Design and performance of Elvington balancing and settling lagoons

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SYNOPSIS. The three Elvington Balancing and Settling Reservoirs are each capable of storing 205,000 Ml. of water and were constructed in the period 1992 to 1995 to provide the owner, Yorkshire Water Services Limited, with security of supply to the major treatment works at the site. The reservoirs are of earth embankment construction with the material being won partly from excavation on the site and partly from adjacent borrow areas. A bentonite cement slurry wall was constructed as a cut-off through underlying sand and gravel layers, and the internal face of the lagoons were lined with an HDPE membrane. The total area of liner was around 95,000 m^2.

The reservoirs have been operational for around eight years and the paper will concentrate on the design aspects, in particular the bentonite cement cut-off and geomembrane. A brief description of the overall performance of the reservoirs to date will be given.

INTRODUCTION AND BACKGROUND

Elvington Water Treatment Works is owned by Yorkshire Water Services Limited and is located beside the River Derwent approximately 12km to the south east of York. The works was originally built for Sheffield Corporation in 1964 but are now one of the main source works for the Yorkshire Grid strategic transmission network which is capable of supplying customers throughout most of Yorkshire.

The primary source of water for the treatment works is the River Derwent although since 1996 water can also be brought to the site from the River Ouse at Moor Monkton approximately 20km away. The treatment works has a maximum hydraulic capacity of over 250Ml/day but the River Derwent abstraction license limits the normal average capacity to

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205Ml/day which is approximately one-sixth of the company's daily demand for water.

Due to the strategic importance of the works it was decided in the mid-1980's that the raw water supplies should be protected from short-term pollution of the river and that a storage facility should be constructed which would also have the added water quality advantage of allowing the settlement of solids to take place. The Babtie Group was appointed to design the works in 1990 which were then constructed by Edmund Nuttall Ltd between 1992 and 1995.

DESIGN

General

The site chosen for the reservoirs was on a relatively flat area of agricultural ground immediately adjacent to the existing Works. Three reservoirs, each of 205Ml capacity were required, such that they could be operated in series, with one being filled, one being maintained full for at least 24 hours to allow for quality testing and settlement to take place and one being drawn down into supply.

A number of alternative design options were studied including conventional reinforced concrete tanks, combinations of earthworks and structural solutions, and earth embankment structures using cut and fill techniques to make the best use of the material available on site.

Ground investigations indicated that the sequence of geological strata was generally consistent across the site and comprised:-

Topsoil ; Upper laminated clay; Upper sand and gravel; Clay till; Lower laminated clay; Lower sand gravel; Sandstone (bedrock)

The thickness of the upper sand and gravel layer varied, but in general was no more than 600mm. At some locations it was absent.

Piezometers installed at locations across the site indicated that there was artesian pressure in the upper sand and gravel which responded within a very short space of time to water level changes in the River Derwent, which ran along the eastern boundary of the site. Any design which involved excavation into or through this layer would, therefore, have to accommodate any flows from it or uplift pressures generated within it.

In view of concerns about the suitability of the upper laminated clay for earthwork operations, a trial embankment was constructed, about 30 metres long, 5 metres high, and with side slopes of 1 in 3. Instruments were installed to allow monitoring of the formation during and after construction.

The trial embankment confirmed that the material was capable of being transported and compacted without significant difficulties. Consolidation settlement of the foundation was also found to be fairly rapid, no doubt due to the near horizontal sand lenses within the laminated clay which allowed dissipation of pore pressure into the adjacent excavated area.

Based on the results of the investigation, the decision was taken to proceed on the basis of an earthworks solution with the reservoir basins being formed by excavating down into the clay till, with perimeter and division embankments being formed, founded on the upper laminated clay. A plan showing the general layout of the reservoirs is shown in Figure 1.

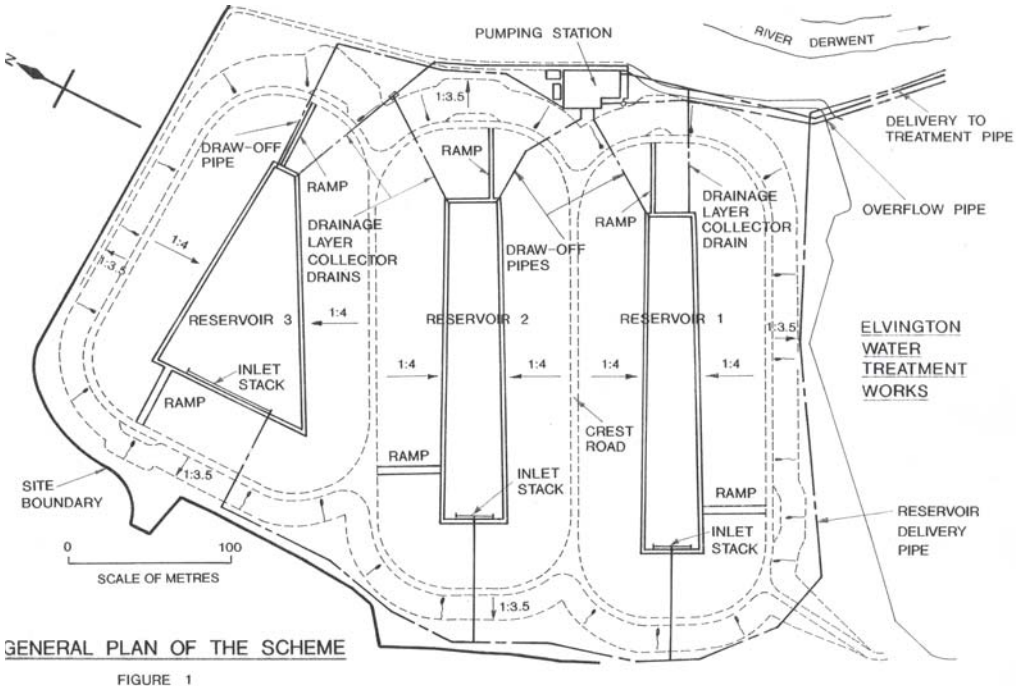

Figure 1: General plan

The decision to adopt an earthworks solution, together with Yorkshire Water's desire to have lagoons that could be cleaned internally led to the generalised lagoon cross-section shown in Figure 2.

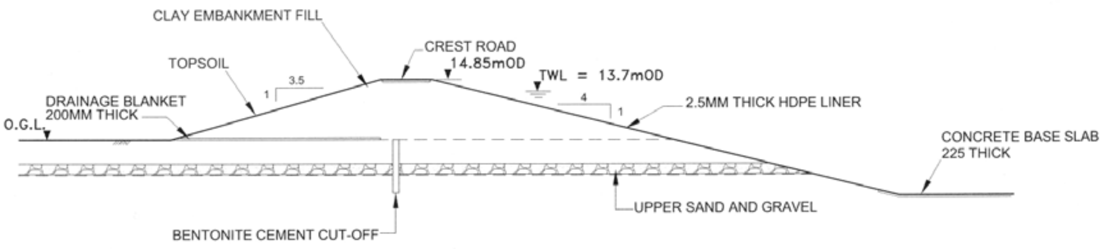

Figure 2: Typical cross-section

Embankments

To simplify construction and to make best use of site won material, it was decided that the embankment fill design parameters would be based on those of the poorest material to be excavated. This was the laminated clay, which had been found to be suitable for earthworking, provided weather conditions were reasonable. The embankments would be of homogeneous construction.

Table 1 summarises the design parameters used for the fill and for the foundation materials.

Table 1: Summary of Design Parameters

Material Type	**γ_b kN/m^2**	**Cu kN/m^2**	**C′ kN/m^2**	**Ø′ Deg.**	**u′**	**M/C %**
1.Embankment Fill	19.3	50	0	25	0.3	26.5
2.Upper laminated clay	19.3	80	0	25	0.3	27
3.Upper sand gravel	18	0	0	32	0.25	-
4.Clay till	21.9	100	0	29	0.25	14
5. Lower laminated clay	19.3	100	0	25	0.3	27
6. Lower sand and gravel (and weathered rock)	19	0	0	36	0.25	-
7. Bedrock sandstone (unweathered)	25	N/A	N/A	N/A	0.20	-

Table 2 summarises the design conditions considered and the corresponding factors of safety for the embankments.

Table 2: Summary of Design Conditions

Design Condition	Factor of Safety
1.Reservoir water level at 13.70m OD and liner undamaged	
Upstream slope	>4.63
2.Reservoir empty and liner acting as an impermeable barrier	
Upstream slope	1.46
3.Rapid drawdown, liner badly damaged	
Upstream slope	1.12
4.Reservoir full, liner badly damaged	
Downstream slope	1.39

A 200mm thick drainage blanket was installed at foundation level on the downstream shoulder of the embankments, just downstream of the cut-off. The effect of this has been ignored in design conditions, case 4, for the downstream slope, and the analysis can, therefore, be considered conservative.

While seismic effects were not considered in the original design, the situation was reviewed following the publication of “An Engineering Guide to Seismic Risk to Dams in the United Kingdom” (Ref. 1) and its associated application note (Ref. 2). The embankments fall into Category “II” of this guide and as there are no factors particularly vulnerable to damage by earthquake, a seismic analysis was not considered necessary.

Bentonite Cement Cut-off

A bentonite cement cut-off trench, 0.6m wide, was constructed below formation level of each embankment along the approximate line of the embankment crests of all three reservoirs. The purpose of the cut-off was to reduce seepage beneath the embankments and to isolate the foundation and underdrainage system from groundwater in the surrounding land as well as from neighbouring reservoirs. The cut-off, therefore, prevents the river charging the reservoir and closes a potential leakage path from the reservoirs. It also prevents the liner system being subjected to uplift pressure higher than the design values.

The base of the trench was generally the deeper of 1.5 metre below the top of the clay till and 4 metres below top soil strip level. The minimum depth of 4 metres was a requirement to ensure that local variations in the clay till level were catered for.

The design requirements of the bentonite cement hardened slurry were specified as:

- Permeability to be less than 10^{-8} metres/sec under water head of 12 metres at 28 days;
- A minimum strain of 5% without failure by cracking at 90 days;
- A minimum strength of $80kN/m^2$.

Reservoir Liner

The lining system to the reservoirs had to be capable of being cleaned on an intermittent basis to remove silt, etc. In addition, it had to be capable of dealing with uplift forces in the event that the bentonite cement cut-off failed to operate efficiently.

A number of options were considered for the liner including asphaltic concrete, geosynthetic liners, and reinforced concrete slabbing. As Yorkshire Water were keen to be able to run vehicles on the base of the lagoons for cleaning and maintenance purposes, the design adopted was a combination of reinforced concrete slabs in the base and high density polyethylene (HDPE) membrane on the side slopes.

Each reservoir has a reinforced 225mm thick concrete base slab which continues up the internal slope for 2 metres. The slabs were formed in-situ with C40/20 concrete. Pressure relief valves were cast into the bases to prevent unacceptable uplift pressures developing. The slabs were founded on a 250mm thick drainage layer on top of the clay till, connected to a pumped herringbone underdrainage system.

Around $95{,}000m^2$ of HDPE liner were required and its use in an exposed location such as at Elvington was most unusual. However, in this instance, it was chosen after careful consideration of a number of factors including its ability to accommodate differential settlement along the embankment fill and cut slopes, durability and cost. The cost benefit analysis undertaken for comparing alternative liners, assumed complete membrane replacement after 15 years, although manufacturers were prepared to guarantee the material for up to 25 years.

A 2.5mm thick HDPE membrane was specified. The liner was laid on top of a 200m thick drainage layer of granular material, connected to the base slab underdrainage system. Some of the key material parameters for the liner are given in Table 3.

Table 3: HDPE Liner Technical Data

Properties	**Units**
Density	0.94 g/cc min
Carbon Black %	2-3%
Tensile Properties:	
- Strength at Yield	16 Mpa/inch width
- Strength at Break	27 Mpa/inch width
- Elongation at Yield	13%
- Elongation at Break	700%
Tear Resistance	289 N
Puncture Resistance	578 N

To counteract uplift forces due to the design wind speed of 45 m/s, the liner was bolted onto concrete anchor beams which run down the internal slopes. At the base, an HDPE connection piece was cast into the concrete base slabs (Ref 3).

Overflow Provisions

The main overflow system for the reservoirs is within the wet well of the reservoir pumping station. Each reservoir has its own double sided weir, separated from adjacent weirs by concrete dividing walls. There are no valves on the pipelines between the reservoirs and the control structure. The water in the wet well rises with the reservoir level up to the weir level of 13.7m AOD. Any discharge over the weir goes into an overflow channel and then into a 1650mm diameter overflow pipe. The overflow pipe discharges into the River Derwent downstream of the supply abstraction point.

The inflow pumps have variable speed drives and will normally be operated at 205 Ml/d i.e. equivalent to the capacity of each lagoon. However, they can be stepped up to a maximum inflow of 324 Ml/d.

Shortly after reservoir construction was complete, it was decided by Yorkshire Water that a second supply source should be added to the system, from their Moor Monkton intake on the River Ouse. The result of this was to increase the normal service maximum inflow from the Derwent and Moor Monkton sources to 355Ml/d, with an absolute maximum of 474Ml/d.

Under the various inflow conditions, the freeboard to embankment crest over stillwater level is shown in Table 4.

Table 4: Reservoir Freeboard

Inflow (Ml/d)	Freeboard (min)
0	1.15m
205	0.62m
355	0.35m
474	0.24m

To provide additional security, high level overflow weirs were constructed between adjoining reservoirs as part of the Moor Monkton contract. Each weir is 7m long and discharges freely down the HDPE slope of the adjoining reservoir. These weirs are set at a level of 14.3m AOD, 600mm above normal top water level.

CONSTRUCTION

General

The contract for the lagoons was awarded to Edmund Nuttall Limited and work started on site in November 1992. The completion certificate for the works was issued in August 1995. The Final Certificate for the lagoons under the Reservoirs Act 1975 (Ref. 4) was issued on 13th June 2000.

Embankment Construction

The earth embankments were constructed over two seasons in 1993 and 1994. A method specification was included for compaction.

The material was generally excavated and placed using tractors and scraper boxes. The embankments were built up in layers 225mm thick. At the start of construction the placed material was compacted by 6 passes of a towed tamping roller but was subsequently reduced to 4 passes. The Contractor also elected to change to using a self-propelled CAT 815 wedge foot roller (dead weight 20 tonnes); the layer thickness remained the same.

Laboratory tests were carried out regularly on samples from the placed embankment fill. The results are given in Table 5. Results showed a surprisingly high, 23%, number of undrained shear strength results which were below the value assumed in the design. The majority of these low results were from areas where laminated clay had been placed and it was thought that the presence of laminations within the samples was causing premature failure under test and did not truly represent the behaviour of the mass fill. The material from each sample was mixed to eliminate these laminations, compacted and retested and results similar or better than the design assumptions for undrained shear strength were obtained.

Table 5: Summary of Earthwork Test Results

	Cu (kN/m^2)	**γ_b (Kg/m^3)**	**M/C (%)**	**γ_d (Kg/m^3)**
Mean	78	2015	21.1	1671
Maximum	221	2086	25.1	2014
Minimum	31	1953	6.0	1388

Bentonite Cement Cut-Off

The construction of the cut-off was sub-contracted to AMEC Civil Engineering. Although the design mix had to be approved by the Engineer it was the responsibility of the sub-contractor to design a slurry satisfying the specified requirements.

The design mix changed several times in the early stages of construction because the permeability design criteria were not being achieved. A second and sometimes third wall was constructed parallel to the first sections. The accepted cut-off was approximately 1950m long. Mix-specific characteristics are given in Table 6.

Table 6: Mix-specific Characteristics

Reference	**Mix Characteristics**
Blue	4.5% bentonite Oil Companies Materials Association grade (OCMA) 90 second mix Single Hany mixer
Orange	5.4% bentonite (OCMA) 180 second mix Single Hany mixer
Green	5.4% bentonite (OCMA) 300 second mix Double Hany mix
Pink	4.5% bentonite (OCMA) 300 second mix Double Hany mixer
Yellow	4.5% bentonite Civil Engineering (CE) Grade 300 second mix Double Hany mixer

Constituents common to all mixes were:

- 112kg of ordinary Portland cement to BS12
- 336kg of ground granulated blast surface slag to BS6699: 1986
- 2799 litres of potable mains water

The consistency of the slurry was checked daily for compliance with the specification using a Marsh cone and a mud density balance.

The following tests on the hardened slurry were carried out on a regular basis:

- Unconfined compressive strength to BS1377 Part 7 Test 7 with 2% strain rate at a minimum of 28 days
- Permeability in a triaxial cell to BS1377 Part 6 1990 Test 6 constant head test at approximately 28 days
- Consolidated drained triaxial compression test to BS1377 Part 8 Test 8 for 5% strain at 90 days

Tests carried out on the pink and yellow mixes indicated compliance with the specification. The other three mixes generally failed to meet specified requirements for permeability. The Contractor had used short hydration periods for the bentonite in the blue, orange and green mixes, whereas the final two mixes adopted a minimum 24 hour hydration period prior to mixing. Microscopic examination of the mixes indicated a "balling" effect in the first three mixes which it was felt was caused by a lack of hydration of the bentonite. In addition, the OCMA grade bentonite has a more angular grain shape than the CE grade, which made adequate hydration and mixing times even more important.

<u>HDPE Liner</u>
During the manufacture of the membrane, samples were taken and tested in accordance with ASTMD638. A quality control certificate was issued with the material. The liner was manufactured by the Gundle Lining Construction Corporation. Installation started in September 1994 and was completed in May 1995 with work being suspended between November 1994 and mid-March 1995.

Two types of welds were used on site (Ref. 3). Where panels overalapped, a hot shoe double fusion weld was formed, and where the liner attached to anchors, and elsewhere where the sheets did not overlap, extrusion welds were used. Destructive and non-destructive tests were carried out on both types of weld. The non-destructive tests consisted of air pressure testing the double fusion welds and spark testing the extrusion welds. The destructive tests were "peel" and "shear" tests. In addition to checking the integrity of the site welds, these tests were also used to check the welding equipment on a daily basis prior to it being used on site. A non-destructive test was carried out on every weld.

Instrumentation

Sensors to measure underdrainage flows and geotechnical instruments were installed to provide information throughout the service life of the reservoirs. The inflow into the chambers is measured by ultrasonic sensors upstream of v-notch weirs and the sensor values are relayed to the main control room. There are also level probes in the chambers which set off an alarm if the water level rises above a certain level.

Geotechnical instrumentation consisted of hydraulic, pneumatic and standpipe piezometers to measure pore and uplift pressures and vertical extensometers to monitor formation settlement

Survey pins were installed along the crest to allow the settlement of the embankment to be monitored. The spacing of the pins is generally 20m.

PERFORMANCE

General

One of the recommendations contained in the Final Certificate stated that annual performance assessment reports should be prepared to provide guidance on the significance of the behaviour of the reservoir, its foundations and the surrounding ground as revealed by instrumentation monitoring and visual inspections. Such reports have been prepared for Yorkshire Water Services by TEAM (an amalgamation of MWH and Arup) under the supervison of a Panel AR Engineer. In addition the reservoir was inspected under Section 10 of the Reservoirs Act 1975 for the first time in June 2002. These reports have all confirmed that the reservoir is behaving in a satisfactory manner.

Settlement

In general the settlement of the embankments has been minimal. However, soon after construction was complete, a depression appeared around the top of the magnetic extensometer on the main embankment of lagoon 1. This extensometer had also become blocked soon after installation. The depression covered an area of approximately 2 metres by 1 metre and had a maximum depth of approximately 0.2m causing cracking of the crest road surface and extending under the top of the liner. After a period of close observation it appeared that the settlement had ceased so the area was reinstated in 2000 and no movement has been observed since. The precise cause of the settlement is unknown but it was concluded that the depression must have been caused by local irregularities during installation of the extensometer.

Interior of the lagoons

The design brief for the lagoons stated that the sides and bases of the reservoirs should have smooth surfaces to facilitate the removal of accumulated sludge and other debris. However the geomembrane liner as constructed has a much folded and wrinkled appearance which has proved difficult to clean and detracts from the appearance of the structure. In addition a number of small splits in the HDPE liner have been found which have been easily repaired and have not caused any concern.

All three reservoirs have now been emptied for cleaning. Each time that a reservoir has been refilled after cleaning a rapid increase in underdrain flow has occurred. For example, Reservoir 1 has a normal base flow of less than 0.3 litres / min but after refilling in 1999 the flow suddenly increased to 3.5 litres / min before reducing to its previous value over a period of approximately 3 months. This action has been attributed to self-seating of the pressure-relief valves in the base slabs and the subsequent re-deposition of silt.

CONCLUSIONS

The lagoons at Elvington were innovative in their use of exposed HDPE liner on such a large scale. However, it was an economical material to use, easy to install, and has performed well in service.

The problems that were encountered with the bentonite cement cut-off highlighted the need for adequate hydration times for bentonite and also the differences between OCMA and CE grade materials. Despite this the cut-off appears to be performing well in minimising uplift pressures on the liner system.

The reservoirs are now forming an important element in Yorkshire Water's supply network and are giving increased security of supply to over 4.5 million customers. Long-term liner performance will remain an interest but with three lagoons, remedial or replacement work should be able to be carried out sequentially without a material effect on supply.

ACKNOWLEDGEMENTS
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