The British Dam Society

Challenges in inspecting and assessing performance legacy bellmouth drop shaft and siphon spillways

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SYNOPSIS The majority of impounding reservoirs have overflows comprising a spillway discharging into an open channel that leads to a receiving watercourse downstream. During the 20th Century, alternatives were developed including bellmouth drop shafts and siphons. These can introduce efficiencies but can be difficult to analyse. This was recognised at design stage and model testing was typically undertaken to develop the head/ discharge curve. Over time, many of the model test reports have been lost, including the caveats about the limits of the studies. The duty to independently assess all aspects of a dam has been emphasised by the Safety Review Report that was issued following the Toddbrook incident. This can present difficulties in not just confirming the head/ discharge curve but also the physical inspection of the structures. This paper looks at examples, problems encountered and ways forward.

INTRODUCTION

Originally, dams were built using open spillweirs and channels to remove flood water from the reservoir to the downstream receiving watercourse. During the 20th Century, alternatives were developed to the open channel spillways including bellmouth drop shafts and siphons. Hydraulically, those types of spillways are more efficient in passing higher flow volumes in limited space. Often, these are the only overflow provision, and the safety of the reservoir depends on their efficient operation. Any failure of either a bellmouth drop shaft or siphons can lead to overtopping and an uncontrolled release of water.

The report into the incident at Toddbrook included a recommendation that spillways should, where possible, be physically inspected to look for and to try to quantify defects. This can be a challenge for siphons and bellmouth drop shafts. The very nature of them makes physical inspection almost impossible using conventional means. This paper's aim is to highlight some of the challenges encountered in practice when inspecting and maintaining these types of spillways.

The challenges associated with these types of spillways are exacerbated by the increasing unpredictability of climate patterns. Alterations in atmospheric conditions have led to an escalation in the predicted volumes of rainfall for various return periods. Consequently, overflow facilities, once deemed adequate, are progressively approaching their capacity limits.

Simultaneously, the inherent design of bellmouth drop shaft spillways and siphons does not readily accommodate modifications aimed at enhancing performance under conditions of increased flow. Performance rating curves, typically derived from historical reports, are intrinsically linked to the specific design features of the respective spillways. However, it is important to note that caveats from the original design performance assessments are frequently overlooked. This omission can lead to further inaccuracies in comprehending the performance of these spillways under the revised hydrological conditions.

BELLMOUTH DROP SHAFTS TYPICAL CONSTRUCTION AND VARIATIONS

The bellmouth drop shaft typically incorporates a circular opening weir at the top water level (TWL). The vertical cross-sectional shape of the weir may resemble a bellmouth, which lends the structure its name, although this is not a universal characteristic. Indeed, there exists at least one instance where the cross-section remains constant from the apex to the base of the structure.

The lower extremity of the drop shaft is designed with a radiused curve that guides the flow towards an outlet tunnel (refer to Figure 1). Notably, there is a documented example featuring an abrupt ninety-degree bend at the base.

The construction material predominantly used for these structures is reinforced concrete, chosen for its ability to withstand the forces and velocities encountered. However, it is not uncommon to observe masonry facing, which, while aesthetically pleasing, can be subject to the effects of jet velocities and negative pressures on the structural surface.

The drop shaft may exist as a standalone structure or be integrated into the valve tower. Accessibility varies; some structures may feature a footbridge, while others may be completely inaccessible. There is a particular case where, despite theoretical accessibility, the platform configuration precludes a convenient line of sight to the drop shaft.

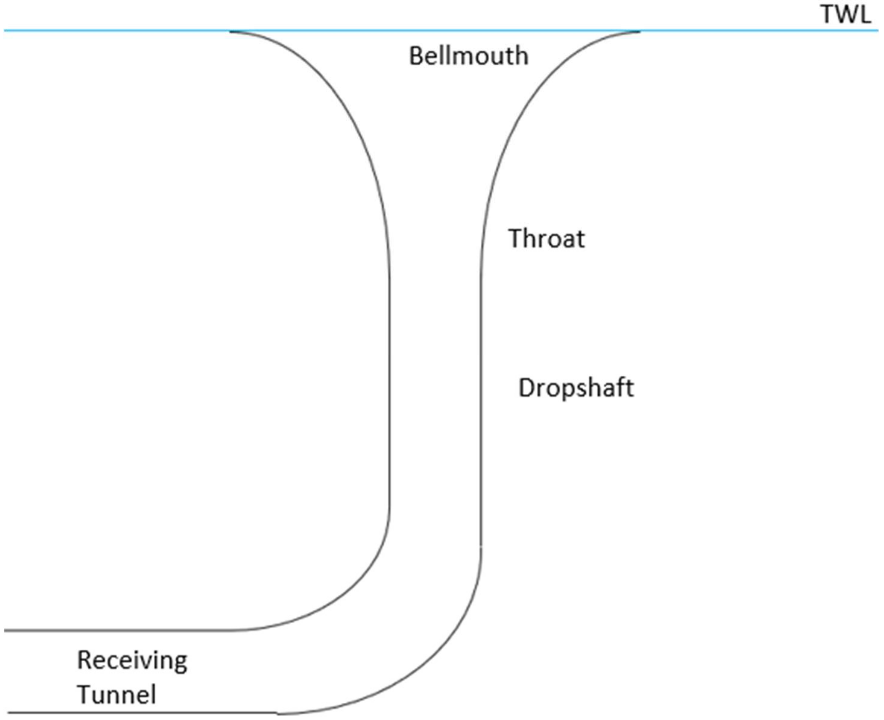

Figure 1. Typical bellmouth spillway section

BELLMOUTH DROP-SHAFT INSPECTION CHALLENGES

The prevailing best practice in reservoir inspections necessitates the inspecting engineer to conduct a physical examination of all components of the spillway structure. However, the unique geometry of bellmouth dropshaft spillways, which typically feature a vertical shaft extending several tens of metres, often precludes the possibility of direct visual inspection.

In instances where a footbridge is present, it becomes feasible to observe the structure from the top. This vantage point offers a clear view of the spillweir, although the visibility of details diminishes with increasing depth. At the throat of the structure, the lighting conditions may be suboptimal, making it challenging to discern specific features. Illustrative examples of the potential views are provided in **Figure** through Figure 5.

Figure 2. Bellmouth view from footbridge

Figure 3. Leakages seen from footbridge

The views in Figure 2 and Figure 3 are obtained from the perspective available from the footbridge. While inspecting the spillway from that vantage point can induce a sense of vertigo, it provides a reasonably clear view of the upper components of the structure. In Figure 2, the throat of the drop shaft is not visible due to insufficient lighting. Figure 3, however, reveals certain defects. Notably, there is a small jet of water emanating from the left, and a significantly larger jet of water in the upper middle.

Assuming the reservoir water level is below the top water level, it should be feasible to traverse the tunnel to inspect the lower portion of the shaft. This, however, can present a challenge. The invert may be slippery, yet navigable. At the base of the drop shaft, typically, the curve steepens from the slight decline of the tunnel to the vertical shaft. The distance that can be traversed is contingent on the traction between the boot and the concrete and the curve degree, which is likely to be suboptimal, and the inspecting engineer's nerve. This endeavour must be balanced with the imperative to maintain safe working practices and prevent slips and falls.

The image depicted in Figure 4 is representative of typical observations from the base of the drop shaft. The contrast created by the light penetrating from the top, particularly on sunny days, complicates the task of observing the sides of the structure. Upon enhancing the image, as shown in Figure 5, potential bands of calcite become discernible, suggesting the possibility of cracking. Conversely, on rainy days, the act of looking upwards can pose its own set of challenges with droplets falling directly on the inspecting engineer, obscuring leakages and increasing the slips and falls risk.

Figure 4. View from the base of the drop shaft

Figure 5. Post-processed image

SIPHON SPILLWAYS TYPICAL CONSTRUCTION

Siphons represent another category of enclosed spillway structures. When utilised as spillways rather than emergency drawdown facilities, they are typically designed to be self-priming, implying that the siphons do not require pumps to evacuate air from the structure. These structures can be found on both embankment and concrete dams.

The structure can be broadly characterised as a weir, topped with a hood. The profile of the siphon is often sinuous, a design feature intended to optimise the efficiency of the streamlines. The profile may incorporate steps to segregate the flow on the discharge side and secure the flow against the hood. This action seals the structure outlet and inhibits air intake from the downstream end of the structure (See Figure 6).

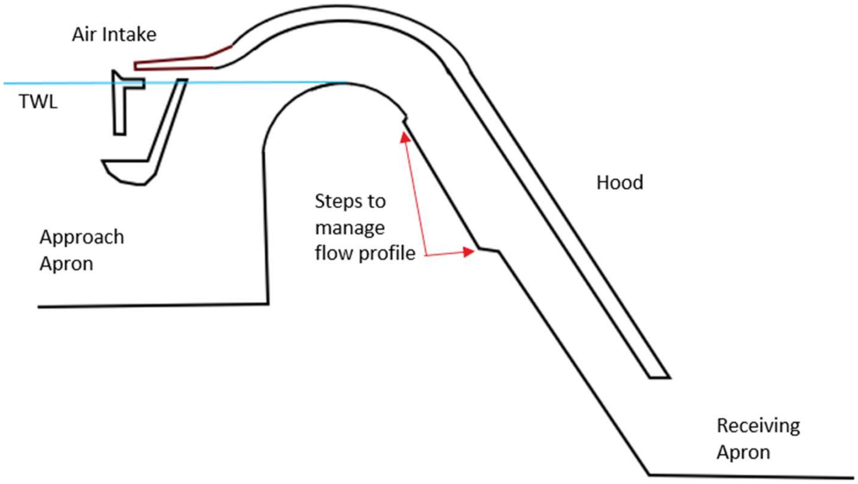

Figure 6. Typical siphon arrangement

The siphons usually have steep chutes, so that the velocity of the flow that develops on the siphon chute promotes air entrainment. In conjunction with the formation of a seal at the inlet, the air is expelled from the siphon, thereby priming it. Additionally, air regulation may be employed to manage the initiation of the priming process.

SIPHON SPILLWAYS INSPECTION CHALLENGES

Siphons can present an even more complex challenge for visual inspection. The inlet leg is characteristically elongated and steep. Inspecting the upstream side may necessitate access by boat, a strategy that is only viable if the water level is below the entry point. The presence of deep water could render the use of ladders impractical. Even in dry conditions, the placement of a loose ladder could pose safety risks.

Should access to the upstream side be possible, the view is likely to be limited. While it is feasible to identify defects, it is equally plausible to overlook them. In the case of structures composed of reinforced concrete, deterioration is inevitable, manifesting as spalling, exposed rebar, and rust spots.

Air-regulated siphons may feature an accessible air intake. On the downstream side, access may be available in proximity to the siphon, or it may only be feasible to observe from the toe of the dam. Gaining access inside the siphon is likely a specialist task, given the confined space and vertical heights. Consequently, the outcome is an impression of the condition, accompanied by numerous caveats.

Figure 2. Siphon inlet inspection from a boat

Figure 3. Siphon inspection with reservoir drawn down

As depicted in **Figure 2**, this perspective of the siphon inlets can be captured from a boat, however the health and safety during a boat inspection is highly dependent on the tranquillity of the day. The presence of wind can induce waves forming, which upon reaching the dam, may reflect and amplify in magnitude, thus potentially rendering the inspection process from a boat rather damp for the inspecting engineers. Occasionally, the reservoir water level is down, and it is possible to perform an inspection of the siphon inlets in the dry as shown in **Figure 3**.

Internally, the structures tend to be in reasonable condition. However, structural defects can be spotted in siphons constructed some time ago. For example, as shown in **Figure 4**, rebar corrosion can be observed on the inside of this siphon structure, causing the cover concrete to spall. At this site, the damage is 5m above the observation point, which can be challenging to spot in reduced light conditions or from a rocking boat.

Figure 4. Spalling on siphon roof, view from siphon inlet.

Figure 5. Rebar corrosion in air intake

For optimal hydraulic performance, siphons require relatively smooth surfaces without steps to obtain the design flows. The damage shown in **Figure 4**would be disruptive and reduce the efficiency of the siphon. In addition, as siphons, when primed, operate with relatively high flows and velocity, and depend on vacuum seals being created under such structures. Irregularities and step changes like this can cause negative pressures and cavitation to occur locally, expanding the damaged area during operation.

In **Figure 5**, corroding rebar can be seen in an air intake. The opening is only 300mm high so access to repair is difficult. There are hidden faces and if corrosion is present on one face, it is likely to be present elsewhere.

If repairs to the siphons have been carried out, it is difficult from a distance to determine if the original profile has been preserved or if there is unevenness or even steps. There could be a difference in the roughness where a repair mortar might be smooth and the concrete might be rough. Roughness can arise due to dissolving of the cement matrix particularly in areas of soft water.

Figure 6. Siphon internal structure, view from downstream end of siphon.

As illustrated in Figure 6, the roof is situated approximately 10 metres above the observation point at the downstream end of the siphon. The drawings indicate the presence of steps designed to separate the flow from the invert and pin it against the siphon hood. However, the visibility and condition assessment of these steps pose a challenge. The precarious nature of a loose ladder on a curving invert renders it unsafe, thereby limiting observations to a distant perspective.

FLOW CAPACITY ASSESSMENT

Engineers have long recognised that traditional hand calculation methods are not suitable for evaluating the capacity of bellmouth dropshafts and siphon spillways. To address this, physical model testing has been implemented to formulate the discharge curves. The resulting discharge curves of these tests are frequently encapsuled in the inspection reports. However, over the course of time, the original model test reports can become disassociated from the primary reservoir file, particularly during the transition from paper to digital formats. Consequently, the only accessible data is often confined to the information contained within the inspection report, which is often limited to the rating curve only. Details about the modelling study become lost.

The physical modelling reports comes with caveats. All model testing is constrained by laboratory space so the biggest scale that can be used might be limited. Trying to model everything might mean a scale that is too small, and the micro water behaviour starts to dominate. Alternatively, parts of the spillway can be omitted, to allow for bigger scale. However, that might mean unforeseen limits on the capacity.

Efforts to retrieve model test reports from alternative archives can be undertaken, albeit with varying degrees of success. It is noteworthy to mention that models predating the 1970s were constructed using imperial units, and on occasion, conversion errors can be present, thereby becoming an evident fact once quoted in the inspection reports.

Capacity Assessment Challenges for Bellmouth Dropshaft Spillways

On bellmouth dropshafts, physical models often replicate the weir, the dropshaft and the start of the receiving tunnel. This is because their efficiency is considered to primarily depend on the capacity of the throat exceeding the discharge at the weir. Once the weir discharge exceeds that of the throat, then any increase in discharge depends on sharply raising the water level. With such model set up, immediately, there are assumptions about the hydraulic capacity downstream of the cut-off point of the model which could become dominant, if the gradient is slack and if the tunnel is long.

At the weir and the top of the drop shaft, the models tend to include any bridge piers, but not necessarily the topography or nearby appurtenant works. This raises the question of whether the flow is from the full perimeter of the bellmouth or whether physical restrictions such as towers or earthworks could adversely affect the flow paths. Only the original report can answer such questions.

Capacity Assessment Challenges for Siphon Spillways

In the case of siphons, the models generally used Perspex that is fairly smooth and a low friction material, so that the air regulation and evacuation can be observed. Therefore, the scale model would struggle to represent the actual friction of the siphon walls, thus introducing uncertainty to the siphon discharge efficiency.

Features are introduced to the siphon geometry to manage and maximise the siphon performance over the range of possible flows, such as steps on the downstream face and air intakes. However, due to the scaling factors of the model air entrainment cannot be modelled accurately, as surface tension and air pressure does not change with scale.

Limitations in the laboratory space might also mean that the test only takes place on a single siphon. In the model test reports, there are warnings given that the results might not be replicable if the siphons are deployed in an array. The warning can become lost and an optimistic rating curve becomes established fact. Post modelling, the designers might have specified slightly different threshold levels to ensure different priming of siphons in an array of siphons to avoid surges as all the siphons prime simultaneously. This indicates a divergence of the finished facility away from the original model data.

DISCUSSION

Alternative Inspection Methods

With the recent development of technologies, alternative inspection options have emerged. In instances where secure access from above is available, point cloud devices can be deployed into a bellmouth dropshaft. These devices are capable of capturing detailed dimensions and identifying cracks or other discontinuities. Although the data necessitates post-processing, it provides a comprehensive record of the current condition. If concerning features are detected, it may be feasible for roped access specialists to furnish more detailed information.

Detailed point-cloud surveys with remote operated vehicles and drones of siphons have also been successfully conducted. However, unless the Inspecting Engineer possesses training in specialist access techniques (roped access in confined spaces) to be able to access and inspect the siphon barrels in person, the information that they will be using will inevitably be second-hand. Despite this, point cloud surveys offers a more comprehensive overview compared to merely observing from the structure’s ends.

Challenging Capacity Assumptions

As discussed above, it is important to be able to question interpretations and challenge previously held opinions. Does the structure being inspected match the structure that was modelled? What are the differences, and could they make a material effect on the capacity of the structure?

As mentioned previously, climate chaos is forcing a rethink on the magnitude of storms for given return periods. Generally, there is an increase to reflect the greater moisture bearing capacity of a warmer atmosphere. As a given, the flood study needs to be reassessed.

The original designs of siphon and dropshaft spillways tended to be highly optimised for given flow figures, with some marginal allowance. There was a flow figure in mind and an allowance for unknowns. A position can be reached where there is uncertainty about the ability of the system to pass the safety check or the design flows. In part, there is insufficient information to be able to use the original design model tests to provide a definitive answer.

In such instances, it is prudent to re-analyse. It is also prudent to obtain an accurate survey. This can pick up features such as adjacent structures or earthworks that can change the approach stream lines and can use actual levels and dimensions. For siphons, it is feasible to verify if different thresholds were provided or if the facility was constructed to a single level. Unevenness can also be taken into account.

The way forward is to use Computational Fluid Dynamics (CFD). This is effectively a 1:1 scale model. There are limits on the computer space but it is possible to obtain a model 'as-existing' and find the actual flow capacities.

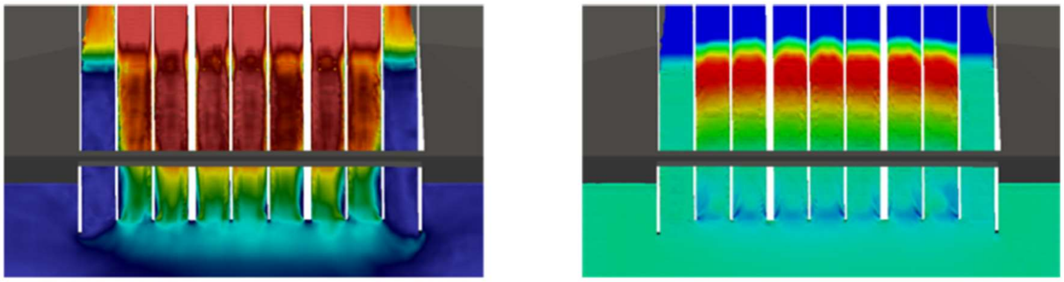

Figure 7. Siphon CFD outputs

The meanings of the colours in **Figure 7** are not important for this paper. They show different discharges for two storm events. The output does show that the siphons, that all had the same threshold level, do not have the same discharges in an array. There are effects at the ends and to the two side units.

This does mean that a discharge curve for the reservoir can be developed. In turn, the level rise for each storm event can be determined.

A feature that was not always included in the modelling was partial blockage. The level rises under PMF conditions can be high. Depending on wind speed and direction, there is a potential for debris to make its way to the outlet. Not all outlets have robust debris barriers. There is a potential for debris to wash into and cause blockage. It is beneficial to include a sensitivity analysis into the effects of blockage. This might feed into a plan to intercept debris. It is certainly important for the development of the flood plan.

As noted previously, these facilities were designed efficiently. A more accurate assessment helps to identify the adequacy of these facilities. Inadequate would be defined by the loss of freeboard because the level rise to achieve the discharge is too much. Solutions are beyond the scope of this paper.

CONCLUSION

In conclusion, there are challenges to follow the recommendations given in the Safety Review. There are techniques that can obtain better information that can improve the quality of the recommendations. It is important to understand the actual discharge curve for the reservoir and that original model tests might not provide sufficient data to do so. In the absence of good information, assessment depends on accurate surveys and re-analysis using CFD. Sensitivity testing can be included to check the effects of blockages.