

Improving Dam Safety: Auxiliary Spillway Design

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SYNOPSIS. This paper describes aspects of the design and construction of a new auxiliary spillway, incorporating a labyrinth weir and collapsible safety screens, for an existing cyclopean masonry dam. The works were required to comply with current dam safety legislation. The role of Designer was undertaken by Atkins Limited on behalf of South West Water Ltd (SWW). At the time of writing the works were substantively complete.

INTRODUCTION

The Reservoirs Act, 1975 (the Act) places a considerable statutory obligation on the Undertaker to ensure the safety of its water impounding infrastructure in the UK. This paper describes the design of improvement works to ensure the continued safety of a dam in the South West of England. Aspects of the option appraisal process together with notable design decisions taken in the interests of health and safety are discussed. An insight to the design of collapsible safety screens is also provided.

BACKGROUND

Venford Dam (NGR SX686711) is located in a popular area of the Dartmoor National Park in Devon, and is owned and operated by SWW. Figure 1 provides an overview of the site location.

The dam was built in 1907 to supply water to the town of Paignton and has a storage capacity of approximately 900,000m³. It is classified as a Category A dam under the Act. Untreated water from Venford Reservoir is drawn off to a Water Treatment Works (WTW), located immediately downstream of the dam, from where potable water is piped into SWW's distribution network. The dam rises to a maximum height of 19m above surrounding ground level, with an overall length of 160m. It carries a single track public road along its crest which is heavily used by tourists, particularly during the spring and summer months, as well as local traffic throughout the year. It is a cyclopean masonry dam with a mortar and rock

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'plum' core. Four spillway openings allow flood water to safely pass the dam when reservoir TWL is exceeded. Figures 2 & 3 show the upstream and downstream faces of the dam.



Figure 1. Aerial Image of Venford Dam and Reservoir

Section 10 Inspection

A recent inspection by the Inspecting Engineer recommended a number of improvements to the dam. Improvements identified to be undertaken in the interests of dam safety under Section 10(6) of the Act, were:

- Works to ensure the safety of the dam with regard to sliding and overturning under applied loads during a PMF event and Seismic event (but not acting concurrently).
- Additional spillway capacity provided to safely pass the PMF without exceeding safe working loads on the dam.
- Works to the existing stilling basin to improve performance and to reduce flood risk to the WTW.

In response to these recommendations, the Undertaker commissioned Atkins Limited, as Designer, to develop concept designs for the improvement works. Following consultation and agreement with statutory consultees and SWW these designs were then developed by Atkins Limited into detailed designs for construction.

Phased Implementation

Implementation of the works was programmed to be undertaken in two phases. Phase 1 activities entailed:

- design of a new reinforced concrete stilling basin structure;
- design of a new flow transition wall downstream of the stilling basin;

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- design of access flood gates and erosion prevention works along the banks of the exiting downstream channel (Venford Brook).



Figure 2. View looking West to East on upstream face of Venford Dam

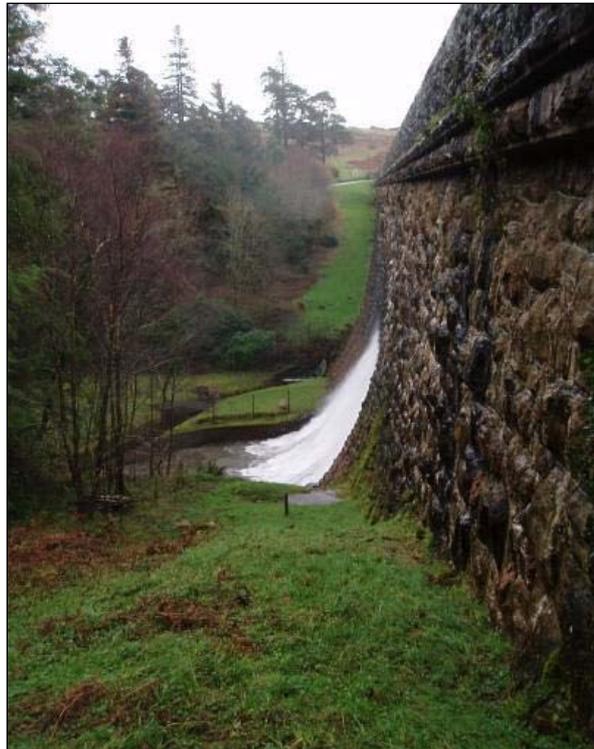


Figure 3. View Looking West to East on downstream face of Venford Dam

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Construction of the above works was completed in December 2007.

Phase 2 activities entailed works to improve the stability of the dam during extreme flood events, through provision of auxiliary spillway capacity. The capacity of the new auxiliary spillway was designed to limit the maximum water level in the reservoir during PMF conditions. The result was to improve dam stability - factors of safety - to acceptable levels under PMF conditions. Key activities included:

- Design of a new labyrinth type weir and receiving channel, approximately 25m in length.
- Design of a buried culvert (4.5m by 3.25m in section) leading from the labyrinth weir, through the abutment of the dam, and continuing to its point of discharge, approximately 50m downstream.
- Design of collapsible safety screens at both the entrance and exit to the buried culvert.
- Design of a permanent debris boom at the approach to the labyrinth weir, approximately 42m in length.

DAM STABILITY

Detailed flood studies and dam stability analysis had already been completed by other consultants and indeed the findings of these studies informed the recommendations of the Section 10 Report. The conclusion of these analyses was that the respective factors of safety for overturning and sliding were unacceptably low during extreme flood events and in particular during that of the PMF.

The option to anchor the dam to the underlying bedrock was ruled out early on by the Panel Engineer as the effectiveness of this technique could not be guaranteed, given the form of dam construction at Venford. As a result it was decided to restrict the maximum water level in the reservoir and provide additional auxiliary spillway capacity.

The auxiliary spillway capacity was assessed to be 38m³/s using theoretical hydrological flood routing analysis and hydraulic calculation. The findings of the theoretical analyses were further verified through scaled physical modelling undertaken at Exeter University, see Figure 4.

SPILLWAY ALIGNMENT

At an early stage in the project alternative alignment options for the auxiliary spillway were identified. These were limited to the west bank of the reservoir as the east bank was impassable due to the location of the existing WTW, surrounding topography (steep and heavily forested) and the

proximity of the Undertaker's property boundary, see Figure 1. Two alignments were considered on the west bank as shown in Figure 5.



Figure 4. Physical Model of Labyrinth Weir in Operation

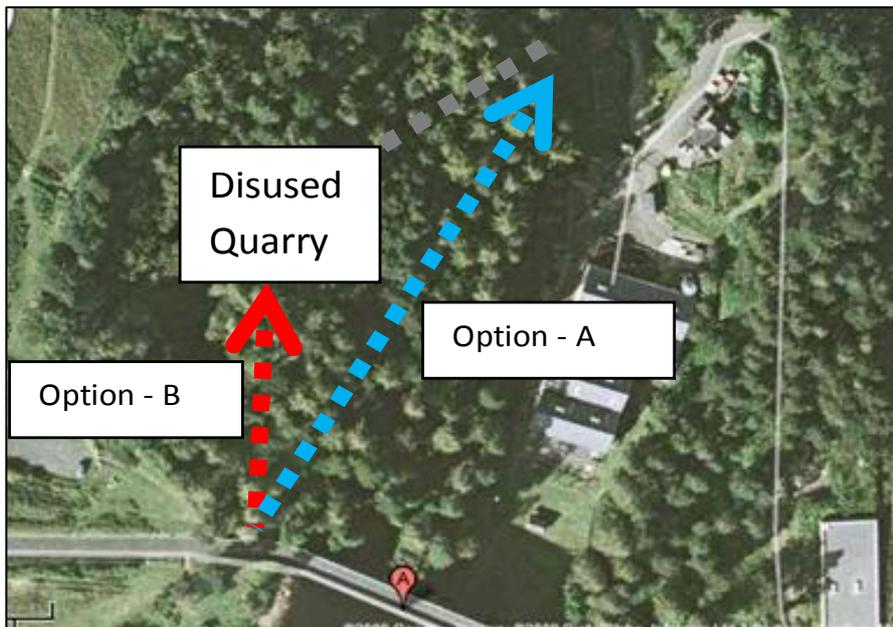


Figure 5. Schematic Overview of Alignment Options

The left bank of Venford Brook is steep (slope varies from approximately 1 in 2 to 1 in 6) and is heavily forested. Alignment A would have required construction of a 125m long (approximately) spillway with significant

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energy dissipation works along its length and would also have required felling a significant number of mature trees in an environmentally and aesthetically sensitive area.

Alignment B maximised the potential of existing topographical features, most notably an existing disused quarry and an existing depression in the left bank of the Venford Brook. Alignment B also benefited by being hidden from view from the public road crossing the dam and would require significantly less excavation works and tree felling. As a result Alignment B was adopted in the final design.

GENERAL ARRANGEMENT

The final form of the auxiliary spillway was the result of detailed option appraisal with due consideration provided to technical, environmental, health and safety, whole life cost and aesthetic aspects of design.

Form of Spillway Channel

The following arrangements for the spillway channel (section of auxiliary spillway between the dam and disused quarry) were assessed:

- Open Channel – unlined and concrete lined rectangular and trapezoidal sections.
- Covered Open Channel – unlined trapezoidal channel with near vertical sides.
- Buried Culvert - single and multiple barrel concrete box and circular sections.

The following factors were decisive in arriving at the final design:

- Depth of excavation.
- Uncertain ground conditions.
- Relatively high discharge capacity requirement.
- Proximity of works to public amenity and access areas.
- Access for operation, maintenance and inspections.

The invert level of the spillway channel was between 6m and 8m below existing ground level, dictated by the crest level of the new weir. Early ground investigations located un-weathered granite rock head at 1m to 2.5m below existing ground level. As a result a significant proportion of the spillway would need to be cut through granite bedrock. A mechanical analysis of rock cores, taken along the line of the spillway, suggested sub-vertical discontinuities in the unweathered rock matrix which could lead to localised slab failures. However, the findings of the ground investigations

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were not fully conclusive and the presence of more significant failures, during and following excavation, could not be ruled out.

Open channel options were ruled out on a number of grounds including health and safety, available space and cost. Uncertainty, in the short and long term, of the stability of the excavated unweathered rock faces was a notable deciding factor. The potential safety hazard to operational and inspecting personnel in maintaining an unlined open channel up to 8m deep, together with its proximity to an area of high public amenity, was considered unacceptable. As such a lined buried culvert option was selected in the final design (Figure 6).



Figure 6. Construction of Buried Culvert in Progress. View looking downstream toward quarry

The choice of a single box culvert was driven by hydraulic performance, access for maintenance and inspection activities and cost considerations.

Culvert through Dam Abutment

A particular design challenge was to ensure the safety of the dam during construction works through the dam abutment. An initial appraisal of options aimed to meet SWW's request for continuous vehicle access across the dam during construction. The options assessed included:

- Tunnelling methods using mechanical excavation.
- A Cut & Fill method.

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Both precast and insitu concrete forms of construction were considered in combination with each option. The tunnelling option had the benefit of allowing continuing (albeit load restricted) access across the dam. A system of beam supports placed in horizontally drilled holes, through the dam and below road deck level, was assessed. However, the option was technically convoluted, and was considered unnecessarily hazardous, and was ruled out.

Further consultations with Dartmoor National Park Authority (DNPA), and a revision to the construction programme by SWW led to a cut and fill option being selected in the final design. A six week road closure period was agreed between SWW and DNPA to allow the works to be completed. As the works were programmed to be undertaken outside the peak tourist seasons the impact on the local economy was minimised. A temporary road bridge was also used to allow limited access for local residents and construction traffic. Figure 7 shows the cut through the dam during construction.



Figure 7. View Looking Downstream through Dam Cut with Temporary Bridge in Position

The stone parapet walls of the dam were dismantled and each block numbered for reinstatement. Unweathered rock head was encountered close to road base level and a stitch drilling technique was used to minimise the extent of excavation through the dam. The Contractor was required, by the QCE, to provide appropriate temporary works to maintain the standard of protection provided by the dam to PMF level. This was achieved by earth filled one tonne bags wrapped in plastic sheeting.

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Due to the relatively small scale of the works, and width constraints on the approach road to the dam, it was decided to construct the buried culvert (spillway channel) in situ. As the sides of the excavation were close to vertical it was possible to use the exposed unweathered rock faces as a back shutter, negating the requirement for extensive backfilling. The culvert through the dam was then backfilled with foam concrete to sub base level before reinstating the roadway and parapet walls, see Figure 8 below.



Figure 8. Showing Reinstated Parapet Wall and Near Complete Entrance Works to Buried Culvert

Labyrinth Weir & Receiving Channel

Options for the arrangement of the new weir were limited due to on-site constraints, the most notable of which was an existing inlet structure and associated water main (Swincombe Main Inlet). There was also a strong drive to minimise the visual impact of the proposed works.

Two principal options were considered, namely a broad crested weir and labyrinth weir arrangement. Following a detailed hydraulic assessment of the overall feasibility of each option the labyrinth weir arrangement was selected over that of the broad crested weir. A high level summary of the weir selection is provided Figure 9.

The labyrinth weir was designed to operate at flood events with less than a 1% (1/100) annual probability of occurrence. While preferable from an aesthetic and capital cost point of view, an option to leave the receiving channel unlined was not viable, particularly due to the high relative permeability of the unweathered granite bedrock and the level of the

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overlying weathered rock band. This, combined with the highly fractured nature of the unweathered rock in the receiving channel area, and the highly turbulent flow conditions expected during operation, meant that the only viable solution was to design a reinforced concrete lined receiving channel. Leaving the channel unlined would also have compromised safe access for future inspection and maintenance activities. Figures 10 and 11 show the completed labyrinth weir and receiving channel

Option 1 - Broad Crested Weir	
Advantages	Disadvantages
<ul style="list-style-type: none"> • Simple design • Relatively straightforward to construct 	<ul style="list-style-type: none"> • Length of structure required would be approximately twice that of Option 2 for the same discharge • Significantly more excavation required in comparison with Option 2, increasing associated truck movements. • Construction would require felling additional mature trees in comparison to Option 2 • More expensive in comparison to Option 2; additional rock excavation costs would offset any apparent savings due to the complexity of Option 2
<u>Rejected</u>	
Option 2 - Labyrinth Weir	
Advantages	Disadvantages
<ul style="list-style-type: none"> • Minimises length of structure for same discharge and reservoir water level • Minimises extent and volume of excavation • Minimises visual impact • Minimises extent of temporary works and construction access • Minimises re-engineering required to accommodate the existing Swincombe Main Inlet • Reduced footprint area of the works provides overall cost savings • Design minimises loss of mature trees 	<ul style="list-style-type: none"> • Increased complexity in design and construction
<u>Selected</u>	

Figure 9. High Level Summary of Option Appraisal for Weir Selection

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OPERATIONAL ASPECTS

Collapsible Safety Screens

Safety screens were provided at the entry and exit to the buried culvert. The primary purpose of these screens is to prevent unauthorised access into the buried culvert. However, the screens could not be allowed to cause a reduction in the discharge capacity of the auxiliary spillway as a result of debris building up on the face of the screen. The final arrangement of the screens required a detailed technical viability assessment and particularly a detailed health and safety risk assessment. Key design constraints included:

- To prevent excessive debris accumulation in front of the screens leading to a reduction in spillway discharge capacity. As a reduction in capacity could lead to reservoir TWL increasing to a level that may impact dam stability.
- To ensure safe access for personnel in operating mechanical components associated with the screens and for safely carrying out inspections and maintenance activities of the buried culvert.

In the event of debris entering the receiving channel the safety screens were designed to collapse under an applied design loading. Determination of an appropriate collapse load for each screen was based on sensitivity testing of the culvert hydraulics and on engineering judgement.

In each case it was assumed that during a PMF event a proportion of the screen flow area would blind with floating debris leading to a reduction in spillway discharge capacity. Sensitivity (hydraulic) analysis (and engineering judgement) led to determination of an acceptable load case to trigger collapse of each screen. The load case so determined was designed to prevent an increase in reservoir level (ensuring the integrity of the dam) and to be greater than the hydraulic loading expected during un-blocked operation of the spillway at PMF.

Entrance Screen

Shear pins were built into the top fixings. When the design collapse loading is exceeded on the face of the screen (due to debris build-up) the shear pins are designed to shear, and the screen will collapse downstream into the mouth of the culvert. The bottom fixings are permanently hinged to prevent the screen being dragged into the culvert (potentially causing a blockage inside the culvert or hanging up on the exit screen). Figure 8 shows the general arrangement of the entrance screens. At the request of the Panel Engineer, provision has also been made to manually collapse the screen. A simple latching mechanism, accessed from above the culvert entrance facilitates this requirement, see Figure 12.

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Figure 10. View of Completed Labyrinth Weir and Receiving Channel Viewed from the Dam



Figure 11. View of Completed Labyrinth Weir and Receiving Channel with Reservoir Level at TWL, viewed from the Dam

The mechanism has been designed to provide a ‘safe’ mode which takes the shear pin out of the collapse mechanism. It is intended that this mode may be adopted during maintenance activities on the screen or during inspections as an added safety measure. Provision has also been made to test the

operation of the screen during statutory inspections by means of a manually operated ratchet winch.

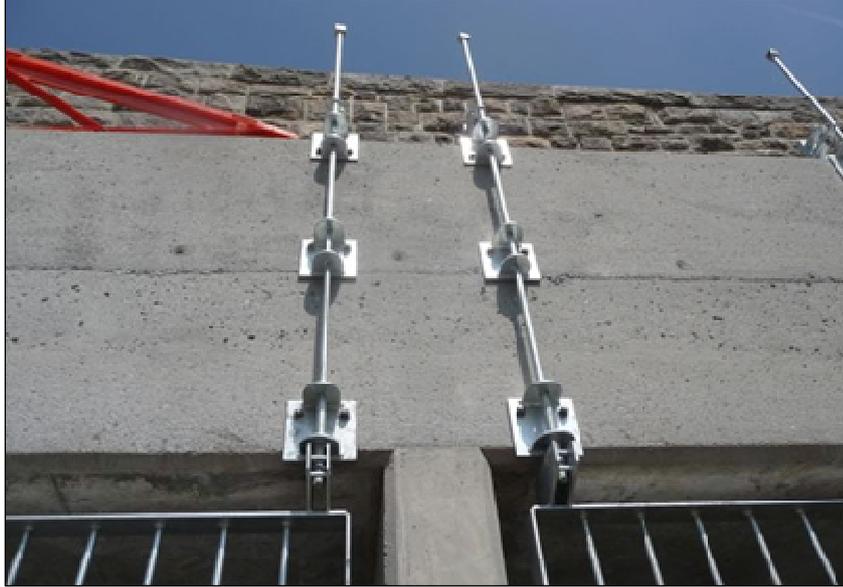


Figure 12. Entrance Safety Screen – Shear Mechanism Under Construction

Exit Screen

A captive shear pin is positioned within the top hinge fixings. When the derived collapse load, applied on the upstream face of the screen, is reached the shear pins are designed to shear. The entire screen is then designed to be released and forcibly ejected by flowing water into the disused quarry downstream. A third (central) top fixing is also provided. During operation this would not have any captive shear pin. However, it allows for insertion of a (non-shear) captive pin to isolate either of the outer shear pins for maintenance, inspection and/or screen replacement activities (Figure 13).

The top fixings are deliberately positioned on the culvert soffit to enable ease of inspection from inside the culvert. Hence, there is no requirement to approach the screen from its downstream side. The screen is also positioned close to the culvert exit to minimise manual handling, allowing the screen to be safely installed/replaced by crane from above. The screen is installed on a slight angle, again to allow ease of installation

The self weight of the screen was designed to repel any attempt at unauthorised access from the disused quarry. Safety harness eyes were also positioned close to the entrance and exit of the culvert to ensure the safety of those operatives undertaking manual tasks during maintenance and/or inspection activities.

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Figure 13. Exit Screen Viewed from Inside the Buried Culvert

Floating Debris Boom

A permanent debris boom was a requirement of the Panel Engineer to prevent floating debris being pulled into the auxiliary spillway during operation.

Due to the position of the weir in relation to the dam it was not possible to design a permanent means of clearing accumulated debris from in front of the boom. As such this activity remains a residual design risk and it was agreed with SWW that a specialist contractor would be required to clear debris on a periodic basis.

At the time of writing the design of permanent pile fixings for the debris boom was ongoing. The decision to adopt permanent piles over a floating buoy and mooring arrangement was a preference of SWW based on their previous, unsatisfactory, experience of a buoyed arrangement at other sites.

CONCLUSIONS

1. In determining the most viable alignment for auxiliary spillway works, make best use of existing topography and geographical features. The most direct alignment may not always be the most appropriate.
2. Maintaining a good working relationship with all parties to the contract allowed design and programme issues to be discussed and resolved in a spirit of mutual respect, which ultimately provided the client with the best possible outcome.

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3. Early and continued liaison with the local planning authority allowed for inclusive decisions and early warning of issues that may affect design/construction programme and/or costs.
4. The design of collapsible safety screens are largely based on application of appropriate and experienced engineering judgement. Specific attention must be given to safe access for maintenance and replacement of the screens and for future inspections by the Inspecting Engineer.
5. The arrangement of a floating debris boom will not always allow for ease of clearing debris and the need for specialist contractors may be unavoidable.
6. No matter how detailed a ground investigation, uncertainty and residual risks remain.

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