The British Dam Society

Adapting earthworks design for adverse weather conditions

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SYNOPSIS Undertaking earthworks in winter and wet weather is generally avoided due to construction difficulties and potential quality implications. However, with changing climate and programme related challenges, it may not always be possible to avoid this.

Barrowford reservoir has had a long history of seepage and stability issues and due to the constrained nature of the site, the preferred solution was agreed to reduce the top water level and to regrade the slope within the existing site boundary to improve the factors of safety. The north embankment showed signs of accelerated settlement when compared with the other embankments and signs of internal erosion having been noted in the history of the site. A filter blanket was designed for the north embankment to prevent migration of the fine material.

Delays in construction meant that winter working was required in order to maintain regulatory compliance. This paper summarises how the works was investigated and designed to improve slope stability and reduce risk of internal erosion at Barrowford Reservoir and how the design was revised part-way through construction in consultation with the Construction Engineer, Undertaker and Contractor to allow winter working to be undertaken and quality was maintained by adopting a method specification with performance testing of the earthworks.

BACKGROUND

Site Overview

Barrowford is a non-impounding storage reservoir that was formed in 1886 by the construction of a perimeter earth embankment some 1,000m long which retains a volume of 453,840m³ at top water level (TWL). The maximum height of the embankment is 8.8m. The upstream slope is 1 in 2.5 (V to H) and is lined with stone pitching. The crest is some 2m wide and grass covered with gravel footpath. The downstream slope is generally 1 in 2 (V to H) and is grass covered. Barrowford is owned and operated by the Canal and River Trust (the Trust).

The historic data indicates that the reservoir was constructed around a natural depression, however some cut and fill is evident along the line of the embankment, with cut to the north and fill to the south, east and west. The fill from the embankments was likely sourced from material excavated from this cutting, the basin and possibly also from the nearby canal.

Managing Risks for Dams and Reservoirs

The reservoir is founded on Glacial Till of variable composition including distinct bands of granular deposits. The Glacial Till overlies bedrock of the Mill Stone Grit.

Historic Context

Inspection records of the embankment extend back to 1931, however the first leak was recorded in 1981. Various leaks, superficial slips, sink holes, depressions, etc were recorded from 1981 onwards with 1983, 1984, 1991, 1994, 1997, 1999 being particular cases. It is unclear why this change in behaviour occurred. A review of historic climate data indicated a general trend of increasing temperatures but nothing distinctive is apparent in the early 1980s.

A possible change in the operation of the reservoir may have occurred during this time which may have precipitated this behaviour – such as greater fluctuation in reservoir levels or extended drawdowns, but records were not available to confirm this.

A number of investigations were undertaken at Barrowford over time including ground investigations, ground temperature measurement for leakage by GTC (Kappelmeyer GmbH), Willowstick resistivity survey for evidence of leakage and a British Geological Survey (BGS) geophysical survey.

A series of interventions were undertaken to stop or manage the leakage at the reservoir, including installation of trench sheets in the upper portion of the embankment to parts of the west and south embankments and most recently installation of counterfort drains to the north-east embankment in 2008. Approximately 25% of the dam is known to have had works done to the upper part of the embankment to address seepage related issues.

The Trust would regularly attend to site to remediate topsoil slips on the slope over the winter period where high rainfall would precipitate movement. This resulted in additional burden on the maintenance teams each year.

The Trust, as operator of Barrowford, commissioned Mott MacDonald to develop solutions to address leakage and slope instability of the embankments to ensure the safe continued operation of the reservoir following a Measure in the Interests of Safety under the Reservoirs Act 1975.

ANALYSIS AND DESIGN OF PROPOSED SOLUTION

Review of Monitoring Data

Piezometers and drainage

Long term piezometric data was available for seven cross sections spread along all but the west embankment. Some spot records were available along three cross sections of the west embankment from a ground investigation in 1991. All cross sections consisted of three piezometers each – one in the crest, one in the downstream shoulder and one in the toe. Toe drains were only present on the north-east embankment.

Along all but the south-east embankment, a strong change in piezometer readings was noted when the reservoir was at or above top water level for prolonged periods. This was supported by the drainage monitoring data and it was known that seepage ceases whenever reservoir level is dropped.

The piezometers closest to the reservoir (irrespective of tip level) were seen to have the most direct relationship with reservoir levels. Piezometer readings suggested that the core was of variable quality, but this did not produce significantly high pore pressure in the downstream fill nor foundation.

The review of the data indicated that foundation seepage occurs at discrete localised coarse deposits on the north and north-east embankment. It was considered that foundation seepage is of a modest extent given the limited piezometric response and absence of significant issues observed in the area of foundation seepage.

Settlement

Long term monitoring pins were present generally at 20m intervals along the crest of the dam. The settlement and strain experienced by the embankments were noted to be in line with expected behaviours. The rates experienced by the north-east, south-east and west embankment, were on average, recorded to be in line with this range.

On the north embankment, extensive settlement and high rates of strain were noted to have occurred in the embankment which could not be attributed to reservoir draw down nor compressible founding soils. It was noted that the zone of excessive movement along the north embankment corresponded directly to the area where seepage and sinkholes had been observed. It was concluded that the excessive crest settlement was most likely caused by the erosion of the fill when seepage flows overtop the (low) core and pass out through discrete preferential paths in the downstream shoulder.

Review of Historic Investigation

Extensive investigation has been undertaken at Barrowford reservoir which is summarised in Table 1.

Table 1. Summary of Ground Investigation at Barrowford Reservoir

Year	Description
1991	Soil Mechanics (9 boreholes and 6 trial pits to west embankment)
2007	White Young Green (9 boreholes to north-east embankment)
2007	GTC Kappelmeyer (Geophysical survey south-west corner (south Embankment)
2015	Hyder (6 window samples to north embankment and 6 to south embankment)
2017	Arcadis (6 trial pits to north embankment)
2017	GTC Kappelmeyer (Geophysical survey north-east and south embankment)
2018	Arcadis (30 trial pits along entire crest)
2019	Arcadis (4 window samples to south embankment)
2018	GTC Kappelmeyer (Geophysical survey along entire embankment)

Year	Description
2019	Willowstick (Geophysical survey along entire embankment)
2019	BGS (Geophysical survey to North-East and South embankment)
2020	Arcadis 4 window samples and 7 trial pits spread across all embankments, partly to ground truth the BGS study

Ground Investigation

The majority of the historic ground investigation had been conducted from the crest of the embankment. A review of all ground investigation concluded that the embankment fill was highly variable with a likely central clayey zone rather than a well-defined clay core. This clay was easily identified in some areas, and less so in others. In some cases, over a 10m length of crest, there would be evidence of clay central to this, with no evidence of clay from the ground investigation 5m either side. There was no evidence of a cutoff into the foundation.

Kappelmeyer

A Kappelmeyer survey was undertaken in March 2017 along a 130m length of the embankment that was of greatest concern. This included the whole of the north embankment and some 40m of the north-east embankment. The investigation recorded seepage flow through the embankment at two discrete lengths totalling 30m of the total 130m under investigation. The results showed high level seepage down to a depth of 2.5m below crest level.

A second Kappelmeyer survey was undertaken along the whole embankment in January 2018. The investigation recorded small seepages down to a depth of 2m below crest level. These investigations correlated with the piezometer data and drainage flow measurements recorded along the embankment.

Willowstick

A Willowstick survey was undertaken in 2019 and identified a number of seepage paths.

In the north embankment, the survey did not record seepage through the embankment but did record seepage through the foundation at two preferential locations, A and B (Figure 1).

- Inferred Seepage Path A: A series of three piezometers were installed at the location of the inferred seepage path into the foundation. All three piezometers recorded a distinct response to variation in reservoir level. The monitoring data related well to the findings of the Willowstick survey.
- Inferred Seepage Path B: Limited piezometric data was available in this location and due to a lack of long-term evidence the relationship could not be confirmed. However, the borehole log recorded the presence of blowing sand at elevation some 3m about the inferred seepage path. The presence of the blowing sands is indicative of high confined water pressure which would tend to support the presence of a seepage path in this area.

- A piezometer located in between the two preferential locations recorded no response with variation in reservoir level - which correlates with the findings of the Willowstick survey.

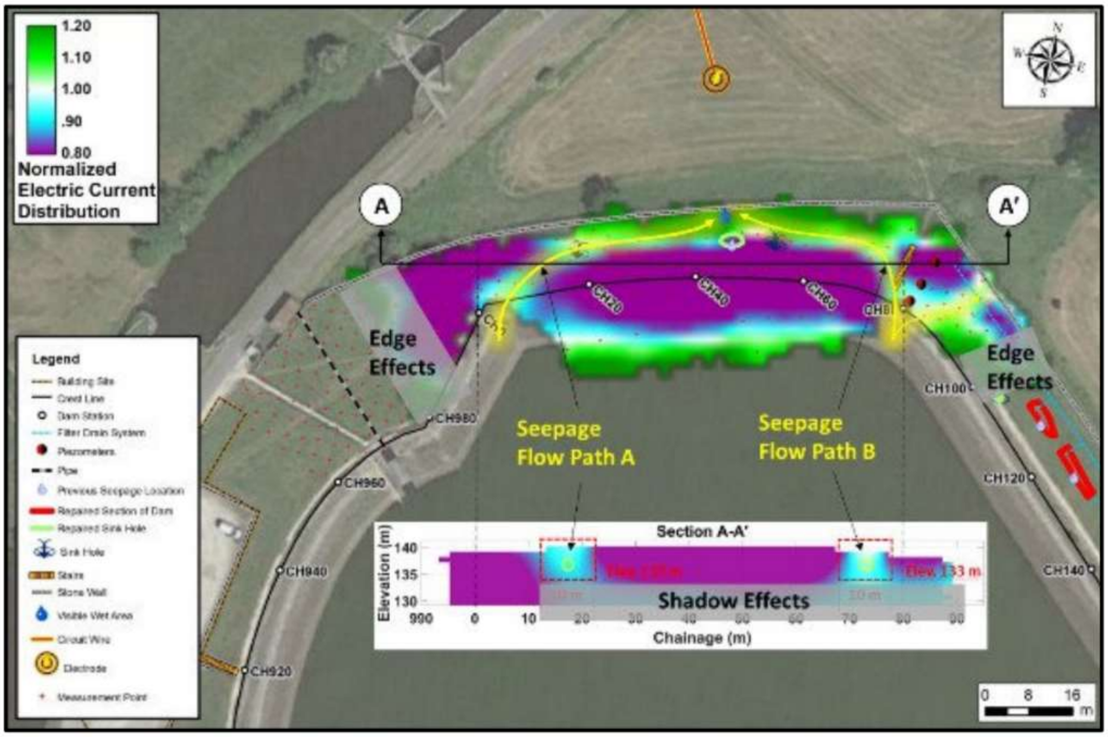

Figure 1. Seepage Paths in the North embankment

In the north-east embankment, the survey identified seepage at three preferential locations, C,D and E (Figure 2).

- Seepage Path C: An inferred seepage path was recorded in the foundation. No piezometers were installed here, although drains are installed along the downstream toe, however the invert of the drainage is above the inferred seepage path. The intensity of the reading at C is akin to that recorded at seepage paths A and B.

- Seepage Path D: An inferred seepage path D is recorded in the foundation and a piezometer was installed in the foundation in this location. A relationship between piezometric level and reservoir level exists here but it is modest – piezometric levels varying by 0.7m for 6m of reservoir head, a ratio of 1 in 8.6 variation in reservoir level. Willowstick records a weaker signal here than at inferred seepage Path C, indicating greater seepage there than at D.

- Seepage Path E: Seepage throughout the embankment is indicated over a 40m length a in the upper embankment. This does not correlate with drainage, piezometer nor Kapplemeyer data. A nominal seepage path was also inferred in the foundation at a discrete point in this area. No piezometer data was available here. The indicated seepage here was very low and was not considered a significant concern.

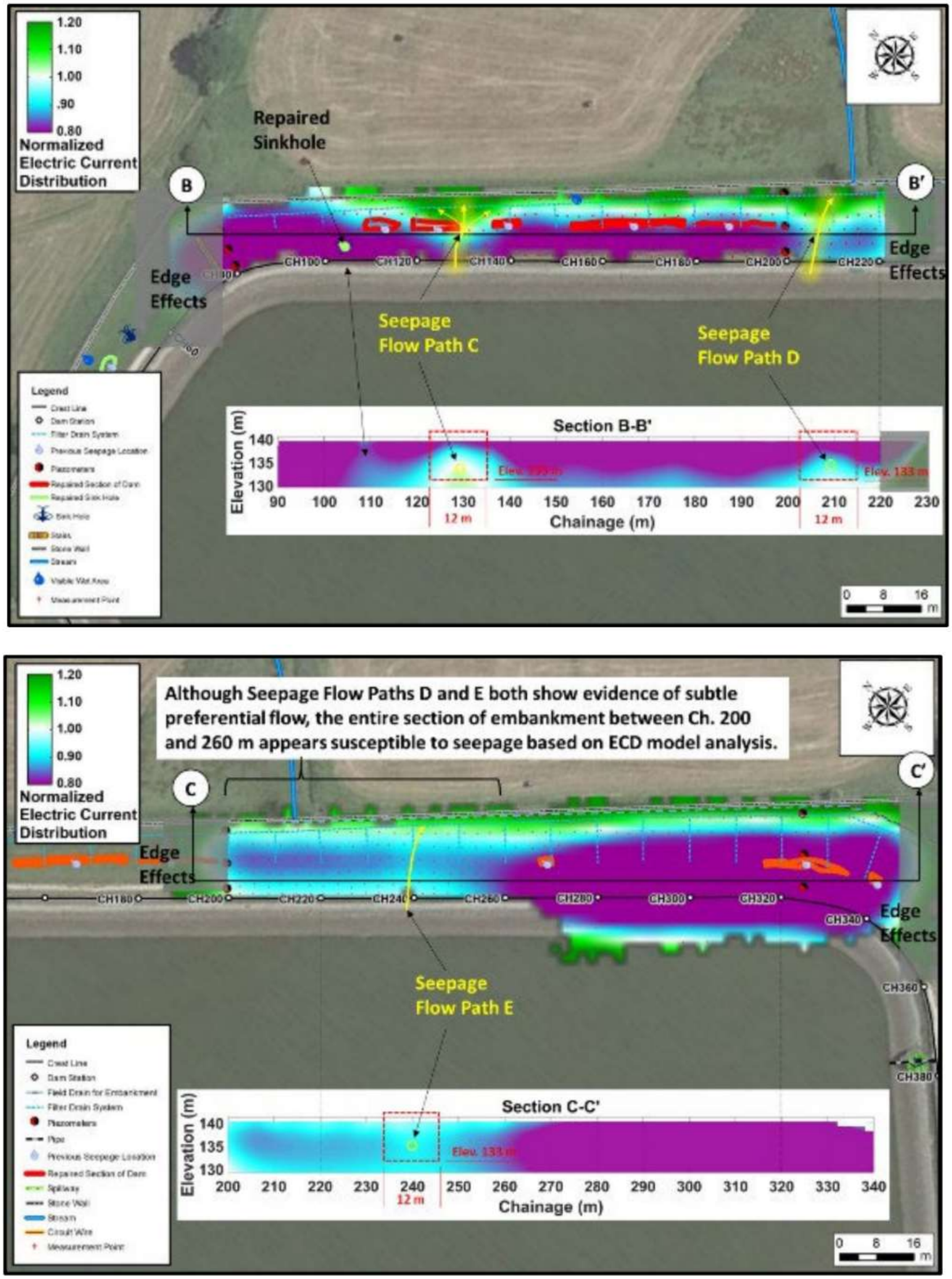

Figure 2. Seepage Paths in the North-East Embankment

In the south embankment, the survey identified seepage at one preferential location (Figure 3). High level seepage was indicated in the embankment upstream of the core for approximately 130m in length of the embankment. This corresponds to the piezometer data (as the core readings record a connection but shoulder fill does not) and generally with the Kapplemeyer survey.

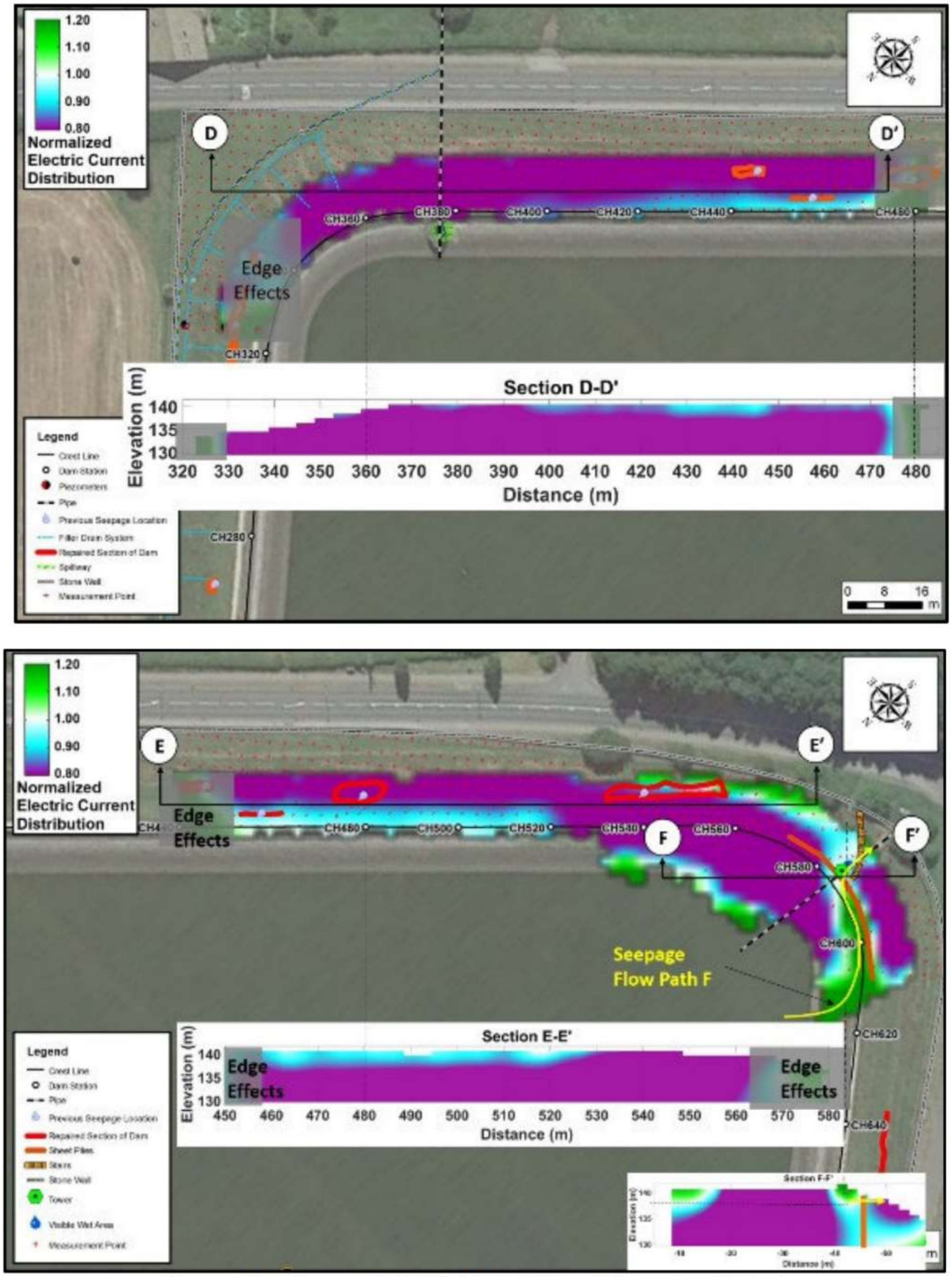

Figure 3. Seepage Paths in the South Embankment

In the west embankment, the survey identified a possible seepage-prone area for a 40m length (Figure 4). A line of piezometers installed at this location record no such issue in the downstream shoulder fill nor the foundation. A high-level relationship was noted in the core piezometers and was also recorded by the Kappelmeyer survey.

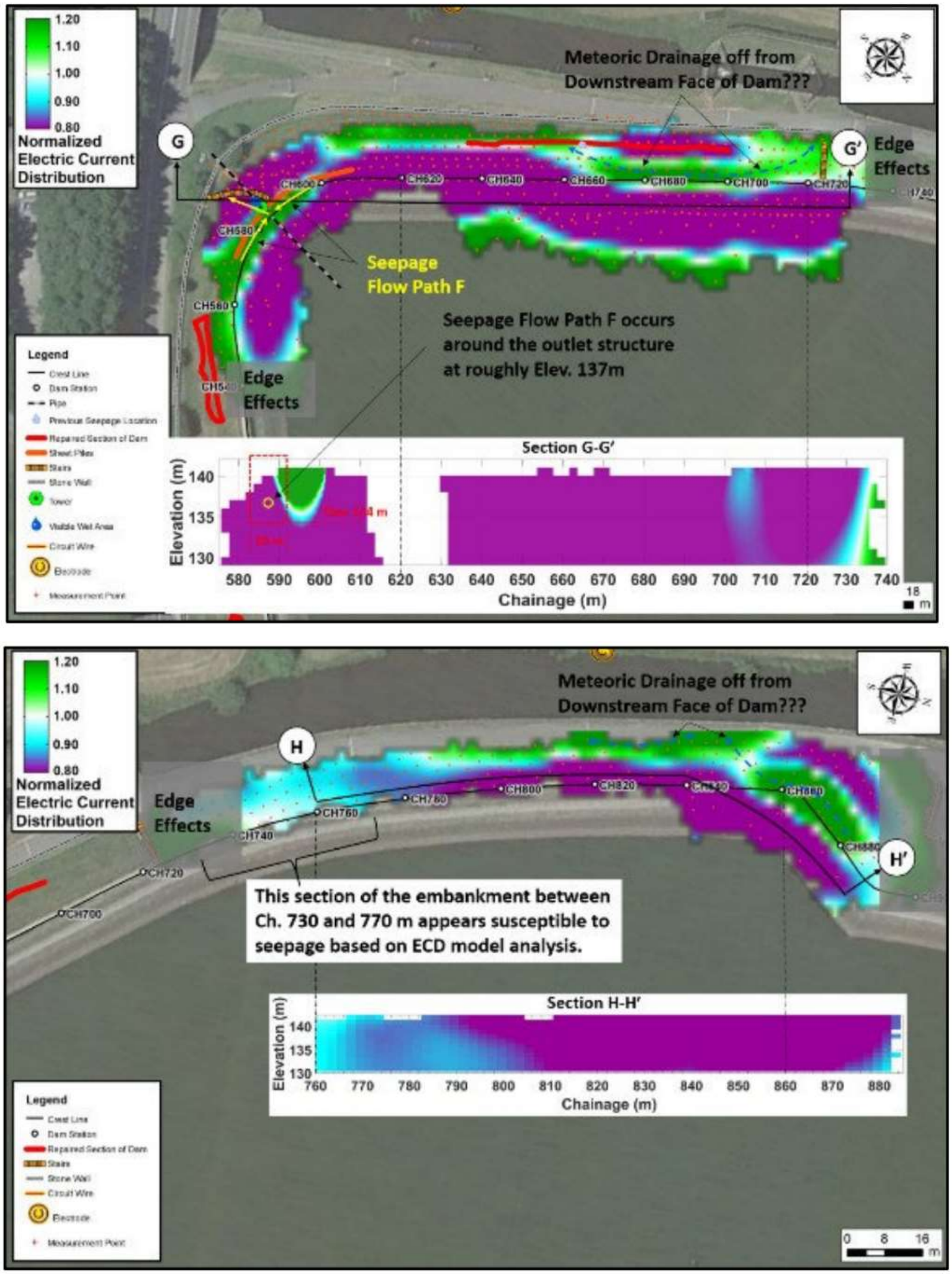

Figure 4. Seepage Paths in the West embankment

Geophysical survey and Ground Truthing

The BGS Geophysical survey results were made available shortly after Mott MacDonald begun work to optioneer potential solutions. The survey had used a combination of techniques to build up a picture of the embankment. The techniques used included electrical resistivity tomography and multi-channel analysis of surface waves. The results of this investigation concluded that there was a high potential for a raised upper core, doglegged above the original core towards the downstream side of the crest. Historic records did not indicate any known raising of the core so it was thought that if this was the case it was undertaken towards the end of the original construction period.

In order to ground-truth the results, ground investigation including trial pitting and window sampling was undertaken at the locations where the BGS survey had targeted.

The survey also revealed a localised area of shallow granular material on the downstream face of the two cross sections produced. During the works, these were revealed to be wall drains, likely to have been put in during the original construction to help manage pore pressures. These are detailed further in the paper by Brown et al (2024).

DESIGN

Slope Stability Analysis

Slope stability analysis was undertaken considering a range of scenarios including the static case, seismic analysis, rapid drawdown and the temporary construction case. Four different sections, one along each embankment were analysed. The slope stability analysis showed a marginal factor of safety in the static case in the existing embankment, as expected based on site observations.

Suffusion and Erosion Investigation

During the review of the existing data, it was clear that the north embankment had suffered high level seepage, sinkholes and undergone excessive settlement which could not be explained by either reservoir drawdown or compressible founding soils. Therefore, an investigation as to whether erosion was the root cause of these issues was undertaken.

The assessment found that the fill and foundation at the north embankment were extremely unlikely to be susceptible to internal erosion from the mechanisms of suffusion, backward erosion and contact erosion. The extent of seepage through discrete granular layers in the foundation was therefore determined to not be the root cause of the excessive movement of the north embankment.

Erosion of fine soil through concentrated leakage in the embankment fill was noted to be a possibility with regard to either cracking in desiccated soils at the crest and /or zones of permeable fill, the latter being the more plausible.

It was noted that the zone of excessive movement along the north embankment corresponded to the presence of all noted seepages and recorded sink holes as observed in the downstream face. The excessive crest settlement here was noted to possibly be caused by the erosion of the fill when seepage flows overtop the (low) core fill and passing out through discrete preferential paths in the downstream shoulder.

Dispersive soils were not recorded in the embankment fill. It was noted that there was potential for dispersive soils to be present in the foundation but such were likely to be of limited extent based on available ground investigation data and given the less onerous conditions (lower height and lower hydraulic gradient) compared to the rest of the embankment were unlikely to contribute to the recorded issues in the embankment shoulder.

Preferred Solution

A range of options was considered and concept designs developed in conjunction with a contractor. It was noted that the core is likely to be of such a varied nature, quality, condition and extent that accurate determination of its details was not practicable. The design and effective construction of any core raising option would be hampered by the variability in nature and position of the lower core.

Following a review of all the options and undertaking a buildability and cost build-up exercise, the proposed solution which was agreed was to permanently reduce the top water level by 1.8m and regrade the downstream shoulder to a slope of 1:2.5 so that the operation of the reservoir level avoids, as much as practicable, the reservoir being impounded at or above the upper core. This was supported by slope stability analysis to confirm adequate factors of safety were being achieved.

The adoption of this approach was supported with evidence from the BGS geophysics, long term monitoring data and temperature monitoring results which showed a potential linear defect in the core at this elevation.

Separate Consideration of the North Embankment

Due to the accelerated settlement on the north embankment and evidence of washout of the embankment, it was agreed that a slightly different approach would be taken at the north embankment.

To address this, the crest was to be left 500mm higher than the rest of the embankment to allow for the accelerated settlement. A filter blanket was designed to filter potential seepage from the embankment and prevent migration of the fine material. The final profile of the north embankment was designed to be shallower than the rest of the embankment with a profile of 1:3, with the filter to be covered with a compacted cohesive material and ultimately topsoiled and seeded.

New settlement pins were proposed along the whole of the crest of the embankment at 10m intervals, however the frequency was reduced to 5m for the north embankment, and settlement pins were also installed at the toe, to help identify movements of the slope.

Due to the presence of the preferential flow paths identified in the foundation during the Willowstick survey, as well as the presence of blowing sands, boreholes were proposed to target the permeable layer in the areas identified so that the groundwater could be alleviated and monitored long term.

CONSTRUCTION

Sourcing of filter material

Throughout 2023, suitable material suppliers were searched for to meet the specified requirements of both filter materials. Both fine and coarse filter material required a narrow grading with no fines smaller than 0.75mm and 2mm respectively. Due to these requirements, sourcing an acceptable material was challenging, with the Contractor deciding on sourcing a bespoke blended material for each in order to achieve the requirements of the specification. In July 2023, a crushed microdiorite basalt from the Minffordd Quarry was selected for the coarse filter and a blend of crushed tuff and quartz from the Cefn Graianog Quarry was selected for the fine filter.

Compaction trials

Compaction trials for both coarse and fine filter were initially undertaken in early June 2023 (Figure 5). The trials consisted of the construction of two small embankments approximately 20m in length by 5m width. The number of proposed layers being defined as the number required to determine a suitable compaction method to achieve the specified relative density of between 70% and 80%. A number of combinations of compactive plant, vibration frequency, layer thickness and passes were undertaken in order to define the optimum compaction methodology.

Figure 5. Fine Filter Compaction Trial

Upon undertaking the compaction trial of the fine filter, it failed to achieve the minimum relative density requirements of 70% reliably. Upon analysis of the trial results, it was determined that the minimum density testing results used to derive relative density were unusually high with results of 1.67Mg/m^3. Table 1 of BS8002 indicated, with a unit weight of 15 to 17kN/m^3 appropriate for uncompacted fine filter, that a realistic range of minimum density should be between 1.316 to 1.574Mg/m^3 with an average of 1.37Mg/m^3. Upon retesting the material for minimum density, the value reduced and as a result both material trials were re-attempted and met the relative density requirements of the specification.

Particle Size Distribution (PSD) testing undertaken throughout the compaction trial to validate the material source showed evidence that up to 5% material finer than 2mm diameter was present in the coarse filter material, contrary to the requirements of the specification which stated no material finer than 2mm was acceptable. Thorough processing of the material, including washing, eventually achieved the specification requirements by reducing the material below 2mm diameter to as low as was practically achievable (3%). The risk of increasing <2mm material during the wetter winter months was raised, as processing materials in a wet environment can result in higher entrained silts and clays in the processed material. To mitigate this risk, Mott MacDonald completed a site visit to the Cefn Graianog Quarry in order to ensure the material was washed and processed to a sufficient standard in all weathers.

Move to winter earthworks

Mobilisation of the Contractor began in October 2021. Works to regrade the west embankment were generally undertaken in summer 2022 with provision for coir matting where this was undertaken after August to help stabilise the topsoil over the winter period.

Works to regrade the north-east and south embankment were generally undertaken in summer 2023. Due to programme and procurement related delays, works to the north embankment, including the filter blanket were delayed until September 2023 and with inclement weather and the statutory deadline fast approaching, and the need for the reservoir to be back in service for the 2024 boating season, the design was revisited with all parties.

Adaptation of design

Due to the above noted delays, it was now approaching winter and as such there was concern that the relative density requirements would be difficult to achieve in wet weather. To combat this, the compaction specification was altered to a method specification, with the provision that in-situ relative compaction should be regularly monitored to reduce the risk of over compaction. Both filters were to be compacted in 300mm layer thicknesses and subject to four complete passes of a vibratory smooth drum roller with a static weight of 8T. Filter located on the slope incline was to be compacted in 225mm layer thicknesses and subject to four complete passes of a vibratory plate compactor with a frequency of 60Hz. Accounting for the difficulties of placing and compacting a cohesive material in the ‘wet’ season the shoulder fill atop the filter was changed from a cohesive to a granular material (SHW Type 803/1). The material surrounding the filter was altered to an associated hybrid specification, part end product and part method-related.

Compacting on top of peat

Winter working also meant the formation level to the filter blanket, which comprised 2m of peat overlying 2m of Alluvium, had become saturated with water due to a combination of surface runoff from heavy rains and artesian groundwater issuing from a nearby existing open well. Attempts were made by the Contractor to start work in the area, however the ground proved very soft due to the saturated conditions and they were unable to achieve the required compaction. It was necessary to improve the underlying peat via the provision of coarse granular material (200mm SHW 6G). This material was “pushed” into the formation with an excavator bucket, to ‘tighten up’ the peat, providing a suitable surface on which to place and compact the filter material. The 6G was designed to be placed in such a way that there was no continuous coarse granular layer at the base of the filter, which would have provided an unintended pathway for water flow.

Managing artesian groundwater

To combat the artesian groundwater issuing from a nearby well, the water was re-directed into the recently laid drainage run which ran along the toe of the proposed filtered embankment. Upon first placement of the first layer of filter material (which was to be fine filter material) in early November, the ground had frozen, due to its north facing location, whereas the filter material stockpile remained unfrozen and free moving. This significantly aided compaction of the first layer of filter material placed on the improved peat formation, building out of the wet material and ensuring a firm embankment base.

Two pressure relief wells were installed in the north embankment to alleviate artesian groundwater in the areas identified by the Willowstick Survey. Challenges were encountered during installation with managing the artesian groundwater and allowing suitable installation of the filter material around the perforated pipe. This was overcome by socketing the casing into a suitably impermeable layer of ground to provide conditions to assist with installation.

Testing

Once the first layer was complete, Nuclear Density Meter (NDM) testing and Sand Replacement Density (SRD) testing were undertaken on the fine filter and NDM testing completed on the coarse filter (as this material was unsuitable for SRD) proving a relative compaction of 89% on average was achieved in the fine filter and 92% in the coarse filter. The 803/1 shoulder fill material, requiring 95% relative compaction for compliance achieved an average of 99% with 100% of tests passing. PSD testing was also undertaken to ensure the filter materials had not significantly degraded (i.e. increase in finer sized particles due to particle breakdown) during compaction with acceptable post compaction results of no more than 4% below 2mm diameter achieved for the coarse filter, which was deemed acceptable. The coarse filter, fine filter and Type 1 embankment fill were subsequently placed without incident (Figure 6), with in-situ density testing and PSD testing carried out on each layer to ensure compliance to the specification.

Figure 6. Compaction of coarse filter

CONCLUSIONS

Whilst winter earthworks can prove challenging, this paper demonstrates that by adapting the design of earthworks, it may be possible to continue working through adverse weather conditions whilst maintaining safe working conditions and satisfying the requirements of the specification. The challenges faced at Barrowford included frozen ground, adverse weather, compaction on top of peat and working with elevated groundwater levels.

ACKNOWLEDGEMENTS

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REFERENCES

Brown A J, Brown D H, Tudor S and Reynolds A (2024). Wall and pillar drains in puddle clay embankment dams. *Dams and Reservoirs* **34(1)**: 26-41.