The British Dam Society

Megget Reservoir: Investigation into potential internal erosion in an asphaltic concrete core rockfill dam

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SYNOPSIS Megget Reservoir is an impounding reservoir in the Megget valley of the Scottish Borders, which is used to supply water to Edinburgh and the Lothians. The dam retaining the reservoir is a 56m high asphaltic core rockfill dam constructed in 1982, believed to be the only one of its type in the UK.

In 2021, an inspection under Section 47 of the Reservoirs (Scotland) Act 2011 observed dark fine silty deposits within the drainage gallery, which had historically gone unreported. There were concerns that, due to the unknown nature and origin of the deposits, the erosion of material could increase risks to dam safety. AtkinsRéalis carried out an investigation into the source of the material, including a series of advanced soil characterisation tests, alongside a separate comprehensive study into the monitoring data at the reservoir. The outputs were used to determine the likely nature and origin of the material, as well as qualitatively assessing the risks to dam safety due to the erosion and recommending a future monitoring regime to mitigate the associated risks.

INTRODUCTION

Megget Reservoir is an impounding reservoir in the Megget valley of the Scottish Borders. It is owned and operated by Scottish Water (the "Reservoir Manager”) and is used to supply water to Edinburgh and the Lothians. The reservoir is largely rectangular in shape, with a capacity of around 64Mm^3 and a surface area of 2.6km^2 at top water level. The dam retaining the reservoir is a 56m high asphaltic concrete core rockfill dam constructed in 1982, believed to be the only one of its type in the UK.

In 2021, during the visit for inspection under Section 47 of the Reservoirs (Scotland) Act 2011, the Inspecting Engineer observed dark fine silty deposits within the drainage gallery. Anecdotal evidence at the time suggested that the steady accumulation of these deposits had been managed for some time (potentially since construction). However, there was no mention of the deposits in previous inspection reports and no records were available of: the rate of accumulation, the frequency of clearance or nature and origin of the deposits.

Given the lack of record and understanding of the nature and origin of the deposits, there was no way of confirming if internal erosion was affecting dam safety. A listed (safety) measure was therefore recommended: “Samples of the deposit within the drainage collection channel should be taken and analysed to establish its nature and likely origin.”

Four hypotheses were tested as part of the investigation:

- The deposits originate from the bituminous core of the dam.
- The deposits originate from the concrete adjacent to the bituminous core.
- The deposits originate from the transition material downstream of the bituminous core.
- The deposits originate from the drainage material downstream of the bituminous core and situated between the transition material and the concrete gallery.

It was also noted during the inspection that a significant amount of data was being recorded at the reservoir. However, the Reservoir Manager had not been given advice on how to effectively analyse and interpret this data. Therefore, in parallel with the investigation, a recommendation was made to undertake a desk study to review existing monitoring data, published technical papers and available rainfall data.

This paper describes the investigation into the source of the material, alongside the separate comprehensive study into the monitoring data at the reservoir. The findings of these were used as a means to test the hypotheses and subsequently make recommendations for future monitoring and interpretation.

BACKGROUND

Dam

Megget Dam is 56m high and spans 570m at its crest. The construction of the reservoir was completed in 1982 by Lothian Regional Council (LRC).

The dam has two shoulders of gravel fill and a central vertical asphaltic core. The core is located under the crest of the dam and slightly offset to the upstream side. Adjacent to the core are transition zones extending 1.5m upstream and downstream of the core. Beyond the transition zones the embankment consists of a gravel fill material. The crest and downstream berm are protected with grass and concrete blocks, with the upstream berm and embankment slope being covered in riprap above a filter layer to separate it from the main gravel fill (Figure **1**).

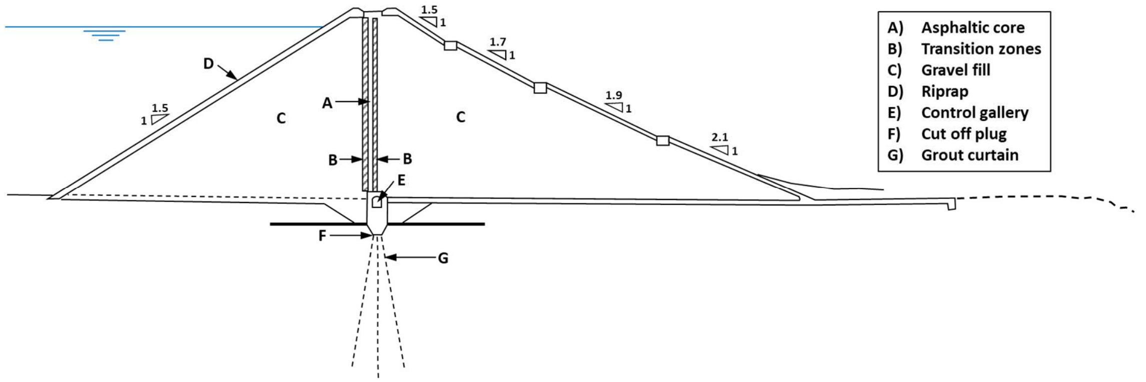

Figure 1. Cross section through Megget dam

A concrete inspection gallery runs along the length of the dam at the base of the asphaltic core. Drainage channels run along the length of the gallery, with drainage pipes from the above drainage material (immediately below the transition zone) discharging into the drainage channels (Figure 2 and **Figure 3**).

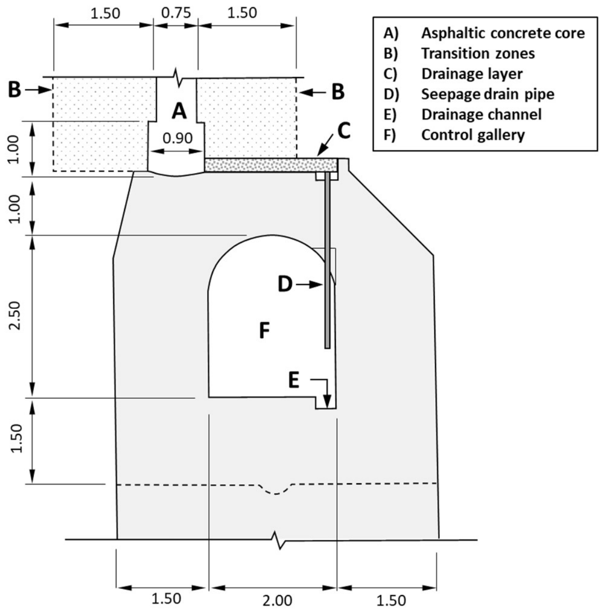

Figure 2. Cross-section through gallery

Figure 3. Photograph of drainage gallery

Construction Details

It is reported that the gravel used as fill for the shoulders was sourced from borrow pits within the reservoir basin (LRC, 1995). The alluvial gravel was described as graded, including coarse silt, sands, gravels, and cobbles, with all particles above 125mm being excluded.

The transition zones on the either side of the core use the same material as that used in the shoulder (with an upper size limit of 100mm and a restriction of 5% - 10% fines passing 2mm), allowing for any seepage through the core to be directed to the control gallery channels, via the drainage layer and seepage drain pipes (Figure 2, notes C and D).

Given the age of the structure, it is likely that the drainage material is an open graded aggregate. The origin or nature of the material is not stated in the records; however it is possible that the material may have been imported and of similar nature to that used in the asphaltic core.

An asphaltic concrete core is said to have been selected as, whilst clay deposits were available close to the site, there was not enough to complete the core, and the use of asphaltic material was the cost-effective alternative. The core is 55m tall at the highest point and 555m long at the top of the embankment dam. The thickness of the core varies with height; for the first 1m above the control gallery it is 900mm thick, then 700mm and finally reducing to 600m thick for the top 23 metres. A mastic material was used as a contact layer between the core and the control gallery.

The design of the asphaltic concrete and the mastic mixes were carried out by a specialist subcontractor. All coarse aggregates used in the asphaltic concrete were crushed basalts, with natural sand and fine crushed aggregate also being used. The final asphaltic concrete and mastic mixes are given in **Table 1**.

Instrumentation

A comprehensive suite of instrumentation was installed during construction to monitor key parameters including seepage, pore pressure, movement and water levels in both the dam and the reservoir, as detailed in **Table 2**.

Table 1. Mix design of the asphaltic concrete and the mastic mix

Asphaltic concrete	%	Mastic	%
20 mm aggregate	14.0	Crushed fines	32.0
14 mm aggregate	16.8	Natural sand	33.0
6.3 mm aggregate	11.1	Limestone filler	20.0
Crushed fines	20.5	Bitumen	15.0
Natural sand	20.5		
Limestone filler	10.3		
Bitumen	6.8		

Table 2. Instrumentation at Megget dam

Monitoring parameter	Instrument(s)	Description
Seepage	V-notch weirs	Collect water from a drainage layer at the base of the transition zone. Water discharges into a drainage collection channel within the drainage gallery. Flow rates are measured over three V-notch weirs with Gauge 1: North shoulder seepage; Gauge 2: North shoulder + Central area; Gauge 3: South shoulder seepage. Additional flow chambers equipped with V-notch weirs near the stilling pool capture seepage from the valve house and downstream culvert drains.
	Additional measures	Seepage is collected in a drainage blanket and measured at the downstream toe.
Pore Pressure	Hydraulic piezometers	Installed in the embankment foundation, both upstream and downstream shoulders and along the culvert in sections both upstream and downstream of the core.
	Standpipe piezometers	Eleven standpipe piezometers are positioned in the bedrock beneath the downstream shoulder.
Movement	Survey stations (SU)	Eleven (SU) for horizontal and vertical movements on the downstream shoulder
	Settlement stations (SE)	Five (SE) for vertical movement

Monitoring parameter	Instrument(s)	Description
	Inclinometers (I)	Ten (I) installed during construction, not monitored currently but available
	Monitoring stations	Thirty-eight monitoring stations in the grouted rip-rap on the upstream face
Water Level	Sensors	Water levels in the reservoir are continuously monitored with sensors in the draw-off tower
	Metric gauge board	Attached to the south-west side of the outlet tower

The instrumentation in the dam was being maintained, readings taken at regular intervals and the results stored on the Reservoir Manager's database. Although a substantial quantity of data was being collected, the Reservoir Manager had not been given directions to allow for effective analysis and interpretation of the data to realise its full potential.

Sampling and Laboratory Testing

Two phases of sampling and laboratory testing have been undertaken. The first phase provided some insight into the nature and likely origin of the material, however there was insufficient data to determine which hypothesis was most likely. Therefore, a second phase was recommended.

First Phase - Sampling

A site visit was made on 7th December 2022, where the following samples were collected from the drainage channel within the gallery, along with water samples from the reservoir:

- 1no. soil sample and 2no. water samples from "north" point
- 1no. soil sample and 1no. water sample from "north-mid" [central] point
- 1no. soil sample and 2no. water samples from "south" point

The north and south samples were collected from the drainage channel immediately upstream of V-notch Gauge 1 and 3. The north-mid [central] samples were collected from the drainage channel immediately upstream of Gauge . Figure 4 shows that the materials were visually more variable than originally observed.

Figure 4. Photographs of dark sediments along the drainage channel

First Phase - Testing

The samples were sent to a third-party testing laboratory with the following tests being specified:

- Chemical test suites (metals and inorganic) on all gallery water samples
- Chemical test suites (metals, inorganic, and organic) on the north soil sample
- Fourier Transform Infrared Spectroscopy ("FTIR") on the north-mid soil sample
- Petrographic analyses[1] on the north-mid and south soil samples

Chemical and FTIR testing were specified to determine if bituminous or organic materials were present in the samples. Petrographic tests were specified to determine the minerology of the samples to allow for comparison to materials used in the construction of the dam.

First Phase - Findings

The chemical test suite results were inconclusive as to the presence of bituminous material in the samples, with the majority of the organic tests indicative of bituminous material being below the limit of detection.

The results of the petrographic analyses are shown in the table below, expressed as percentage by volume of the sample.

Table 3. Petrographic south and north-mid sample constituents

Constituent	**Percentage by volume (of sample)**	
	South sample	**North-mid sample**
Quartz	43	-
Soil	22	-
Substantially altered rock	10	2
Quartzite	5	-
Opaque debris	2	58
Calcite	-	7
Precipitated calcite	-	33
Other*	18	<1

*Other constituents were typically <5% of the sample and are not fully listed for brevity.

Of note is the substantial percentage of "opaque debris" found in the north-mid sample. This was described as *"[resembling possible manganese oxide] and precipitated calcite with lesser amounts of calcite grains, substantially altered rock (too fine to be fully distinguished) and traces of chert"*. This material appeared opaque and black on the petrographic thin section images, meaning it could not be described. Approximately 29% by weight of this sample passed the 63µm sieve, with the <63µm fraction appearing to be very similar in appearance to the opaque debris.

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[1] Testing was carried out in accordance with BS EN 932-3: 1997. Tests for general properties of aggregates (BSI, 1997) and in-house test methods.

The FTIR results indicated that no discernible polymeric/hydrocarbon material was present and bitumen was not found in the sample. The FTIR spectra indicated the presence of limestone and quartz in the sample. However, FTIR testing only detects certain compositions including organics. Materials including metals (such as possible manganese oxide) would not show up on FTIR spectra (Figure 5).

In order to resolve some of inconclusive findings of this phase, the inspecting engineer recommended further tests (based on the recommendations of the testing laboratory), which included Scanning Electron Microscope ("SEM") tests to confirm the nature of the "opaque debris".

Second Phase - Testing

In consultation with the testing laboratory, an SEM test with energy dispersive x-ray microanalysis ("EDX") was undertaken on the north-mid sample collected during the first phase. EDX testing is used to determine mineralogical composition of samples. This testing aimed to determine the nature of the "opaque debris" observed previously, which formed a substantial volume of the material at 58% of the sample.

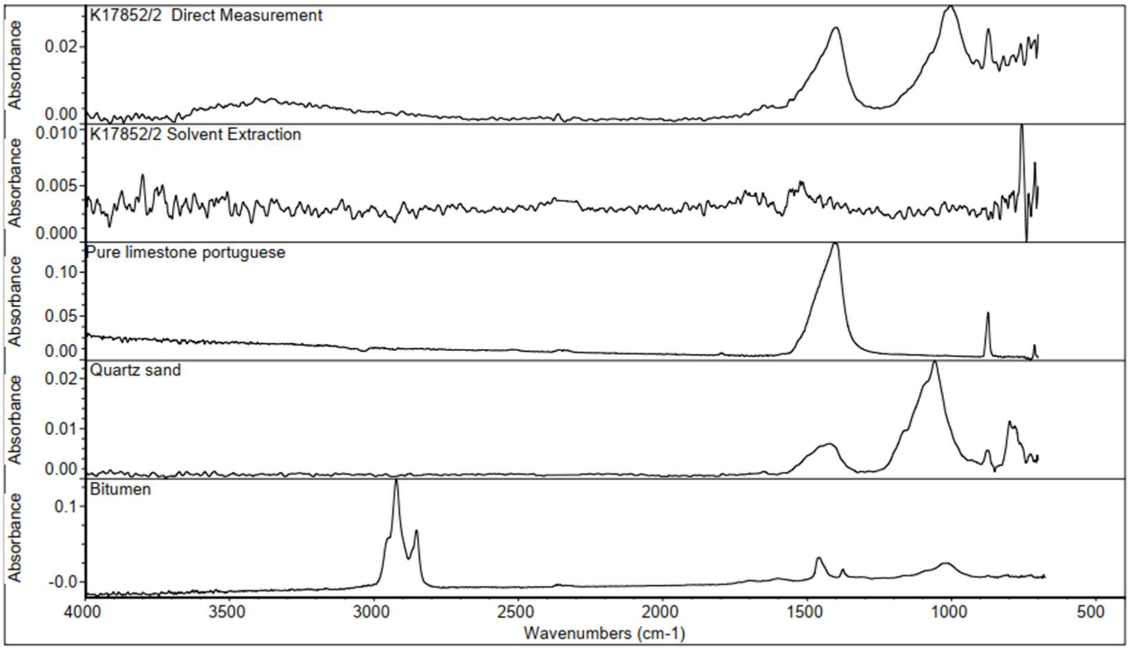

Figure 5. Fourier Transform Infrared Spectroscopy spectra for "north-mid" sample

Second Phase - Findings

The key finding from the second phase of investigation was that the opaque debris (and hence a large proportion of the sample) is clay-grade and predominantly manganese oxide, which would be opaque in the petrographic analysis and black to dark brown in the sample, both of which were found to be the case.

Table 4. SEM and EDX test results

Grain size	Approximate proportion (%)	Description of material
<5µm	80	Irregular clay-grade particles that are typically composed of clay minerals and high proportions of manganese oxide. The average composition of these particles exhibits over 50% manganese (54.2% MnO). These particles would be opaque in thin section and would be black to dark brown in hand specimen.
5-20µm	5	Spherical grains that are dominantly composed of clay minerals and rarely iron oxide. The composition [is typical of] clay minerals within the spherical particles.
20-50µm	15	Angular grains that are dominantly composed of lithic material. The grains are frequently composed of quartz and feldspar.

MONITORING DATA ANALYSIS

Having a better understanding of the nature of the material provided a good basis for testing the hypothesis but to further test the hypotheses into the likely origin of the deposits, advantage was taken of the growing understanding of the performance of the dam, from the preparation of a Monitoring Report – made in response to a separate recommendation made by the Inspecting Engineer (as a listed (safety) measure). The development of the Monitoring Report included a desk study to review existing monitoring data from the dam, published technical papers and available rainfall records.

Available data

There was a significant amount of data that had been recorded from the instrumentation that was utilised in the studies. However, the data was collected in such a way that interpretation of the data (and therefore the behaviour of the dam) was not possible without additional manual processing. Prior to use therefore, all data was assessed to allow anomalous data to be corrected or removed and presented in a format that allowed for visual and statistical assessment.

Seepage monitoring

Collection values for head over the V-notch weirs are typically collected weekly (going back to April 2008). These values were converted to flows and divided by the linear length of dam that drained into each of the respective V-notches to allow for effective comparison between them. The flows per linear metre of dam were plotted against reservoir level and rainfall readings from the nearest available rain gauge (**Figure 6**).

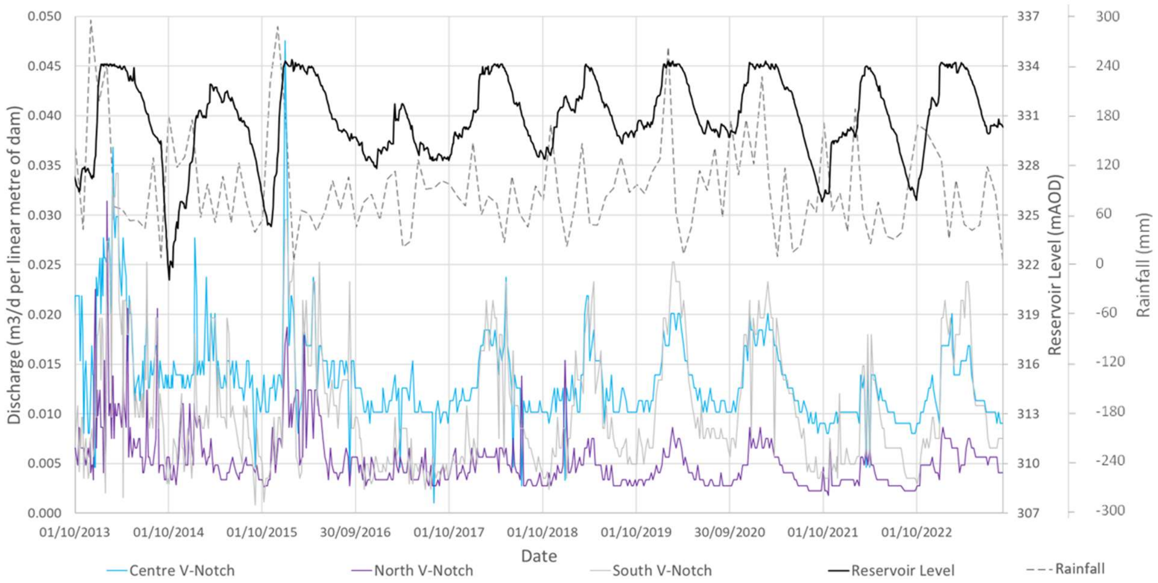

Figure 6. V-notch flow rates per linear metre of dam against reservoir level and rainfall

Pearson's Correlation Coefficient ("PCC") was also calculated to compare the relationship of flow rate per linear metre over each V-notch weir with both reservoir level and rainfall. The coefficient was calculated for all results recorded (between 2008 and 2023), results recorded between 2018 and 2023 and between 2022 and 2023 (Table 5). The aim of this calculation was to determine whether the correlation coefficient to reservoir level and rainfall was stronger in more recent years, which may indicate worsening conditions.

The PCC can vary between -1 to +1 with a score near 1 showing a strong positive correlation, a score of 0 showing no correlation; and a score near -1 showing a strong inverse correlation. However, it should be noted that the calculations for PCC have a large limitation, as it only takes into consideration the dates where readings were available for both variables being compared. Dates where only one of the variables were measured could not be used in the calculation of PCC and had to be selected out of the data set.

Table 5. Pearson's Correlation Coefficient for v-notch flows against reservoir level and rainfall

V-notch	**PCC (flow vs. reservoir level)**			**PCC (flow vs. rainfall)**		
	2008-2023	**2018-2023**	**2022-2023**	**2008-2023**	**2018-2023**	**2022-2023**
Centre	0.41	0.78	0.83	0.08	0.43	0.99
North	0.39	0.71	0.80	-0.22	0.07	0.75
South	0.67	0.84	0.88	0.30	0.06	0.47
Chamber A	0.18	0.16	0.00	-0.36	0.14	0.84
Tailbay (North)	0.20	0.19	0.26	-0.29	0.43	0.97
Tailbay (South)	0.14	0.16	0.07	-0.15	-0.22	0.42

An opinion was reached that the V-notch flows in the gallery showed a strong response against reservoir level, with a secondary response to rainfall. The maximum recorded flows appear to be relatively consistent over the range of data, with no obvious signs of increasing flows.

The PCC for unit flows against reservoir level showed a strong correlation across all V-notches in the gallery over the five years prior to the study, however the correlations were much weaker when considering all the data. This might suggest seepages measured at the V-notches are becoming more responsive to changes in reservoir level over time (maybe as a result of increasing leakage). However, it was recognised that there was a lack of available data to calculate PCC over the last year as there were very few dates where data was collected for both variables. This explains why values such as 0.99 were obtained for the centre V-notch flow rate against rainfall between 2022 and 2023, as there were only three dates with data for both variables during this period. This means the value obtained is much less reliable and this should be used with caution when interpreting behaviour.

It should be noted that the maximum combined flow of all three V-notches in the gallery was recorded at 10m^3/day in 2023 at top water level, whereas the certificate of efficient execution of works (LRC, 1995) mentions that seepage through the core was 290m^3/day in June 1983 and decreased to 140m^3/day in April 1987. The seepage flows through the core are therefore substantially less than they were.

Piezometers

The available hydraulic piezometer readings on the upstream and downstream of the core were reviewed, with any erroneous readings identified, corrected or removed. The revised data was analysed (with mean, 5% and 95% confidence intervals calculated) and values plotted against reservoir level in order to visualise the effectiveness of the grout curtain.

The plots indicate that the piezometers upstream of the core (within the foundation) had a strong response to changes in reservoir level, while downstream piezometers showed a much weaker response (at lower head levels). Both responses were very much expected and showed that the grout curtain and core are still effective (Figure 7). PCC was also calculated between piezometric level and reservoir level, which showed a much stronger correlation for piezometers upstream of the core as compared to the downstream piezometers.

Charts were also plotted for standpipe piezometer levels against reservoir level over time, however there was no clear visual response, likely due to the larger volume of flow required to register a change in standpipe piezometer levels.

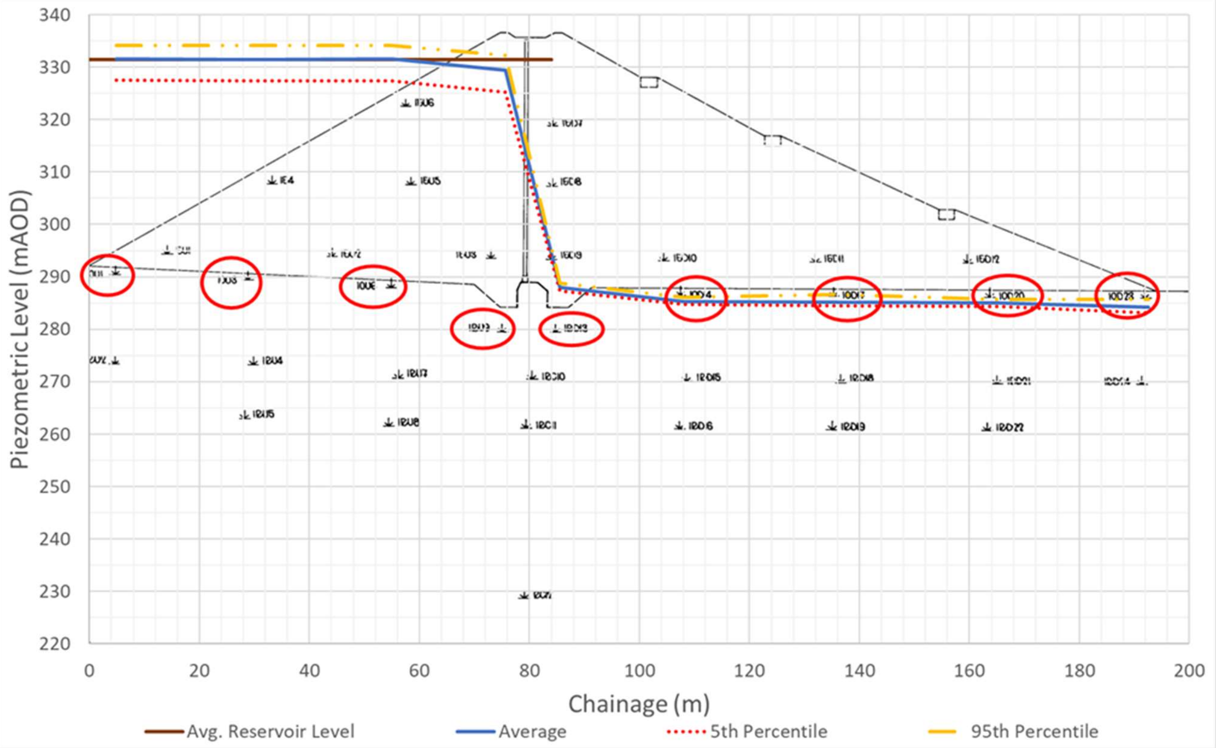

Figure 7. Mean, 5% and 95% confidence interval piezometric levels against average reservoir level through foundation piezometers

Movement monitoring

Plots were created for vertical movement of settlement stations at each elevation, to show the cumulative vertical movement of each point at different chainages from initial readings taken in 2010. Similarly, the cumulative horizontal movement of each station was plotted for movement in x-direction and y-direction as well as the vector sum. The plots showed no clear trend in either the cumulative vertical movement or horizontal movement of the points.

A previous report into the movement monitoring data (BRE, 2010) identified a gradual downward trend between 1982 and 2010. This, along with evidence that other dams with an asphaltic core behaved in a similar way (with the core settling vertically downwards and displacing horizontally downstream after construction) (Feng et al, 2020) led to a conclusion that the lack of an obvious ongoing trend is likely to be due to the current surveying techniques not having the levels of precision required to provide reliable results.

DISCUSSION

The petrographic analysis in combination with SEM and EDX determined the presence of quartz, calcite and precipitated calcite in the south and north-mid soil samples, with a high concentration of clay-grade particles consisting of manganese oxide in the north-mid sample. A review against construction records indicates that the reservoir basin was used as the borrow pit for the embankment shoulder material, and that the results of the analyses are consistent with the material used for construction of the embankment shoulders and transition zones.

The analysis also showed similar materials that would be expected based on concrete eroding adjacent to the core. However, if the eroded deposits were principally from the concrete (or from the core itself) the quantity of the material is such that it would be expected to lead to an increase in the seepage rates over time. The analysis of the monitoring data shows that the seepage rates against reservoir level are not worsening over time.

Organic compounds were found in chemical tests of the north soil sample, potentially indicating the presence of bitumen. However, the chemical and FTIR test results showed that the material was not bituminous or organic in nature. Given the above, it is therefore highly unlikely that the deposits are formed from eroding concrete adjacent to the core or from the core itself.

It is likely that the drainage material has come from a similar source to the aggregate used in the core or the reservoir basin, however the makeup of the material is not known as there are no construction records relating to this material. Given the age of the structure, it is likely that the drainage material is an open graded aggregate and therefore has no filtering effect on fines passing through the transition zone.

Considering the findings of the investigation and monitoring study, the following is a summary of the conclusions relating to the nature and likely origin of the channel deposits:

- It is highly unlikely that the material within the drainage channel originates from the bituminous core.
- It is highly unlikely that the material within the drainage channel originates from the concrete adjacent to the core.
- It is highly likely that the material within the drainage channel originates in whole or substantially from the transition zone.
- It is possible that the material within the drainage channel originates in part from the drainage material downstream of the bituminous core and situated between the transition material and the concrete gallery.

The completion of the investigation and monitoring study satisfied the aforementioned recommended safety measures, culminating in the issue of the relevant Interim Inspection Compliance Certificates (“IICC”) under the Act.

CONCLUDING REMARKS

The conclusions suggest that the material originates either wholly or substantially from the transition zone (and possibly in part from the drainage material). This suggests that the grading of the drainage material is such that it does not act as a filter and therefore, the current seepage is causing detachment of fines and their subsequent transportation from the transition zone into the drainage channels (the particle size distribution of samples taken from the drainage channel shows up to 95% of particles passing the 63µm sieve).

The scale of the dam structure is such that, if the hydraulic (seepage) conditions remain unchanged, the internal erosion and transportation of fines (and subsequent accumulation of deposits in the channel) should either remain steady or very gradually reduce with time.

Routine monitoring of flow rates across the v-notches in the drainage gallery will highlight any changes in seepage. Increased seepage rates may result in an increased rate of erosion of fine particles and possibly cause detachment and transportation of coarser particles. Given that the drainage material does not act as a filter, such internal erosion may over time lead to a small but meaningful local reduction in the volume of the transition zone (thereby reducing support of the bituminous core).

It is therefore important that, when making observations of any accumulation of deposits in the control gallery channel, attention is given to both the rate of accumulation and any noticeable change in the particle size distribution. There would be benefit in periodically collecting samples to confirm particle size distribution (sedimentation by pipette).

In addition, the need for clear interpretation of any collected monitoring data is vital to understand the behaviour of the dam. This includes analysing the data for any potential erroneous readings that may have arisen through human or instrument error. Interpretation using statistical analysis can be effective, however it is important to ensure that the various records are collected and recorded on the same days to allow for these statistical analyses to work effectively and that there are sufficient data points to allow for meaningful analysis.

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