The British Dam Society

Buckshole Reservoir: Use of Physical Modelling to Optimise a Risk-based Solution

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SYNOPSIS A risk-based assessment has been undertaken to determine proportionate reservoir safety improvement works at the 11m-high embankment dam retaining the Category A Buckshole Reservoir in Hastings, East Sussex. The study addressed a recommendation made in the interests of safety following a statutory Section 10 inspection in June 2016 that related to the service spillway channel not being of sufficient capacity to accommodate the design flood.

In addition to providing a brief summary of the risk-based approach, this paper will focus on a laboratory-based hydraulic physical model study which was commissioned to inform the detailed design of the proposed new 4m-wide, 90m-long spillway channel and stilling basin. The model study helped to overcome the hydraulic challenges posed by the complex plan alignment of the new channel which broadly followed the right mitre of the embankment. The various components of the new channel, including flow deflectors positioned at various locations along the length of the channel and a bespoke stilling basin at the downstream end, were optimised during the model study.

In the case of Buckshole Reservoir, although the risk-based approach justified adopting a solution that would not strictly meet the standards-based approach for a Category A reservoir, the physical model study was instrumental in identifying modifications to the design to ensure that the spillway channel would safely contain extreme flood flows almost equivalent to the routed Safety Check Flood outflow.

The new spillway channel, completed in November 2022, has significantly reduced the risk of out of channel flow and any resulting damage / breach of this Category A reservoir.

INTRODUCTION

Buckshole Reservoir is located on the northern side of Alexandra Park in the heart of Hastings, East Sussex. The reservoir was originally built in 1852 to serve as a water supply for Hastings. However, it is now only used for fishing and provides a public amenity as part of an important Grade II listed public park in the heart of Hastings. The current owner and Reservoirs Act Undertaker is Hastings Borough Council.

The dam comprises an 11m-high earth embankment with a concrete siphon spillway structure located on the right bank which discharges into a concrete spillway channel running down the right mitre of the dam. Given its location, just upstream of densely populated residential and commercial areas close to and within Hastings town centre, the reservoir is classified as a Category A reservoir in accordance with the latest reservoir safety guidance (ICE, 2015).

A report on the reservoir was issued in 2017 following a statutory inspection under Section 10 of the Reservoirs Act 1975. The report included the following mandatory recommendations:

a) *Obtain dambreak maps and [the downstream flood risk] consequence assessment from the Environment Agency when they have been updated to 2016 "reservoir flood map specification", to quantify the incremental consequences if the dam failed in a major flood;*

b) *The output from the above should then be considered by a Panel AR Engineer [All Reservoirs Panel Engineer], and if appropriate an ALARP study undertaken of measures to increase spillway chute capacity, followed by implementation of measures which are proportionate in cost relative to the reduction in risk achieved.*

This paper will focus on two follow-on studies that were completed to help the Undertaker progress the above recommendations:

- **Risk-based assessment**. After completing a dambreak assessment, the Undertaker commissioned a study to investigate the feasibility of options to address recommendation b) above. The study followed a risk-based approach where the required scope of works was ultimately dictated mainly by the cost versus risk reduction principle as applied in the UK (otherwise known as the ALARP approach).
- **Physical model study**. Armed with the outline scope of works from the risk-based study, a physical model study was commissioned to optimise the various components of the scheme, including the proposed new spillway channel along the right mitre and a bespoke stilling basin just beyond the central downstream toe of the embankment.

SPILLWAY STRUCTURE

The original spillway weir structure was modified in 1985. The modified structure comprises five flow paths of which one is a standard ogee weir and the other four are air regulated siphons. The five spillway openings discharge into a siphon chamber from which water is directed to the spillway channel which follows the right mitre of the dam. The first section of the spillway channel, which was constructed as part of the 1985 works, comprises a rectangular reinforced concrete channel which turns through 90 degrees and then reduces in section to connect to the original 19th century trapezoidal overflow channel some 15m further down the mitre of the dam. The 1985 section of channel has a length of about 35m after which it ties into the much smaller original overflow channel. The original overflow channel has a length of some 45m before discharging into the downstream single channel through Alexandra Park.

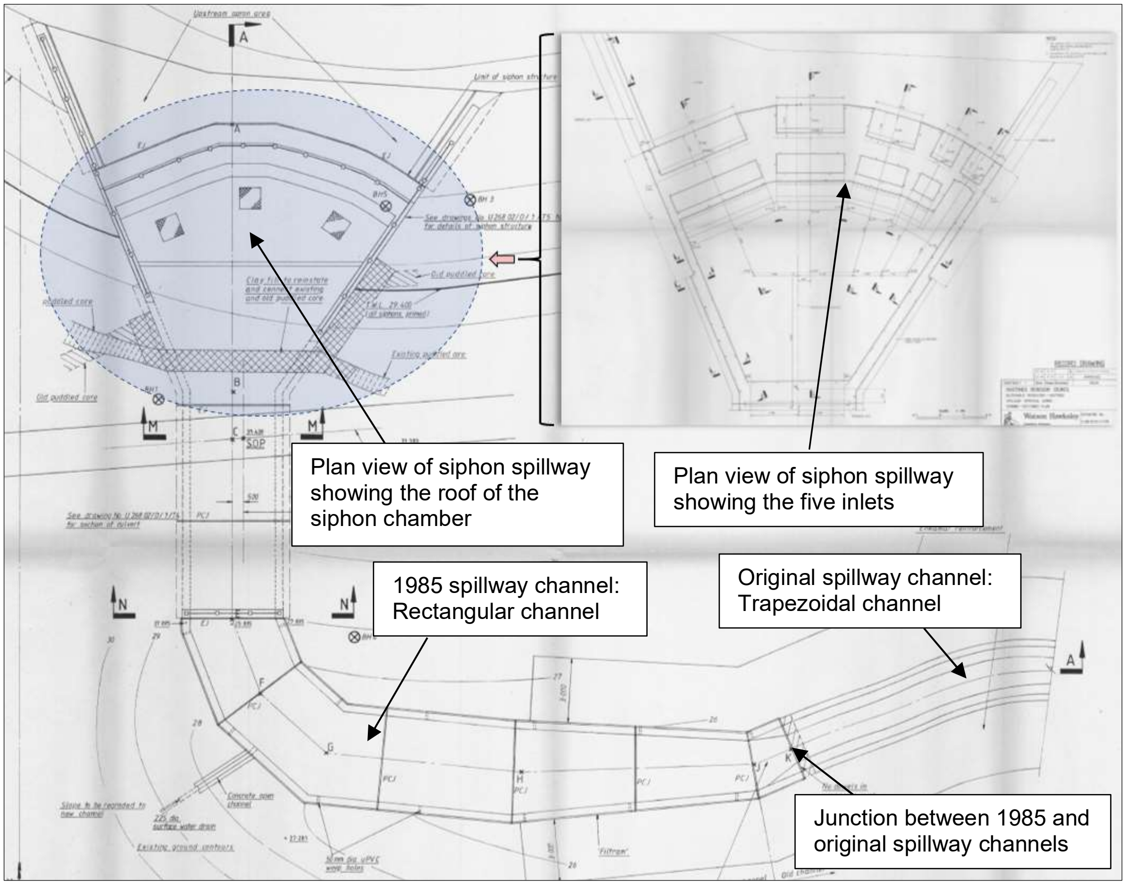

Figure 1. Plan layout of the Buckshole spillway assessed during the risk-based study

The capacity of the siphon spillway was originally determined during a physical model test that was conducted at Newcastle University. The associated rating curve, included in the 2017 S10 report, showed that the spillway should discharge approximately 54m^3/s with the water level in the reservoir at dam crest level, i.e. just before overflowing of the dam occurs. The 2017 Section 10 report stated the following:

"It is concluded that the spillway weir does meet the standard recommended by the ICE for a Category A dam of passing a design flood of 1 in 10,000 chance per year with no damage, and a PMF flood without failing."

A longitudinal section through the spillway arrangement constructed in 1985 is shown in Figure 2 below.

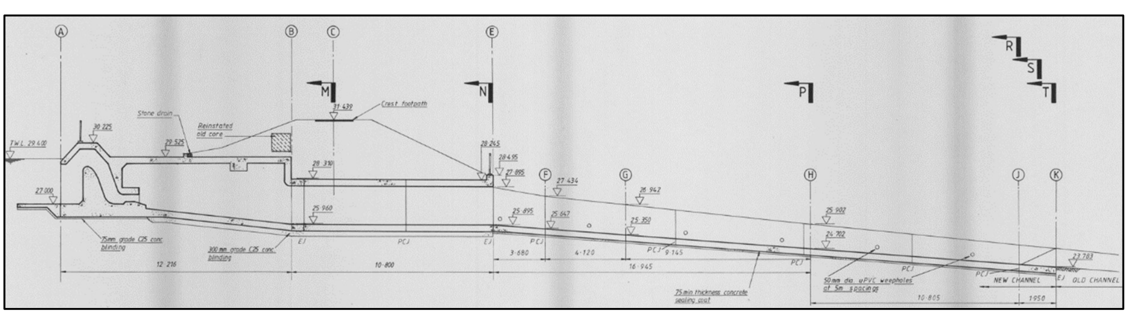

Figure 2. Longitudinal section through 1985 siphon spillway and downstream channel

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Although the upper reinforced concrete channel that was constructed as part of the 1985 works contributed to an improved spillway arrangement (Figures 3 & 5 below), a portion of the original masonry channel was retained, significantly limiting the capacity of the system (Figures 4 & 6 below).

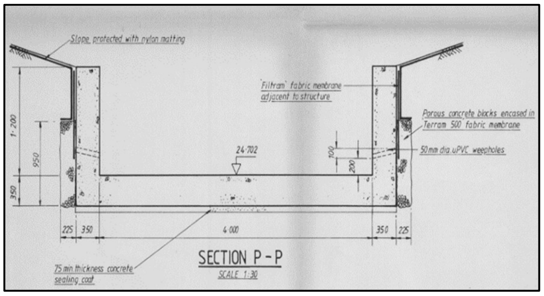

Figure 3. Typical 1985 upper spillway channel section

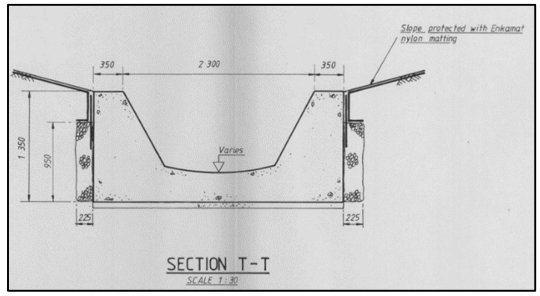

Figure 4. Section of transition to original 19th century masonry channel

Figure 5. View of 1985 spillway channel section (from right abutment)

Figure 6. View of transition to original masonry channel

The 2017 Section 10 report therefore made the following statement regarding the spillway channel capacity:

"In larger flows water will come out of the channel and start to erode the downstream face of the dam. The magnitude of flow and annual chance of failure cannot be estimated reliably without a detailed model study, but it is suggested that erosion sufficient to breach the dam and release the reservoir is quite likely at the 1 in 1,000 chance per year flood.

"It is considered that the spillway channel does not meet the standards for a Flood Category A dam."

This formed the basis for the risk-based assessment which is described in more detail in the following section.

RISK-BASED ASSESSMENT

Background

The UK dam industry is increasingly adopting risk-based reservoir safety management practices. This has mainly been driven by two sets of guidance issued by the Environment Agency: the *Interim Guide to Quantitative Risk Assessment for UK Reservoirs* (Brown and Gsoden, 2004) and the *Guide to Risk Assessment for Reservoir Safety Management* (EA, 2013).

In addition, the current *Floods & Reservoir Safety 4th edition* (FRS4) (ICE, 2015) guidance allows for both a 'standards-based' approach and a 'risk-based' approach when assessing the safety of existing reservoirs.

The standards-based approach follows a set methodology which determines the physical requirements for a dam and associated spillways / overflows to ensure extreme flood events can be passed safely, aiming to ensure the integrity of the dam and spillway / overflow structures. The required standard depends on the flood category of the dam, reflecting the anticipated loss of life and extent of damage, or downstream consequences in the event that the dam was to fail. This failure scenario is referred to as the 'wet-day' failure scenario.

The FRS4 guidance states: *'Where expenditure on remedial works will be significant to meet the standards-based approach to dealing with floods … a risk-based approach could be adopted to assessing the value (cost versus reduction in risk) of undertaking remedial works'*. This approach was adopted for the assessment for Buckshole Reservoir.

ALARP Assessment

The industry-accepted risk-based approach aims to reduce the risk of dam failure 'as low as reasonably practicable' to protect people and property downstream and is referred to as an 'ALARP' approach. It follows a rigorous and logical methodology, identifying options for improvement works where the cost of these works is proportionate to the reduction in risk achieved. According to the Health and Safety Executive guidance (HSE, 2001), the risk has been reduced to an acceptable level where the 'cost to save a life' (see equation below) is less than the 'value of preventing a fatality' (VPF).

$$\text{Cost to save a life (CSL)} = \frac{\text{Cost of risk reduction works}}{\text{Reduction in ``likelihood of failure} \times \text{likely loss of life''}}$$

There is no reservoir-specific guidance on selecting the VPF and so the value that is assigned should be selected under the guidance of an All Reservoirs Panel Engineer, whilst also considering the following:

- Direct costs (measurable), such as the earning potential of the victims, injury and long-term health impairment of other victims not included in the 'Likely Loss of Life' (LLOL) value, and emergency services costs.
- Indirect (business losses).
- Intangibles (psychological impact on people, environmental damage) – it could be argued that a value should be assigned to the Intrinsic Value of a Human Life (irrespective of age, health, education, etc.).

For the Buckshole assessment, it was agreed with the All Reservoirs Panel Engineer that the VPF should be at least five times more than that used for roads and railway schemes. The reasoning for this was that whilst the public can be expected to understand and accept the risks associated with travel, their exposure to the risk of dambreak inundation could be considered to be involuntary. The Department for Transport's assessed VPF for road and rail for 2010 was £1.7 million. Therefore, for this study a VPF value of £8M was adopted.

ALARP proportionality is governed by the following:

$$\text{Proportion Factor (PF)} = \frac{\text{Cost to Save a Life (CSL)}}{\text{Value to Prevent a Fatality (VPF)}}$$

Managing Risks for Dams and Reservoirs

Works are justified in accordance with the ALARP principle when the PF < 1. When the PF > 1, then the cost is considered disproportionate to the level of risk reduction, and there is no requirement to carry out improvement works.

Options for Spillway Channel Improvements

The options for upgrading the spillway channel capacity at Buckshole Reservoir were developed through a long-list / short-list process. Eight long-listed options were screened at a high level taking into consideration factors such as technical viability, practicality of implementation, anticipated cost of implementation and anticipated ecological, landscape and heritage impacts. Four options were deemed to be feasible and likely to provide sufficient reduction in risk to be carried forward to the short list of options.

Having established the current annual probability of dam failure as approximately 2.6×10^{-3}, or 1 in 400, the reduction in probability of failure for each of the short-listed options was calculated by means of an event tree analysis, the details of which fall outside the scope of this paper. A summary description and the reduced probability of failure achieved by each of the short-listed options are summarised in Table 1 below. A plan layout of each option is shown in Figures 7 – 10.

Table 1. Summary of short-listed options

Option Ref	Description	Annual probability of failure after works
2	Large capacity concrete channel with covers to contain flows. This option would meet the standards-based approach, i.e., full requirements for a Category A reservoir.	~ 2.5×10^{-6} (1 in 400,000)
3	Large capacity concrete channel following footprint of existing channel. This option would result in a significant risk reduction but would fall short of meeting the standards-based approach.	~ 8.6×10^{-6} (1 in 116,000)
4	Large capacity concrete channel cutting into existing right abutment downstream of 90° bend, resulting in a straight alignment. This option would result in a significant risk reduction but would fall short of meeting the standards-based approach.	~ 5.1×10^{-6} (1 in 194,000)
7	Replace masonry channel with similar-sized rectangular concrete channel and add erosion protection to the adjacent downstream face of the dam. This option would provide the least amount of risk reduction.	~ 6.2×10^{-5} (1 in 16,000)

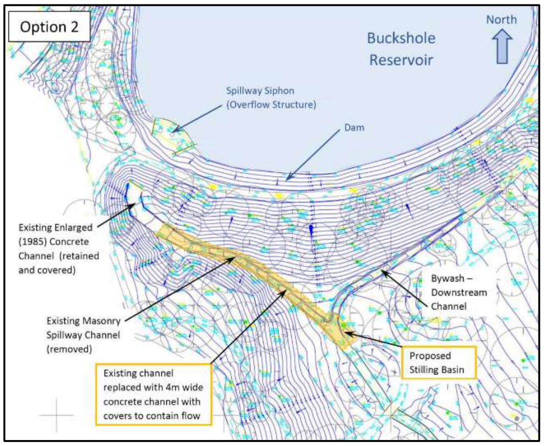

Figure 7. Short-listed option 2: proposed new covered channel

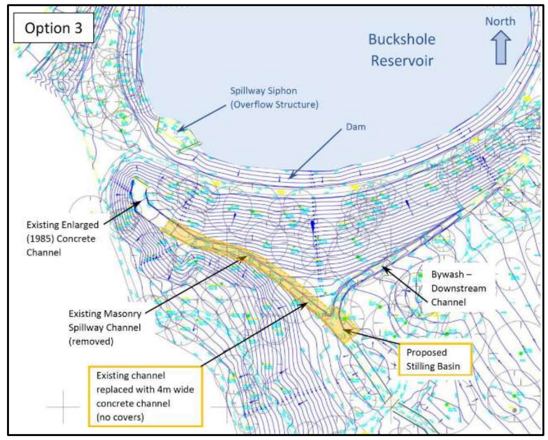

Figure 8. Short-listed option 3: proposed new spillway channel (no covers)

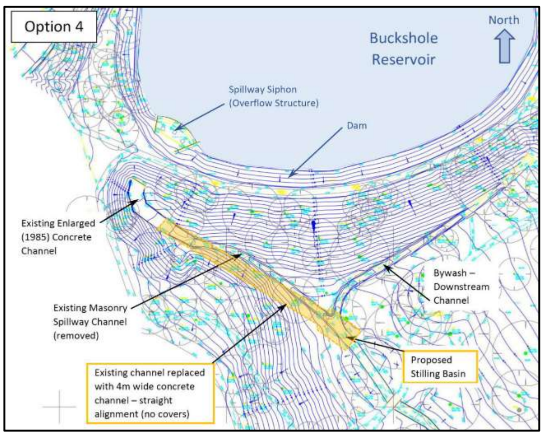

Figure 9. Short-listed option 4: proposed new spillway channel (straight alignment)

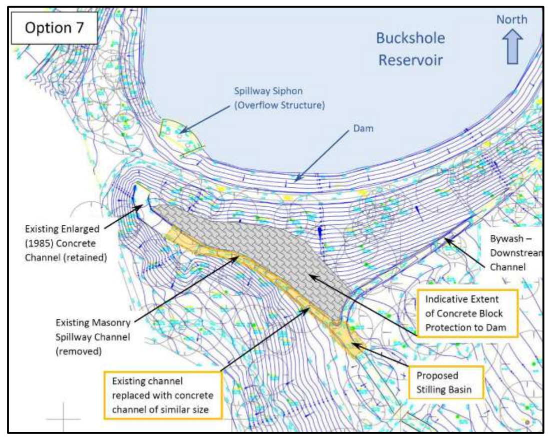

Figure 10. Short-listed option 7: proposed new spillway channel and downstream face reinforcement (concrete blocks)

The risk reductions achieved by each of the short-listed options are shown in Figure 11 below. This shows that for all short-listed options the improvement works reduce the risk into the 'broadly acceptable zone', with the highest cost option, Option 2 providing the greatest risk reduction and Option 7 the least reduction in risk.

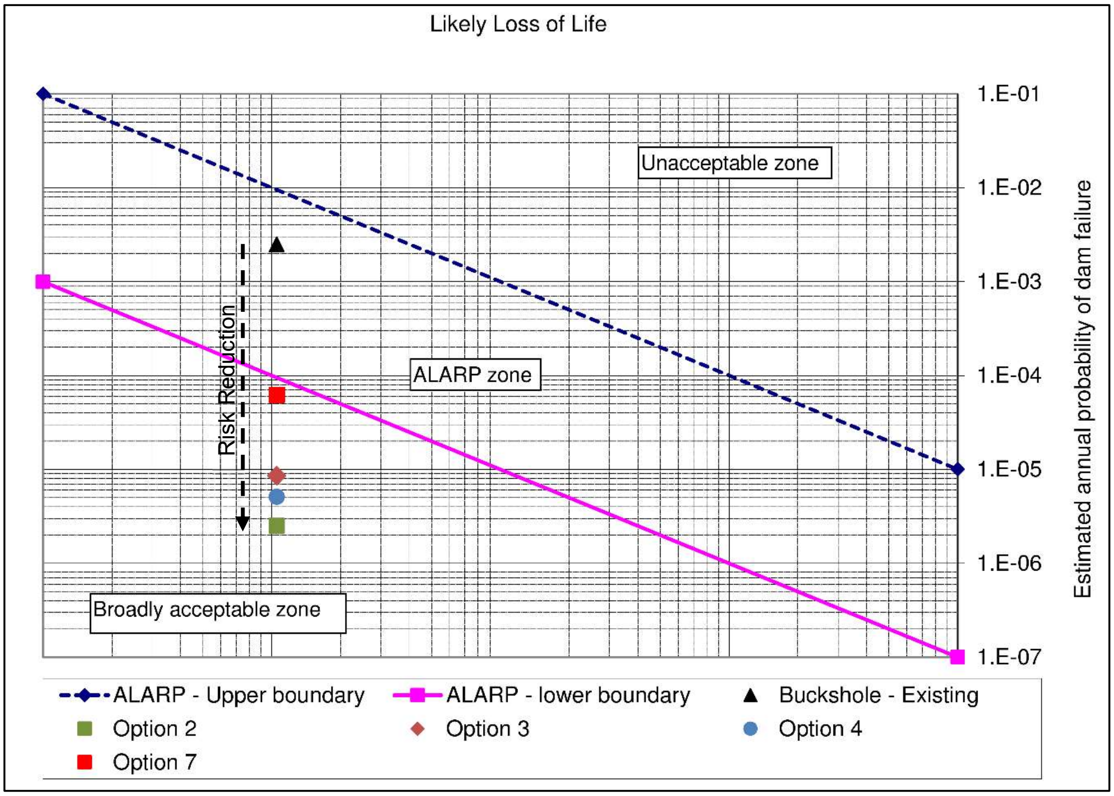

Figure 11. Risk reduction achieved by the short-listed options

ALARP Results

High-level costs associated with each short-listed option were compared with the reduction in risk achieved by the associated works, using the ALARP principle of proportionality. In the case of Buckshole Reservoir, all of the short-listed options were shown to be proportionate, as demonstrated in Table 2 below, compared to the estimated existing probability of dam failure before works of approximately 2.6×10^{-3}, or 1 in 400.

Table 2. Summary of costs and risk reduction benefits for the short-listed options

Option Ref	Description	High-level cost (£k)	Annual probability of failure	Proportionality Factor (PF)
2	Large capacity concrete channel with covers to contain flows.	900	~ 2.5×10^{-6}	< 1
3	Large capacity concrete channel following footprint of existing channel.	650	~ 8.6×10^{-6}	< 1
4	Large capacity concrete channel cutting into right abutment with straight alignment.	750	~ 5.1×10^{-6}	< 1
7	Smaller concrete channel with erosion protection to the adjacent downstream face of the dam.	500	~ 6.2×10^{-5}	< 1

Recommended Option

All the options achieved ALARP proportionality and therefore satisfied the risk-based approach. The choice of which works to implement therefore became one of engineering judgement. Other factors considered included landscape and ecology impacts, public safety, and future operational and maintenance requirements. In addition, the Undertaker's appetite for residual risk and the associated likelihood of future upgrades also played an important role in the decision-making process.

It was ultimately agreed to implement Option 3 (large capacity concrete channel following footprint of existing channel) as this option:

- Provided a significant reduction in the probability of dam failure.
- Minimised adverse landscape and ecology impacts.
- Would reduce public safety risks associated with the existing spillway.
- Offered the lowest ongoing operation and maintenance costs.

Having decided on the preferred works option, the next step was to develop a physical hydraulic model to optimise the detailed design, with the aim of optimising the risk reduction benefits and reducing the cost of the scheme. The study was commissioned mainly in view of the complexities of the hydraulic operation associated with the proposed channel, but also recognising the opportunity for targeted improvements which would further reduce the risk of damage to the dam, bringing it closer to satisfying the standards-based approach for the Category A Buckshole Reservoir.

PHYSICAL MODEL STUDY

CRM Rainwater Drainage Consultancy Ltd was commissioned to undertake the physical model study in two stages. The first stage was to model the existing condition, to confirm the overall hydraulic performance and in particular to identify the events that could potentially lead to failure. This would provide a sense-check of the results obtained during the preceding risk-based assessment. The second stage was to develop and optimise the shape for the proposed new structure through the highly constrained landscape of the park and to test the effectiveness of smaller-scale improvements in further containing flows during the extreme flood events.

Reservoir outflow was limited by the 1985 concrete channel downstream of the siphon spillway to a maximum flow of 44m^3/s. At events well below this, flow was observed to already be out of bank on all parts of the original 19th century masonry spillway channel further downstream. This flow behaviour would be expected to erode the downstream face of the dam and most likely fail the masonry channel.

The use of a physical model to inform the design of the new spillway channel allowed multiple shape options to be readily tested, with overhangs and superelevation added in some areas to improve flow performance. To make the final site construction as simple and economical as possible, whilst minimising the landscape impacts, the new structure was designed in a series of straight-line portions, each with a uniform rectangular section, which had to have relatively sharp bends in certain locations to avoid valuable and protected trees in the park.

These constraints led to difficult hydraulic conditions in the channel as flow was supercritical throughout, and thus would not readily change direction. To avoid higher walls at the bend sections, wall overhangs or flow deflectors ("bus shelters") were used in many places to contain flow within the channel. This allowed the very complex spillway shape to be constructed with the minimum of visual impact in a sensitive area of the park.

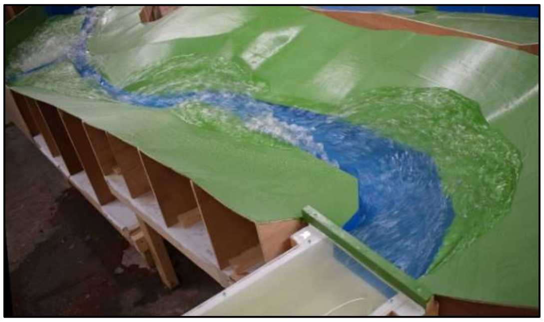

Figure 12. Existing spillway at flow of 44m^3/s (as modelled)

Figure 13. New spillway layout at 44m^3/s (as modelled)

At the downstream end of the channel, and coinciding with the toe of the embankment, a stilling basin was proposed to limit high velocity flows entering the public areas of the park downstream of the reservoir. Again, because of its location, there were significant constraints on this structure. To minimise construction complexity, the depth of the structure below ground level needed to be minimised. However, the height of the structure also needed to be minimised to avoid a significant visual impact. In addition, the difference in level between the stilling basin invert and the existing invert of the downstream channel had to be reduced to minimise the re-acceleration of flows at the downstream end weir of the basin. Further, as the basin discharged into a well-used area of the heritage Grade 2 listed Alexandra Park, any negative aesthetic impact also had to be avoided, in line with conditions imposed in the planning permission. Working within these constraints resulted in a design that would only provide effective stilling up to the 1 in 150-year event. However, it was still possible to modify the design using the physical model to maintain stable attenuated outflows with the basin surcharged during more extreme flood events.

The ideal design for a stilling basin would have incoming flows entering uniformly across the cross section and in line with the longitudinal axis of the basin. However, constrained by important features within the park and planning requirements, this arrangement was not possible. Consequently, the stilling basin design had to accommodate an inflow largely concentrated on the outer wall of the incoming chute, entering the stilling basin at an angle. To improve approach conditions, the final reach of spillway channel was super-elevated, helping to keep the flow evenly spread across the width of the channel. The angle of super-elevation was optimised for lower flow cases where effective stilling would be more critical. The super-elevated design helped to eliminate the worst effects of the approach conditions maximising the stilling of flows. For example, the modelled 1 in 150-year event inflow velocity of 10.8m/s was reduced to 1.8m/s exiting the basin. In the case of the 1 in 1,000-year event the inflow velocity of 11.2m/s was reduced to 4.0m/s.

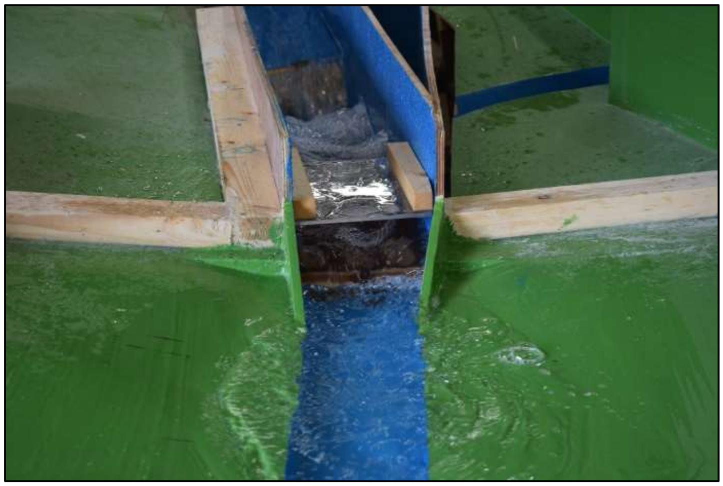

Figure 14. Stilling basin in 1 in 150-year flood event (as modelled, looking upstream)

During more extreme flood events, with the stilling basin surcharged, the velocity reductions were more limited, but still amounted to a notable 25% velocity reduction at the maximum flow. To aid stilling in lower events, baffle blocks ("dragon's teeth") were added. These proved to very effective, although once the basin was surcharged, these features resulted in pluming of flows during more extreme events. To control this effect, the section of stilling basin upstream of the blocks and end weir was covered with a roof section, containing flows and limiting the overall height of the structure. An additional benefit of this feature was that it minimised the visual impact of the stilling basin and allowed the addition of landscape planting as a screen to further reduce the landscape impact of the new larger channel.

Figure 15. Finished spillway channel and stilling basin

CONCLUSIONS

The application of a risk-based approach allows reservoir undertakers to identify and implement works that reduce the risk posed by their reservoirs to an acceptable level or 'as low as reasonably practicable', often resulting in lower capital expenditure than would be the case if simply the standards-based approach was followed. Although the approach may result in a greater level of residual risk compared to that afforded by applying prescribed standards, the risk-based approach justifies this through the application of an industry developed and accepted, rigorous, and defensible qualitative and quantitative methodology.

Whilst simplified 1D hydraulic calculations that can support a risk-based approach are often sufficient to meet the overall objective, in certain cases where the hydraulics are relatively complex, there may be opportunities to further optimise a risk-based solution through physical modelling. As well as providing an opportunity to improve the performance of a design such that the risk benefits are enhanced, this approach can also result in a reduced scheme cost. Further, a physical model can also be used to verify the validity of a risk-based solution, especially in cases where many assumptions are made during the initial risk-based assessment.

The Buckshole Reservoir case study as presented in this paper is considered to be a good example of the value that can be achieved in using a risk-based approach, optimised using physical modelling. The adopted reservoir safety works at Buckshole achieve a standard marginally lower than the standards-based approach; however, given the uncertainties surrounding the hydraulic performance, it was considered that the cost and effort to commission a physical model study were justified, both to validate the risk-based findings and to optimise the proposed risk-based solution. The physical model not only identified 'easy win' modifications to further reduce the risk by more effective flow containment, and reducing scheme cost, but also helped to identify features that would enhance the appearance of the channel, ultimately helping to limit the visual impact within an important landscape setting of a public park.

REFERENCES

Brown A J and Gosden J D (2004). *Interim guide to quantitative risk assessment for UK reservoirs.* Thomas Telford, London, UK.

EA (2013). *Guide to Risk Assessment for Reservoir Safety Management. Volume 2: Methodology and supporting information. SC090001/R2.* Environment Agency, Bristol, UK.

HSE (2001). *Reducing Risks Protecting People*. *ISBN 0 7176 2151 0*. Health and Safety Executive, London, UK.

ICE (Institution of Civil Engineers) (2015). *Floods and Reservoir Safety. 4th edition*. ICE Publishing, London, UK.