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Design and Construction of an Open Stone Asphalt Spillway for Wychall Flood Storage Reservoir

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SYNOPSIS Wychall Flood Storage Reservoir is a Category A flood storage reservoir on the River Rea in the Kings Norton area of Birmingham. A section 10 inspection in 2020 identified shortcomings in the existing spillway provision and recommended measures in the interests of safety. A subsequent flood study identified that the spillway needed to be lengthened and reinforced to withstand overflowing velocities of up to 7.3m/s. The reservoir is located within a local nature reserve and great importance was placed on maintaining biodiversity and minimising the visual impact of any alterations. Opportunities to reduce the carbon footprint of the project was also a priority. Possible options for reinforcing the spillway were a cast in-situ cellular reinforced concrete system, precast concrete blocks, or open stone asphalt (OSA). Following a review of options, OSA was selected as the preferred solution for reinforcement of the spillway. The paper will describe the design, construction and future maintenance of the spillway. It will also discuss the practicalities and benefits of using OSA instead of more conventional reinforcement systems.

The client was the Environment Agency, the designer was Mott MacDonald, the contractor was Jackson Civil Engineering and Hesselberg Hydro (UK) Ltd were a sub-contractor who installed the OSA.

INTRODUCTION

Wychall Reservoir is a flood storage reservoir on the River Rea in the Kings Norton area of Birmingham. The present dam structure was completed in 1991 and the Final Certificate issued in 1995. The dam is essentially a homogeneous clay embankment. It is built on the site of a dam built between 1804 and 1815 by the Worcester and Birmingham Canal Company. Immediately downstream of the dam, on the left flank, was Wychall Mill (now a ruin) which was fed via a feeder stream on the left side of the reservoir from a sluice gate on the River Rea.

The River Rea runs in a channel along the south side of the reservoir and passes beneath the extreme right flank of the dam in a culvert. This channel carries the dry weather flow in the River Rea. In a flood event the River Rea spills into the reservoir via an inlet weir located about 400m upstream of the dam. There is an elevated pathway along the north side of the Rea between the river and the reservoir. This separates the flow in the River Rea from the reservoir in all but extreme flood events when it is inundated and the River Rea channel forms part of the reservoir. As such the reservoir is strictly an on-line structure, although it functions as an off-line structure on low return period flood events.

The reservoir has a main spillway comprising an octagonal drop structure set within the upstream shoulder, connected to a culvert which passes beneath the embankment, and a 73m long, grass, emergency spillway on the embankment crest. The emergency spillway has a central 3m deep sheet piled cut-off which is topped with a reinforced concrete capping beam set within the dam crest. The main and emergency spillways have crest levels of 143.0mAOD and 143.5mAOD respectively.

There is a berm, carrying a tarmac access road, which runs along the downstream shoulder from the right abutment to the left side of the emergency spillway. The toe of the sheet pile cut-off is just below the levels of the access road.

The reservoir was inspected in April 2020. This identified two issues with spillway provision as follows:

- The emergency spillway had a steep, largely unprotected, downstream face with many trees (Figure 1) in the area between the crest and the access road. It was understood that this has been accepted previously because the line of sheet piles through the centre of the dam meant that the downstream face could be regarded as sacrificial. However, this argument was not considered to be tenable as the sheet piles were too short to be able to support the upstream shoulder on their own.
- Flood modelling suggested that the spillway capacity was inadequate and the main, unprotected, section of the embankment would overtop in the PMF.

Figure 1. Original spillway arrangement

For these reasons the following MIOS were recommended:

- Undertake a flood study to confirm whether the dam can safely pass floods up to and including the PMF,
- Undertake a dam breach analysis to determine the impact of a dam breach caused by overtopping in credible failure scenarios,
- Determine appropriate measures (at outline design level), if required, to enable the dam to safely pass floods up to and including the PMF,
- Modify the dam to safely pass floods up to and including the PMF.

FLOOD STUDIES AND BREACH MODELLING

A flood study was undertaken in April 2021. The peak inflow in the PMF was estimated to be $288m^3/s$ with there being minimal attenuation in the reservoir. The study confirmed that spillway provision was inadequate and that there would be significant overtopping of non-spillway sections of embankment.

A separate dam breach analysis was undertaken to check the appropriate categorisation for the reservoir. This was undertaken because there was a possibility that, in a PMF, the downstream area would be flooded to the extent that the breach outflow would be inconsequential. The peak, wet day dam breach outflow was estimated to be $78m^3/s$. It was found a dam breach in the PMF did still cause a significant increase in the population at risk, so it was accepted that the dam needed to be modified to safely pass the PMF.

It was thereafter determined that to pass the PMF, the length of the spillway needed to be extended by 25m and that the spillway needed to be capable of withstanding velocities of up to 7.3m/s. In addition, the left flank needed to be raised to above PMF level and the right flank made capable of limited overtopping. The layout of the dam in shown in Figure 2.

OPTIONS FOR MODIFYING THE SPILLWAY ARRANGEMENT

In the outline design phase two high level options were proposed to modify the spillway to enable the safe pass of floods up to and including the Probably Maximum Flood (PMF). The options considered were:

1. Extending the spillway by 25m, raising the left flank crest maintaining the 4m width, reprofiling the spillway and right flank and providing erosion protection along the spillway face.
2. Extending the spillway by 25m and installing a new 10m sheet pile wall upstream of the existing sheet pile wall with the assumption that the downstream slope would be sacrificial. Raising the left flank of the crest and maintaining the 4m width.

Option 1 was taken forward to detailed design stage as it offered the advantages of being less intrusive, lower complexity and would ensure the embankment integrity was retained during flood events.

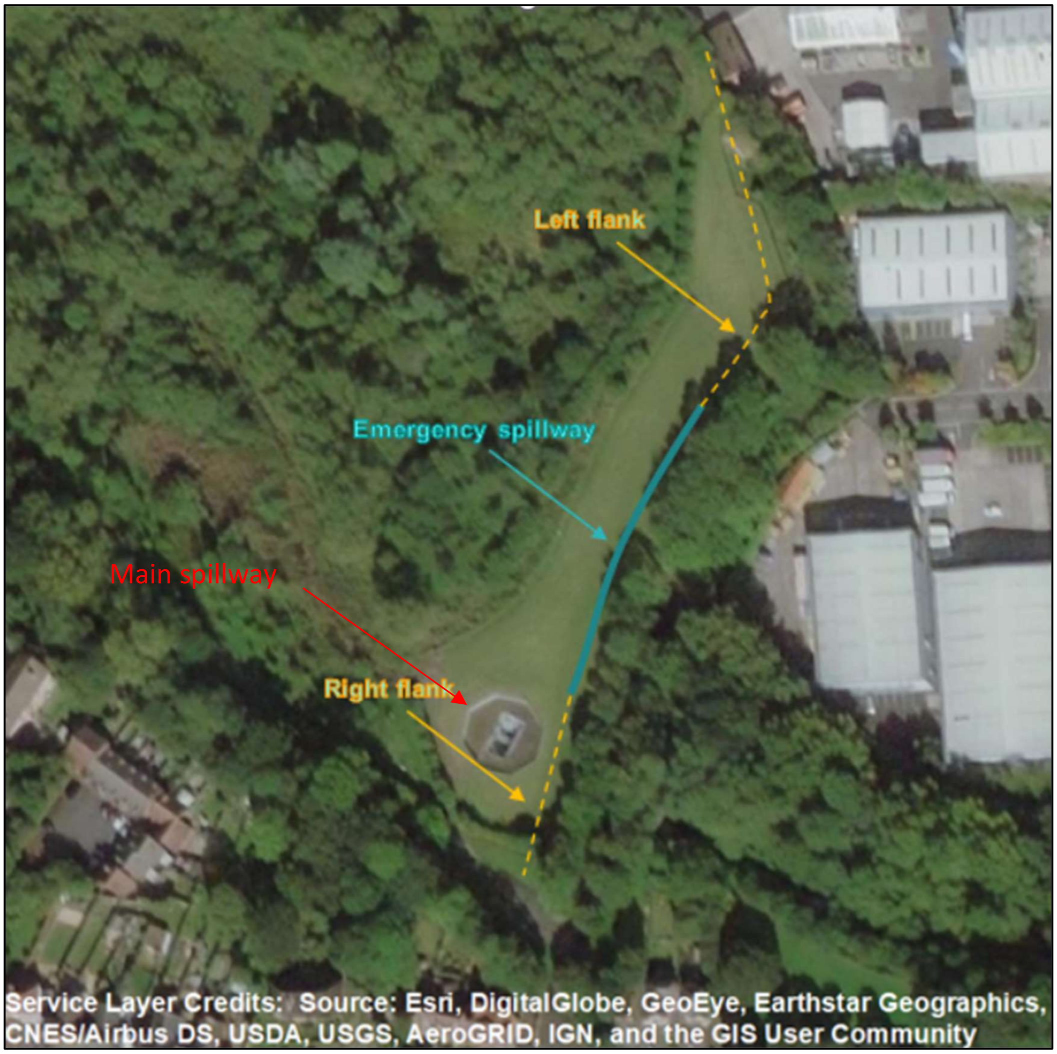

Figure 2. Plan of Wychall Reservoir with indicative spillway layout

ENVIRONMENTAL CONSIDERATIONS

Carbon

To meet their net zero carbon ambitions the client was keen to identify lower carbon revetment options than traditional concrete block systems. They suggested OSA as a potential alternative, as it had been used on a similar project. Further carbon savings were made by using fibre reinforcement in the concrete crest beam.

Visual aesthetics

Another priority for the client was the visual aesthetics of the completed works to appear non-engineered, particularly as the reservoir is in a publicly accessible Local Nature Reserve (LNR). This led to a desire for the chosen revetment to be dressed with soil, and vegetation established. It was accepted this would be sacrificial in overflowing events. Previous examples of OSA being used as spillway protection have taken advantage of covering it with soil, and this gives the extra advantage of reducing the effect of UV degradation.

SELECTION OF SPILLWAY PROTECTION SYSTEM

The spillway had to be designed to withstand a velocity of 7.3m/s. This ruled out the use of geotextile type grass reinforcement. As such, the usual options to consider were a cast in-situ cellular reinforced concrete system or some form of concrete block system. A concrete block system was not considered to be appropriate as the spillway has an irregular shape which would not lend itself to using panels of reinforced blocks. At this point the conventional thinking was challenged by the Client and the designer was requested to investigate the use of Open Stone Asphalt (OSA). This was, in part, driven by recent success that the client had had with OSA on another scheme. Open Stone Asphalt is a homogeneous, permeable mixture of coarse aggregate and asphaltic mastic which comprises bitumen, sand and filler (Bieberstein, 2004).

Open Stone Asphalt (OSA) and the cellular reinforced concrete system were therefore identified as the preferred options that could be used to provide erosion protection. See Table 1 for a comparison of the two materials; this was prepared during the design stage.

DESIGN AND DETAILING OF THE SPILLWAY EROSION PROTECTION

Spillway cross section

The adopted arrangement was a 150mm thick layer of OSA overlying a 100mm drainage layer placed on a non-woven geotextile, as shown in Figure 3. The downstream face was cut back to an angle of 1v:2.5h which was as far as it could be taken whilst preserving space for an access track on the crest. The OSA was extended across the crest to tie into the existing capping beam on the sheet pile cut-off. The OSA was taken down to the level of the tarmac access road. Although this was only about half the total height of the embankment it was acceptable as the downstream toe area would be inundated in an extreme flood.

A toe drain was provided and the OSA was locally thickened to 400mm at the tie-in to the crest beam.

At either end of the spillway there are transitions to higher levels to contain the spillway flow. These were readily formed with OSA.

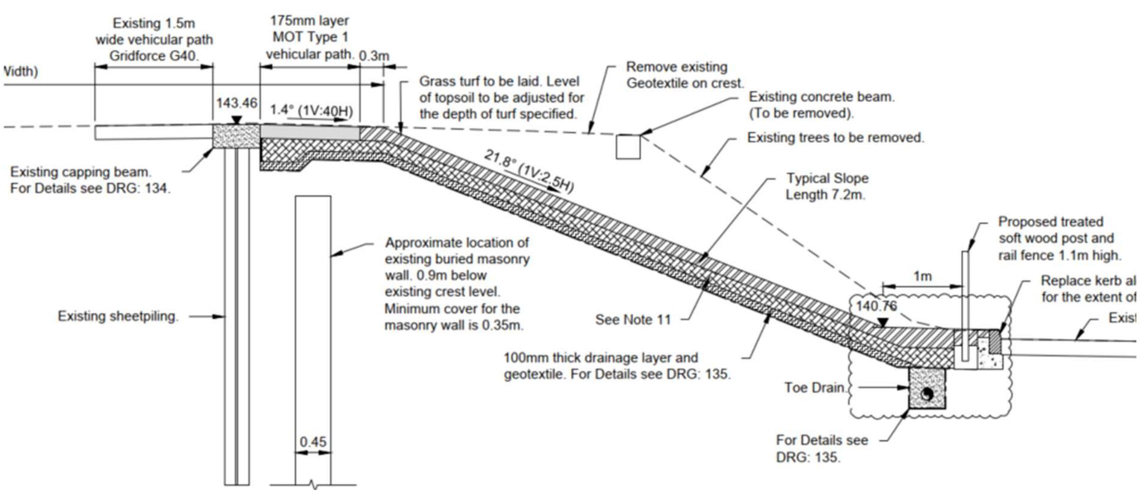

Figure 3. Spillway cross-section

Table 1. Comparison of cellular reinforced concrete system and OSA (specific to Wychall Reservoir where appropriate)

Ref	**Cellular reinforced concrete system**	**Open Stone Asphalt**
Velocity limit	Up to 8 m/s	Up to 8.6 m/s (Bakker, 2008; Hesselberg Hydro, undated)
Slope	Can be laid on slopes up to 1:1	Stable on slopes up to 1:2 without anchors
Design life	100-years	50 years
Carbon footprint	The Client's carbon tool calculates cellular reinforced concrete system erosion protection at a rate of 0.5 T CO_2/m^2.	0.015 T CO_2/m^2 (based on 150mm layer of OSA with a layer of geotextile). The supplier is currently trialling warm asphalt which would further reduce the carbon footprint.
Aesthetics	Relies on the grass spreading in the pockets	OSA can be covered with topsoil and either seeded or turfed.
Lead time	6 weeks	4 weeks if prior notice is given.
Installation time	Approximately 5-7 weeks	2 weeks installation for a site like Wychall.
Construction	Toe beams and expansion and contraction joints are required Requires sand layer and geotextile layer.	OSA is placed in a continuous layer, with no construction joints reducing impact from movement. Geotextile separation layer will be required, and a drainage layer typically recommended. Edging details are likely to be required
Health and safety	Formers and mesh to be installed before concrete is poured. Hot works is required to remove the top of the void former.	OSA is a hot installation (typically 130°C - 170°C) so gloves, eye protection and overalls are required. Reduced manual handling although edging is likely be required
Other		Possible risk that the topsoil layer is washed away during large flood events. This will not impact the functionality of the erosion protection.

Material selection/development

OSA comprises 20/32mm Aggregate bound together with a bituminous mastic comprising bitumen, filler and sand. The design of the OSA concentrates on the following:

- The 20/32mm aggregate must have a good natural affinity to bitumen. Limestone is usually used but some gritstones and basalt have proved to be suitable.

- The bituminous mastic must have the correct viscosity. It must be low enough to fully coat the coarse aggregate but high enough to prevent segregation of the material during transport and placing.
- A volumetric check is carried out to ensure the amount of mastic is sufficient to coat the coarse aggregate with a 0.9mm - 1.3mm layer.

Standard OSA can be mixed in virtually all batch-mixing plants and can be transported for a maximum time of approximately 1½ hours from plant to site.

A 'Warm Mix Additive' is now common in most plants which enables asphalt mixtures to be used at lower temperatures. This means they can be mixed at lower temperatures to reduce energy consumption, or they can be transported further and still remain usable.

When a plant is producing OSA for the first time it is essential for a contractor with experience in OSA to supervise the process. Minor tweaks to the constituent percentages may be required to produce the optimum mixture.

Design life/maintenance

The design life of OSA is considered to be in the order of 50 years. When OSA was first installed as coastal revetments in 1988 and as a dam revetment in 1991, a design life of 25 years was accepted. These examples have performed well to date and many examples in Europe are older, so the design life has now been increased to 50 years. This has been accepted by the client. In future, a longer period may be considered if the revetments continue to perform well.

There does not appear to have been a difference in performance if the OSA is, or is not, exposed to UV light. It is noted the top film of mastic over the aggregate will oxidise if exposed; however, the mastic between the aggregate (which holds the OSA together) is a larger volume and most tends to be in shade within the layer where UV light does not penetrate.

In the event of settlement tension cracks could develop if settlement/movement is rapid (unlikely). If cracks do appear they can be cleaned and filled with hot-poured bituminous mastic.

Joints with structures are initially sealed with hot-poured mastic. In the event of these joints opening up at all due to differential settlement they can be cleaned and re-filled with hot-poured bituminous mastic.

In the event of surface damage (e.g. impacts from water-borne debris) the area to be repaired can be cleaned, edges prepared and primed, and OSA can be used to re-fill. In the event of small holes (up to about $1m^2$) appearing these may be filled with a mixture of coarse aggregate and bituminous mastic, or resin-bonded aggregate.

CONSTRUCTION

Site works were undertaken between 19th April and 14th November 2022. The placement of the OSA was undertaken during a two-week period, from 6th to 15th Sept 2022.

OSA was placed over an area of $1250m^2$, with 270m of edge details where the OSA is thicker.

Site constraints
The site was constrained, with access via a busy residential main road. Works on the spillway were either conducted from the crest, with a maximum 20kPa surcharge limit, or from the existing 6m wide asphalt track. These factors limited the plant and equipment the contractor could use and delivery timings and frequencies.

Preparation works
Preparation works involved trimming back the embankment slope to the desired profile, placing the geotextile and drainage layer and constructing the toe drain. All preparation works were completed before the OSA was laid.

OSA installation
The process for the installation of the OSA was as follows.

- OSA delivered into a steel delivery skip placed along the toe of the dam.
- Material transferred from delivery skip into a 6T site dumper, taken to the crest of the dam and discharged into a 10T capacity skip on the crest.
- A 13m long-reach excavator placed the material on the slope and profiled it using a travelling shutter to control layer thickness.
- A smaller excavator at the toe completed areas beyond the reach of the crest excavator.
- When the OSA was completed the hot-poured mastic seal was applied to the OSA edges that abutted concrete or steel structures.

Figures 4 and 5 show the procedure in operation.

OSA quality assurance
Various checks were recorded as the works continued, as follows

- Formation/drainage layer and edge details checked for line/level
- Edge of previous day's OSA cleaned & primed
- OSA delivery checks included a visual check (no segregation, well coated aggregate) and a check that temperature was correct (130°C - 170°C)

Finishing works
Once the OSA had been placed the spillway was turfed to enhance its aesthetic appearance. To mitigate for the loss in trees and contribute towards biodiversity net gain targets, the client suggested a wildflower turf, instead of a standard grass mix. This was considered acceptable from a technical perspective as the vegetation and soil above the OSA does not contribute to the erosion protection.

A UK low growing native turf consisting of 20% grass and 80% wildflowers was installed. To provide strength and stability the turf incorporates a fine degradable net in its root zone. Additionally, swathes of bulbs were planted to further increase biodiversity. There remains the option to adjust the diversity of the wildflower mix or revert to a traditional grass mix in the future, if required.

Figure 6 shows the final appearance of the completed spillway.

Figure 4. Placing OSA (dumper being loaded at downstream toe)

Figure 5. Placing OSA (long reach excavator taking OSA from skip on crest)

Figure 6. Completed spillway with turf installed

PRACTICALITIES OF OSA

Practical considerations

- In-situ material which is quick to place and easily follows irregular shapes and contours of dam spillways without awkward joints.
- Easy to place around manholes and other concrete/steel structures on the spillway.
- Thermoplastic properties give good resistance to impact loads whilst also allowing finished revetment to follow settlements expected with new earthworks.
- OSA is stable on slopes up to 1 in 2 without the use of anchors. Where stability of the revetment is a concern due to uplift pressures/high flows then support can be provided at the crest. Geotextile beneath the OSA layer can be extended at the crest and buried beneath concrete sill or in a trench.
- At the toe and sides of the spillway the edges of the OSA are usually thickened to resist any tendency for the layer to 'flap' under high flows. This also gives the edges greater security against scour.
- Day joints are formed by cleaning and priming the existing OSA edge so that the new hot-placed OSA fuses the two materials together, forming a 'monolithic' plate without joints.

- Being a bound material, if damage does occur to the revetment, e.g. vandalism, damage is limited. With concrete blocks, often the removal of one block can lead to rapid progressive failure.
- Vegetation growing through the asphalt will not damage it as the flexible material can withstand deformations over time (avoid trees/large shrubs).
- In the event of internal erosion occurring in the dam voids may develop. Voids beneath asphalt will result in the flexible material following the voids and therefore they can be picked-up during routine dam inspections. Concrete has the ability to span voids for a period of time and so may go un-noticed until catastrophic failure occurs.

Environmental advantages

- Lower carbon content when compared to a concrete-block system capable of withstanding similar loading.
- OSA is compatible with the environment – it is used in drinking water reservoirs, SSSIs, etc. Asphalt is manufactured with bitumen refined from petroleum which is inert and will not harm the environment. Tests investigating the leachability of PAHs, heavy metals and other chemicals from bitumen show that concentrations in the test water was well within the surface water limits for EU countries and were also more than an order of magnitude lower than the current EU limits for potable water.
- OSA can be produced at practically any asphalt mixing plant, so the material procurement will benefit the local economy.
- At the end of its design life, OSA can be re-used as 'Recycled Asphalt Planings'. The OSA is crushed, and the resulting aggregate/bitumen can be used in new road asphalt mixtures. Both OSA that has, or has not, been exposed to UV light can be recycled; testing is conducted on the bitumen element to determine the quantities of new bitumen required for the recycled asphalt.

Limitations

- An asphalt plant within 1½ hours travel time of the site is required.
- Access for road delivery lorries to within approximately 3km of the works location is required.
- Access for an excavator with sufficient reach is required at either the crest or the toe of the revetment area to enable installation.
- Working area must be above water. OSA can be placed underwater but only as a prefabricated mattresses.
- OSA cannot be placed in heavy rain or very strong winds. The OSA may cool too quickly (minimum temperature 110°C) and in heavy rain steam restricts visibility of the excavator operator. Light rain is acceptable and OSA can be held in delivery wagons/sheeted over in the event of showers.
- There is no minimum ambient temperature requirement but if ice is present on the formation soils OSA should not be placed.

MAINTENANCE AND PERFORMANCE

Access improvements

A key requirement for the client is ensuring their reservoirs are safe and cost effective to maintain. Their operations teams were actively involved in the project and suggested operational safety improvements, including an access berm and slackening the spillway's crest transitions to 1V:6H from 1V:3H. Retrofitting these to an existing asset was simplified by using OSA, as it can easily be installed at transitions.

Maintenance regime and equipment

The change in spillway revetment and resulting change in vegetation requirements has allowed a change in maintenance regime and equipment. Previously, grass cutting was conducted six times per year, using ride on equipment operating on the slope. However, the frequency can now be reduced, maximising biodiversity benefits and resulting in a lower operational carbon footprint. The equipment the client intends to use is a tractor mounted flail arm. This is so the wildflowers can be cut without equipment being driven over the surface, as there are concerns this would disturb the soil layer. To allow safe tractor access, the client specified a minimum crest width of 4m. To allow for occasions when the tractor and flail are not available, the slopes (1V:2.5H) and accesses have been designed to also allow the safe use of a remote-controlled mower.

A one-year wildflower maintenance contract was formed. In its first full summer (2023) the soil above the OSA appeared to hold sufficient moisture for the wildflowers to successfully flower. They were cut and arisings raked off in autumn. Due to the spring 2024 growth, it was decided no early cut was required and an autumn cut is likely all that is required.

Establishment/since construction

A plastic grid and MOT type-1 track were reinstated on the spillway crest, to prevent rutting during emergency and operational access. The track was seeded with an amenity grass seed mix; this did not establish well over the first winter, leaving the crest exposed. It is thought to have contributed to shallow longitudinal tension cracks (up to 45mm deep) opening along the downstream shoulder during the first spring/summer season. Also, shrinkage cracks opened along the downstream toe kerb. All cracks were filled with general purpose topsoil and are being monitored. None have reopened and vegetation on the crest track has now established.

The reservoir has impounded water once since construction completed, during Storm Babet on 20th October 2023. However, water levels were well short of the emergency spillway level, so the OSA and sacrificial topsoil have not been overflowed. Surveillance of the reservoir during impoundment, using a reservoir specific checklist, identified no performance concerns.

Inspection, surveillance and repairs

A maintenance plan was agreed with the client to cover queries regarding future OSA inspection and maintenance. It included that removing the soil layer to expose the OSA was not routinely required, unless features such as slips and depressions were identified during regular visual inspections or surveillance. Minor OSA damage could be repaired by competent operatives; however, the manufacturer should be consulted for anything else. The plan also covered surveillance activities during impounding events, such as monitoring the toe drain outfall.

CONCLUSIONS

A new spillway arrangement capable of withstanding a velocity of 7.3m/s was required to safely pass the PMF. Following an evaluation of different types of spillway reinforcement, Open Stone Aggregate (OSA) was selected. The OSA provided an extremely practical means of reinforcing the spillway. It was placed in a relatively short time period with no complications. To provide an aesthetic/environmental finish the OSA was overlain with sacrificial turf.

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