society

Upper Carno: A case study of multidisciplinary remedial works to an embankment dam

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SYNOPSIS Upper Carno is a 14m high embankment dam in south Wales. Items of remedial work had been identified by Dŵr Cymru Welsh Water (DCWW). Investigations undertaken by Mott MacDonald Bentley (MMB) to inform the remedial works highlighted risks, and a subsequent Section 10 inspection resulted in eight measures in the interest of safety concerning the spillway condition and capacity, embankment stability, and drawdown condition and capacity. The resultant suite of remedial works required careful management of interfaces between the various workstreams throughout design and construction, to reduce the risk of failure to acceptable levels and to improve the working life of an aging asset.

This paper outlines the arc of the project and highlights the importance of developing the permanent works, temporary works and dam safety construction risk management together, given their entwined relationship throughout the whole of the project.

BACKGROUND

Upper Carno is the upper in a cascade of two impounding reservoirs situated in south Wales. The 0.34Mm³ reservoir is retained by a single dam, owned and operated by DCWW. The dam was constructed around 1875 to supply industrial customers in the town of Ebbw Vale, approximately 2.5km downstream, via a treatment works situated immediately downstream of the dam. The treatment works has long been demolished, and the reservoir now supplies raw water to Carno WTW via the downstream watercourse and the lower reservoir. The reservoir has a surface area of 0.063km^2, an operational top water level (TWL) of 444.54mAOD and a total catchment area of 5.1km^2.

The dam at Upper Carno is a 14m high, 270m long Pennine-type embankment (Figure 1) with a central puddle clay core. The reservoir is fed via direct and indirect catchments and has the facility to divert some indirect catchment flows around the reservoir in a bywash channel which discharges to the spillway. An overflow weir is situated at the left abutment, at the top of the 190m long spillway. The original draw-off arrangement was via a valve tower in the upstream shoulder and a brick-lined tunnel containing a supply pipe with an offtake to Carno WTW, which ran in a straight line underneath the embankment from the valve tower to the dam toe, and then bent to follow the line of the toe towards the spillway and discharged to the downstream end of the spillway.

The reservoir has a history of remedial and improvement works, most notably, the spillway capacity was upgraded and a section of the toe of the dam stabilised in 1986.

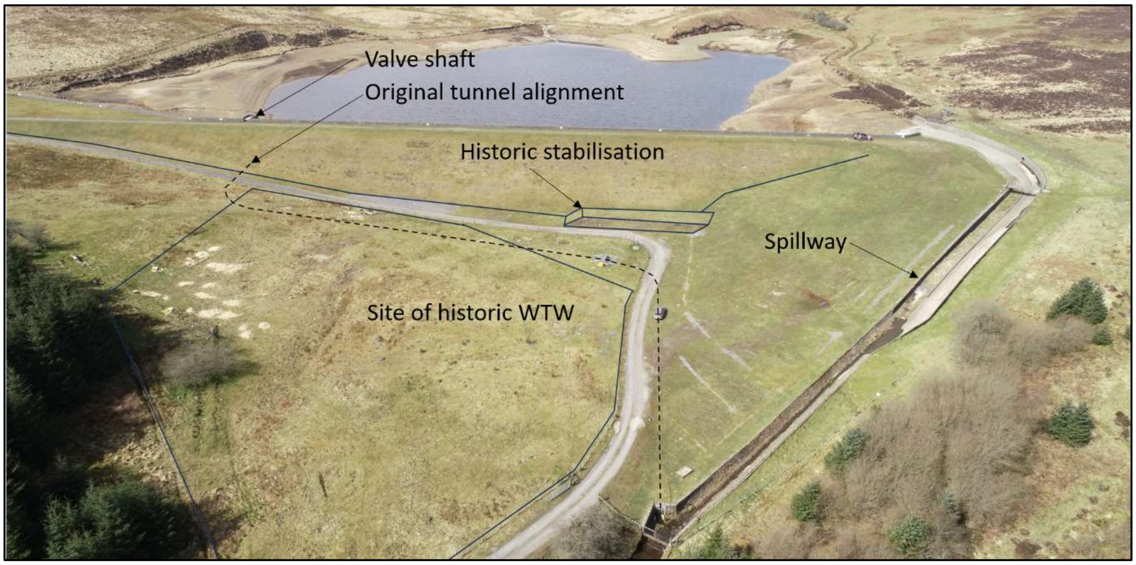

Figure 1. Upper Carno before works (MMB)

INVESTIGATIONS & DESIGN DEVELOPMENT

A Dam Safety Asset Survey undertaken by DCWW had highlighted that much of the pipework and valves at Upper Carno were in poor condition or inoperable. There was a risk that failure of any part of the system could result in an uncontrolled release of water from the reservoir and damage the dam. MMB was appointed to refurbish the existing draw-off system by repairing or replacing valves and pipework as required to reduce the risk of failure to an acceptable level.

A separate scheme was concurrently released to MMB to undertake minor repairs to the masonry spillway and brick-lined tunnel, to refurbish a system of French drains installed as part of the 1986 works, and to carry out a formal risk analysis of failure of the embankment by performing ground investigation and stability analyses of the upstream and downstream slopes.

Embankment stability

A 2016 Section 10 report noted no excessive settlement of the embankment, and the embankment was seen to be in good condition. However, the steep 1V:2H slope of the downstream shoulder was a cause for concern, and there were indications of poor drainage near to the toe of the highest part of the dam.

It is likely that the stability of the downstream shoulder of the dam would have been reviewed as part of the 1986 stabilisation works, however there is no available record of such assessment, and as such, a stability analysis was recommended. Whilst the wider scheme was being designed and constructed, the reservoir was subject to a precautionary drawdown to a minimum of 3m below TWL, informed by temporary works assessments, as a proactive measure to maintain stability factors of safety within tolerable limits and to help minimise the risk of significant operation of the spillway.

Ground investigation

No previous intrusive ground investigations are known to have been undertaken at Upper Carno, thus a comprehensive suite of ground investigation and laboratory testing was undertaken in two phases to inform the stability analysis.

The first phase of ground investigation was carried out during winter 2018 by Geotechnical Engineering Ltd and comprised 7no. dynamic sampling with rotary core follow-on, 7no. hand-dug pits, 1no. observation trench across the dam crest, and 4no. machine excavated trial pits. Eleven permanent piezometers were also installed.

Peat was found under the toe of the dam. Following review of the initial phase of ground investigation, an additional 4no. hand dug pits and 6no. machine excavated pits and testing were undertaken in August 2019 to further understand the extent and nature of the peat.

Slope stability analysis

The stability of the upstream and downstream slopes was assessed using the Spencer method in Geostudio SLOPE/W for the normal and flood conditions (reservoir level at top water level and probable maximum flood level, respectively), and pseudo-static conditions. A combined SLOPE/W and SEEP/W model was used for a rapid drawdown analysis of the upstream shoulder. The load conditions modelled and the target factor of safety (FoS) acceptance criteria were in line with UK and international guidance.

The results indicated that the dam at Upper Carno did not meet the required FoS in the downstream shoulder under normal, flood and pseudo-static conditions. The upstream slope was found to meet acceptance criteria in all cases.

A number of options for improving the downstream shoulder stability FoS were considered. Options that were considered feasible and found through further stability analysis to meet the same acceptance criteria were: slackening of the downstream shoulder; construction of a berm; and permanently reducing the reservoir TWL. The preferred option was agreed as slackening the slope from 1V:2H to 1V:3H over the full height and length of the downstream face. This option allowed the installation of a filter between the existing and new works over the full height of the structure without extensive excavation to the existing embankment face, thus preventing failure by internal erosion. A typical cross-section of the slope stabilisation is shown in Figure 2.

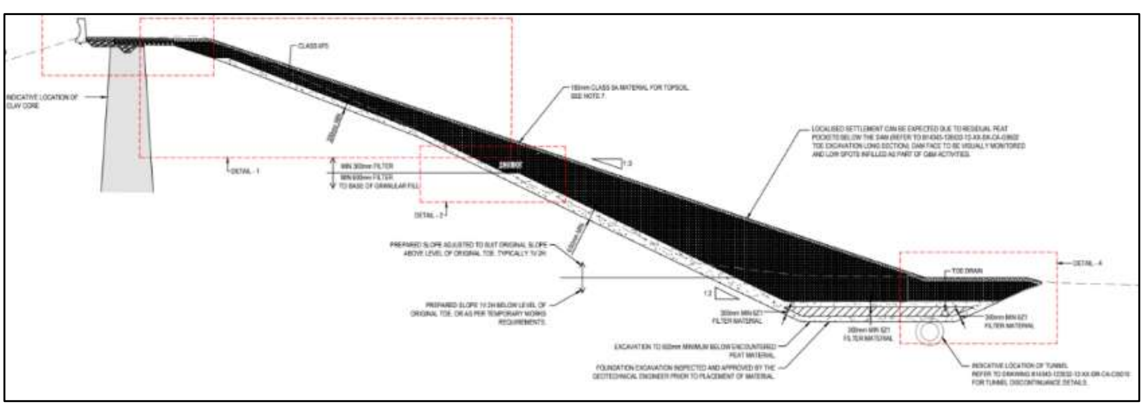

Figure 2. Slope stabilisation typical cross-section (MMB)

Drawoff system

One of the biggest challenges with working at historic assets is often an absence of record drawings. For the Victorian era Upper Carno, the only drawing showing the valve tower and upstream draw-off arrangement was dated 1952, with the upstream pipework labelled as "assumed alignment".

The original draw-off arrangement consisted of a brick-lined valve tower in the upstream shoulder, separated into a 'wet' well and 'dry' well by a cast iron dividing wall, referred to as the "feather" on the historic drawing. The drawing shows the wet well being fed from the reservoir by an upper inlet (TWL -2.2m) and a lower inlet at the base of the tower. The lower inlet appeared to be direct buried, capped at its upstream end, with a tee upstand and strainer at low level in the reservoir. Upper, middle and lower offtakes at the "feather" fed a 15" stack in the dry side, which connected to the supply main running through the tunnel. There was a single gate valve at each valve tower offtake and no control on the upstream reservoir inlets. A short scour pipe discharged directly from the wet well into the upstream end of the tunnel.

There are no records of the reservoir being completely drawn down or the wet well being emptied below the middle inlet. The water level in the wet well was always reported to match reservoir level, including when the reservoir level was below the upper inlet level (TWL -2.2m).

A series of surveys and investigations were undertaken to understand the arrangement of the reservoir inlets and the and condition of the pipework in the tunnel and tower.

An underwater survey of the wet well carried out by Edwards Diving Services (EDS) found that the lower reservoir inlet did not discharge into the wet well, as indicated in the 1952 drawing, but passed straight through the wet well, connecting directly to the supply main. It was therefore concluded that for reservoir levels above the middle offtake that the wet well was filled by reservoir head driving flows through the lower inlet, upwards through the stack and out through the middle inlet into the wet well, and thus the reservoir could only be drawn down using the scour to empty the wet well as low as the middle inlet, in a 'loop-the-loop' arrangement (Figure 3). The upper reservoir inlet was confirmed as indicated on the 1952 drawing during partial drawdown, but several underwater searches were unable to locate the lower inlet.

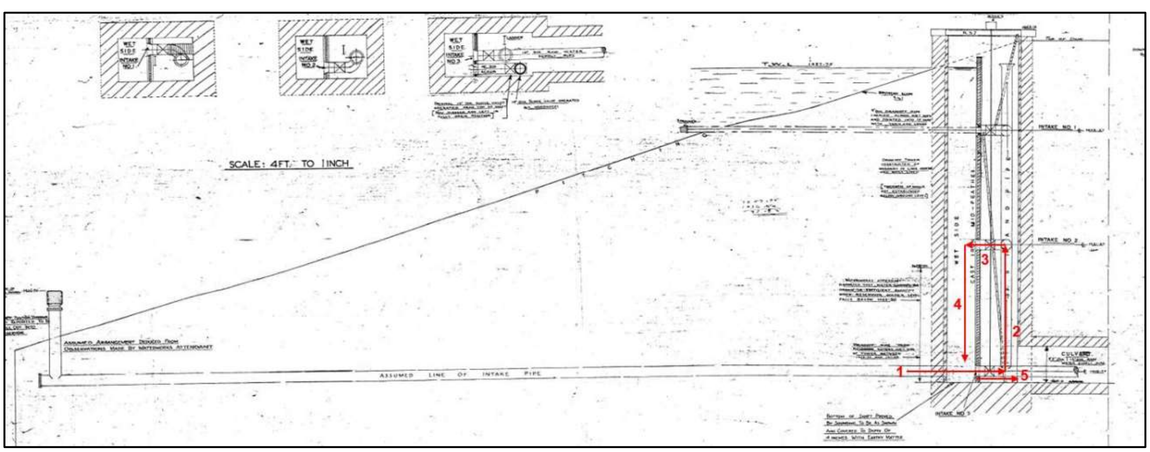

Figure 3. Assumed 'loop-the-loop' draw-off arrangement. Extract from 1952 drawing (DCWW)

Visual inspection and non-destructive testing of the supply pipework in the tunnel by MMB during a tunnel inspection in October 2018 found the pipework to be extensively corroded with considerable pitting. The flange joints were noted to be perished and the bolts corroded.

Valve tower

The valve tower was a congested space, with only half of the 2m x 3m plan area being the accessible dry side, which also included a pipe stack and valves restricting access considerably (Figure 4). It was therefore proposed to remove the dividing wall and convert the tower to a fully dry tower and to provide new access metalwork ladders and landings to ensure safe operation for future use.

Coring at the top of the valve tower found that the structure was formed of a double skin of masonry with an infilled cavity. Conversion to a fully dry tower therefore needed to provide watertightness. It was also important to consider composite behaviour between a new structural liner and the existing structure to maximise working room. Although not thought to have been designed to provide structural support, the 2" thick cast iron "feather" was embedded in the valve tower brickwork and it is possible that it acted as a structural component of the tower and its removal could have affected the integrity of the structure.

Tunnel

The original scope of works relating to the tunnel was to undertake minor repair works. However, significant water ingress and visual ovality of the tunnel directly below the embankment shoulder caused the Inspecting Engineer to express concern over the long-term integrity of the tunnel. Options to reduce the risk of failure of the 1.5m diameter tunnel were: total discontinuance and construction of a new tunnel; or structural reinforcement of the tunnel, which was the favoured option. A 1m diameter structural steel pipe with the annulus grouted was proposed to allow the brick tunnel to maintain its shape. This option would maximise the pipework flow diameter should future alterations be required.

Proposed solution

The suite of investigations to inform the design for the remedial works to the draw-off system revealed additional risks that needed to be addressed, thus the scope of works for the proposed solution was significantly greater than that at the commencement of the project.

The proposed solution for the pipework and valves, valve tower and tunnel was as follows:

- Conversion of the valve tower to a fully dry tower by removal of the cast iron dividing wall and installation of a reinforced concrete liner. Replacement of all access metalwork and pipework, including a duty/guard valve arrangement on each reservoir inlet to provide double isolation in the valve tower. The lower inlet upstream of the valve tower would be left in situ.
- Installation of a 25m long structural steel pipe in the existing tunnel under the dam shoulder from the valve tower to the tunnel bend and infilling the annulus between the pipe and original tunnel structure a with non-shrink cementitious grout. Removal of pipework and infilling of the original tunnel beyond 25m downstream of the valve tower to prevent failure as this would be below a section of the slope improvement works.

- To enable the lining of the tunnel and to route all new pipework outside of the footprint of the slackened shoulder, construction of a new access shaft over the tunnel bend and an additional shaft outside the footprint of the proposed stabilising works. Connection of new shafts by a new length of tunnel containing new draw-off pipework.
- Installation of a combined buried scour/supply main from the new shaft to the watercourse, via a submerged discharge valve (SDV) and SDV chamber to dissipate energy from scour flows through a 600mm main operating under full reservoir head. The SDV chamber discharges into the spillway stilling basin.

The drawdown capacity of the selected option was assessed to confirm its suitability in line with *Guide to drawdown capacity for reservoir safety and emergency planning* (EA, 2017), with allowances for futureproofing the system included.

Spillway

Physical investigation

The original spillway at Upper Carno was constructed on the left abutment and formed of a 3.3m wide, rectangular masonry channel, transitioning to a parabolic channel roughly halfway along its 190m length (Figure 10). Spillway improvement works were undertaken in 1986 which included the replacement of the original tumble bay with a 21.5m long crump weir and concrete tumble bay area, narrowing to meet the original masonry channel approximately 30m downstream of the overflow. From this point, the spillway was modified to comprise a composite channel formed from the original 3.3m wide masonry channel invert and right-hand wall and a 2.7m wide reinforced concrete 'L section', with a 200mm high step dividing the left and right sides of the channel and at the top of the masonry section, such that low spillway flows were directed down the concrete (left) side of the spillway, and the masonry channel would come into operation only when flows exceeded 200mm depth. The composite spillway extended as far at the start of the original masonry parabolic section, which was not upgraded as part of the 1986 works.

A visual spillway condition assessment was undertaken by MMB in May 2018. The quality of the masonry was seen to be good, with sections of the invert which required the pointing to be reinstated. There were sections of the masonry invert that had been replaced by mass concrete. The reason for these repairs was unknown but presumably due to historic events of high flows plucking out masonry blocks. The concrete elements were seen to be in generally good repair.

A geophysical survey was undertaken in the spillway chute in June 2019 by Terradat, which indicated that the masonry invert was potentially laid directly on erodible made ground and showed signs of voiding. Cores and trial holes were excavated in the spillway in June 2019 to confirm the GPR results and to understand the presence, nature and detailing of the clay core and its interface with the spillway. The findings of the site investigation showed that the masonry blocks sat directly on erodible soils and no concrete bedding was provided under the masonry spillway. The presence of concrete backing to the masonry wall was limited. With this arrangement, the residual risk of failure of the masonry section of the spillway was considered to be greater than that of the concrete structure.

The clay core was located outside the right-hand wall and at the base of the right-hand wall within the spillway. No features were observed suggesting a formalised connection between the clay core and spillway base. The investigations suggested that the spillway slab was founded partly on the clay core and partly on rock.

Modelling

A flood study was undertaken in October 2019 to inform a capacity assessment of the existing spillway, which was calculated using the "standard step method" for the Design Flood and Safety Check Flood for a Category A dam as defined by Floods and Reservoir Safety 4th Edition (ICE, 2015). The spillway is required to pass the PMF flood of $49m^3/s$.

The results for the Safety Check Flood case indicated localised overtopping of the left (concrete) wall in some areas. The right-hand masonry wall would be overtopped over its full length, and there would be out-of-channel flow on both sides in the parabolic section of the chute.

The assessment of the spillway chute suggested that, for the Design Flood condition, the chute had sufficient capacity for its length where it passes the embankment, with out-of-channel flow only in the parabolic section. This section of the spillway was located downstream of the dam and, adopting a risk-based approach, out-of-channel flows at this location may have been considered acceptable to the QCE and client.

The results from this assessment also highlighted that the masonry elements would be unlikely to withstand velocities arising from the Design Flood and Safety Check Flood.

High level options to overcome the shortfalls in condition and capacity of the spillway were considered, with the favoured options being those within the existing spillway footprint. The selected option was to replace the majority of the spillway with a modern reinforced concrete spillway, typically 6m wide, with wall heights between 1.60m and 2.75m. All masonry elements would be replaced with concrete, and the existing concrete structure left in situ and lined, utilising the historic concrete base as anti-flotation kentledge, which would reduce the concrete usage and associated embodied carbon.

The upstream portion of the spillway and overflow weir was not included in the scope of the works. Due to the partly inconclusive physical investigation in this area, the upstream spillway slab tie-in detail was designed with some flexibility to accommodate variations in locations/direction and extent of the existing core found on site during construction.

The original structure included no means of energy dissipation at the downstream end. A Type I stilling basin with downstream weir was included in the design to prevent erosion of the downstream watercourse during flood events. The length and position of the stilling basin was adjusted during design such that all permanent works are situated within the DCWW land boundary, and so that a suitable outfall for the new drawdown system could be accommodated.

Computational fluid dynamic modelling was undertaken to assess the hydraulic behaviour of the proposed spillway chute for PMF, 10,000yr and 1,000yr flood events to inform required wall heights, and to assess the hydraulic behaviour of the stilling basin for the 1,000yr flood event and its ability to dissipate energy.

CONSTRUCTION

Upper Carno is situated at approximately 440m above sea level, which means that it is subject to high precipitation and harsh weather conditions. This caused significant challenges during construction, particularly as the majority of the works required reservoir drawdown and proven isolation of the inlet pipework to be undertaken safely.

Drawdown

Temporary siphons discharging to the spillway and a pumping arrangement were installed to empty the reservoir. For further details on the temporary siphon system see parallel paper by Carruthers and McAree (2024).

Works were required to the draw-off system, within the reservoir basin and spillway, and high-risk earthworks to the embankment. As such, the construction programme was phased to reduce health and safety and dam safety risks. The temporary siphons were maintained throughout the first phase of works to the draw-off system and the slope stabilisation. With the new draw-off system installed that could provide emergency drawdown, the temporary siphons were removed and works to the spillway were undertaken.

The precautionary drawdown to 3m below TWL maintained by the existing scour pipe was sufficient to isolate the upper reservoir inlet by installing a blank plate.

The plan to isolate the lower reservoir inlet had been to remove the strainer on the upstand and affix a blank plate using divers, and then CCTV survey the inlet pipe to determine whether the upstream end of the pipe was capped as indicated on the 1952 drawing. If the CCTV survey was unable to prove isolation, a line-stop and cap-main could be installed to guarantee isolation. This would involve the installation of a temporary cofferdam in the reservoir and localised desilting. However, as the location of the lower inlet upstand had not been identified with the scour outlet reducing reservoir levels to around that of the middle inlet level, the only option was to drain the reservoir further using temporary equipment. Drawdown was further complicated by several storms and attempting to maintain the reservoir empty during winter, along with the volume of silt in the depths of the reservoir.

Upstream works

The upstand and strainer on the lower inlet eventually emerged when the reservoir level had been drawn down by almost 9m. As the water level continued to reduce, a brick arch became visible near to the upstand, which turned out to be the entrance to an upstream open culvert running to the upstream side of the valve tower that had not been indicated on the 1952 drawing or been picked up by the underwater survey of the valve tower due to silt causing poor visibility.

The scour arrangement draining the wet well was not the assumed 'loop-the-loop', but more simply the wet well being fed directly by the open culvert. The original supply main, which had been seen to pass directly through the wet well, was not direct buried, but ran though the upstream culvert.

The design was updated following confirmation of this arrangement. The historic pipework in the upstream culvert was removed and a new concrete plug with through pipework installed at the downstream end, adjacent to the valve tower, to maintain the open culvert whilst allowing conversion of the valve tower to fully dry (Figure 5). Once the plug was completed, safe isolation was installed to undertake the works to the valve tower and downstream tunnel.

Valve tower

The cover slab was removed from the valve tower and a temporary scaffold and lifting system was erected to enable the removal of all historic pipework and the dividing wall. Removal of the "feather" was an onerous task due to its embedment into the brick structure and the heavy weight of 3ft deep, 2" thick cast iron panels.

The valve tower was structurally enhanced by lining internally with a combination of conventionally reinforced and fibre-reinforced concrete, and peripheral steel frames at the levels of the new platforms provided additional bracing. The permanent works, temporary works and construction sequence were developed in tandem to negate the need for structural temporary works. This involved removing the "feather" and installing the structural steelwork in short lifts from the top-down. See parallel paper by Teixeira et al. (2024) for more details.

Figure 4. 'Dry' well tower access (looking up) prior to works (MMB)

Figure 5. Lined fully 'dry' valve tower (looking down) (MMB)

Tunnel and scour

To enable the works to the length of tunnel that was to be retained under the embankment, and to route the new draw-off pipework outside the new dam profile, a 7m diameter shaft was sunk 11m vertically through the embankment shoulder to intercept the existing tunnel. This was utilised to drive the 1m diameter pipework sections into the 1.5m diameter tunnel under the downstream shoulder.

There was concern regarding water ingress into this length of existing tunnel. Internally sealing the tunnel by grouting between the steel liner and tunnel brickwork diverted ingress to the tunnel exterior, where left without intervention, it could lead to internal erosion failure of the dam. To reduce this risk, a sand filter was retrofitted around the exterior of the tunnel by driving a 4.3m diameter steel tunnelling heading from the shaft into the dam foundation material (Figure 6).

A 2.4m diameter tunnel was driven between the 7m diameter shaft and a new 4.5m diameter shaft to install new scour pipework to outside the dam profile. The scour at this point was situated 8m below ground, and was therefore installed by microtunnelling for 80m length from the 4.5m diameter shaft to avoid excavating at such depths. The downstream 60m of scour was installed via conventional open cut to a submerged discharge valve and chamber adjacent to the spillway. A connection to an existing main to Carno WTW was included on the scour. For further details on the permanent drawdown system, see parallel paper by Cornelius & McAree (2024).

The remaining 160m of tunnel beyond the lined section was to be discontinued. As it had begun to deform, and the embankment stabilisation works would add more weight to the parts of the tunnel under the dam, this section of tunnel was required to be infilled. This was undertaken by adding drainage through the tunnel and infilling with an expanding polymer void filler (Figure 7). The downstream 80m of the existing tunnel not under the dam was dug down to, the tunnel soffit removed and the tunnel infilled with drainage and backfilled.

Figure 6. View from new tunnel through 7m shaft to existing tunnel during construction (MMB)

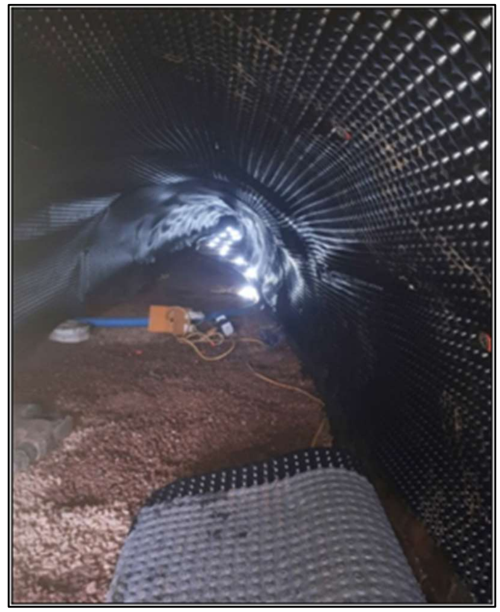

Figure 7. Drainage layer installed in tunnel prior to infilling (MMB)

Earthworks

The slope slackening works consisted of removal of the topsoil from the existing dam and excavation at the downstream toe of the dam to remove peat, up to 3m below the toe. 25,000 tonnes of 6F5 was imported to slacken the slope, a large proportion of which was excavated, crushed and graded for use at Upper Carno from a nearby new service reservoir installation project by MMB for DCWW, which had a significant reduction on the embodied carbon of the scheme and reduced the impact on the local road network.

The slackening detail included a fine and coarse granular filter placed at the interface between the prepared existing embankment shoulder and the imported granular material. The fine filter arrangement protects the dam against future internal erosion and potential failure, whilst the coarse filter acts as a drainage medium and to prevent the fine material entering the 6F5. A new toe drain within the coarse filter drain was installed (Figure 8) to help reduce the piezometric level in the downstream shoulder.

The earthworks were undertaken under reservoir drawdown and working under an Earthworks Temporary Works Risk Management Plan for the excavation of up to 3m depth of peat at the toe of the dam to minimise the risk of slope instability during excavation.

Excavation and backfilling was undertaken in a series of short bays along the length of the dam. The length of each bay was determined based on an anticipated ground model and zoned based on a red-amber-green risk system. For each bay, the toe was excavated to the required depth to remove peat, the toe drain installed and the toe infilled. This sequence was repeated along the length of the dam. Following completion of the high-risk toe excavation works, topsoil was stripped from the upstream shoulder in 500mm vertical lifts and the filter materials were placed by benching into the 1V:2H slope. Imported 6F5 was placed on top and trimmed.

Modification to the crest/core interface was also required to raise the level of the watertight element of the dam such that potential seepage pathways through the dam are reduced for flood scenarios. This consisted of a layer of cohesive material placed between the wave wall foundation and the clay core, and keyed into the clay core

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Figure 8. Installation of toe drain and filters (MMB)

Figure 9. Works complete (DCWW)

Spillway

The MMB design and contractor team worked closely together during the detailed design phase and it was decided to replace the existing concrete elements instead of lining due to the constructability implications and risk of damage to the existing concrete walls when excavating for shear keys.

As the gradients of the spillway were not overly steep, the construction methods were considered, and it was deemed appropriate to utilise a semi-precast system (Figure 11) with similar considerations as presented in the paper by Robson and Bull (2012). FLI Carlow precast panels with an in-situ base were used through the straight chute section, and the upstream end and stilling basin were constructed fully in-situ.

Shear keys and provision for cross drainage were included. A robust back-of-wall drainage system was also included to reduce the loads due to floatation and therefore optimise the new concrete wall and invert thicknesses. The wider, flatter upstream part of the spillway, where floatation is a bigger risk, sits directly on bedrock, which was utilised to reduce the spillway base thickness required to resist uplift by including a system of dowels connecting the new base to the underlying rock. A concrete cut-off and key-in to the clay core on the right-hand side was included at the upstream end of the spillway to tie the new structure into the existing structure left in situ.

Figure 10. Previous composite spillway (MMB)

Figure 11. New reinforced concrete spillway (MMB)

CONCLUSION

The completed Upper Carno Asset Rehabilitation Scheme (Figure 9) included installation of a new full draw-off system, construction of a new spillway, and slope stabilisation works. The construction sequence and drawdown methods used reduced risk to the dam and managed the interfaces between the different elements of the work. The project was delivered over a two-year programme on site and MITIOS sign-off for the associated recommendations was received prior to the statutory date.

ACKNOWLEDGEMENTS

The authors wish to thank Dŵr Cymru Welsh Water for permission to publish this paper.

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