The design and construction of Banbury flood storage reservoir

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SYNOPSIS. The primary purpose of the Banbury flood alleviation scheme is to reduce the incidence and severity of fluvial flooding in the town of Banbury. This is achieved by storing part of each severe flood in the flood storage reservoir – which is located upstream of Banbury, largely within the natural floodplain of the River Cherwell – limiting flows passed downriver to an amount that does not cause unacceptable flooding in the town.

The principal elements of the scheme are:

- an 'on-line' flood storage reservoir, with a storage capacity of approximately 3 million cubic metres;
- the raising of an 860m long section of the A361 road that passes through the flood storage reservoir; and
- the construction of various in-town flood defence banks and walls and a pumping station.

This paper is concerned primarily with the design of the flood storage reservoir. It covers the flood hydrology of the catchment, the development of the overall design of the reservoir and the flood modelling which established how it will perform. It goes on to describe the detailed design of the reservoir, covering the embankment, foundations and structures, then finally describes the construction of the scheme, including temporary works, the embankment materials specifications and river realignments.

INTRODUCTION

The Banbury flood storage reservoir includes the following features, whose general locations are illustrated in Figure 1:

- an embankment of maximum height about 4.5m (average about 2.5m) and length 2.9km, running parallel to the north-eastern side of the M40 and alongside the eastern bank of the Oxford Canal;

- two identical reinforced concrete passive flow control structures, one at the intersection of the embankment with each branch of the River Cherwell;
- primary spillways incorporated into each of the flow control structures;
- an emergency spillway incorporated in the embankment between the two flow control structures; and
- various landscaping and ecological mitigation and enhancement features.

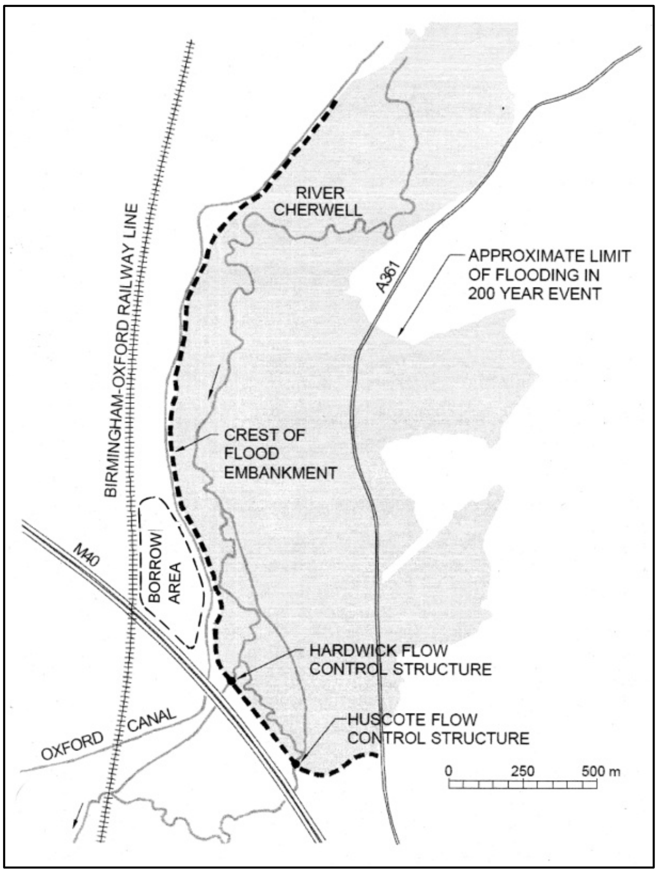

Figure 1. Main features of Banbury flood storage reservoir

The design of the passive flow control devices was described in a paper at the 2004 BDS conference (Ackers *et al*, 2004), which led to the adoption of similar devices for a flood storage scheme in Scotland (Gowans *et al*, 2010).

Following a Public Inquiry in May 2010 into the compulsory purchase orders required for the flood storage reservoir and associated works, the orders were confirmed in late 2010. Implementation of the scheme started in early 2011, with completion due in the spring of 2012. The scheme is levy-funded by Thames Regional Flood and Coastal Committee, with contributions from a number of the key beneficiaries.

HYDROLOGY

Banbury lies on the River Cherwell, a left-bank tributary of the River Thames, which the Cherwell joins in Oxford. The Cherwell has a catchment area of 204km² to the Banbury gauging station, of which about 170km² drains to the site of the flood storage reservoir. Two eastern tributaries of the Cherwell – County Ditch and Chacombe Brook, with a combined catchment of 11km² – join the Cherwell within the flood storage reservoir.

Historic flooding

Banbury has a long history of flooding. The most severe flood in recent decades was in April 1998, which gave rise to total flood damage exceeding £12.5M. Flooding in Banbury is the result of the River Cherwell and associated local watercourses having insufficient capacity to convey the runoff from the upstream catchment, and has been exacerbated by development being allowed to take place on the floodplain, obstructing the passage of floodwaters.

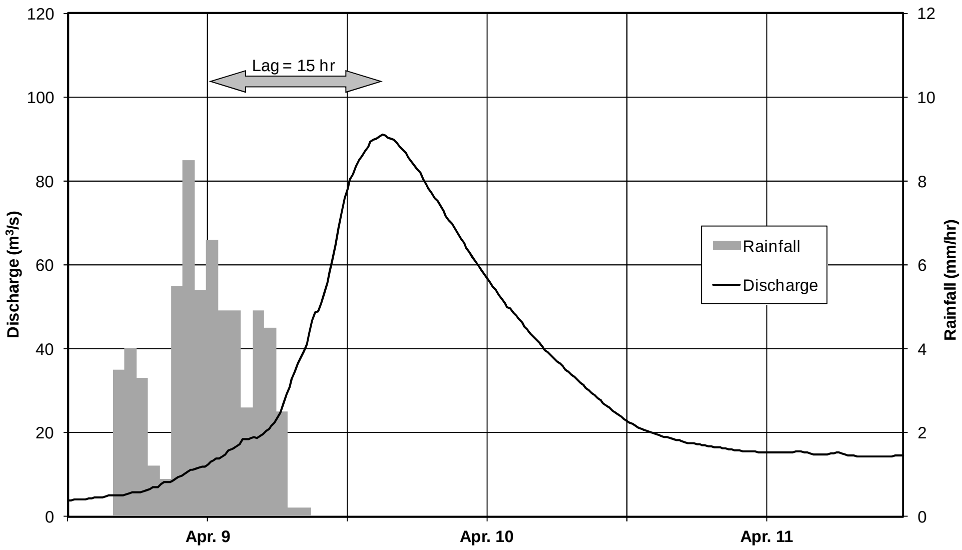

Figure 2. April 1998 hydrograph at Banbury gauging station and estimated catchment rainfall

Flood frequency analyses

Studies into the frequency of flooding at Banbury were based primarily on flood peak and flood volume data since 1964 at Banbury gauging station, supplemented by evidence gathered from newspaper reports and elsewhere regarding earlier severe floods on the Cherwell at Banbury, which occurred in October 1852, October and November 1875, May 1932 and March 1947. This evidence helped to set the April 1998 flood into its historic context and was instrumental in the conclusion that the 1998 flood had a return period of about 100 years (that is an annual exceedance probability of about 1%).

Climate change

The guidance about potential climate change impacts that was relevant to the design of the scheme was issued by Defra in 2006 and confirmed in a July 2009 Defra policy statement. The guidance envisaged two approaches to taking account of climate change in flood alleviation projects, namely:

- a managed approach, which allows for adaptation in the future; and
- a precautionary approach, in which the potential effects of climate change are accommodated within the project at the time of construction.

The Defra guidance stated that the managed approach was preferred in most cases for reasons including value for money. The precautionary approach was only to be preferred where future adaptation would be technically unfeasible or too complex to administer. The managed approach was therefore adopted, basing the predictions of the project performance and economics on the 'base hydrology', without any allowances for flow increases that may result from climate change. Defra also recommended that, when designing a new flood alleviation scheme, the sensitivity of the scheme to a 20% increase in peak flows be examined. This was done, and of course suggested additional future scheme benefits, due to a projected increase in the numbers of floods for which the scheme provides alleviation.

OVERALL DESIGN AND OPERATION

Flood storage reservoir

The principal component of the scheme for the mitigation of flooding in Banbury is an upstream 'on-line' flood storage reservoir, created largely within the natural floodplain of the River Cherwell. The primary considerations dictating the choice of the flood storage site (Figure 1) were:

- the need to locate the storage as near to Banbury as practicable, so that most of the catchment runoff is capable of being 'captured';
- the avoidance of land that is already developed, requiring people or businesses to be relocated; and
- the need to provide about 3 million cubic metres of storage in order to control flood flows passed downriver to the requisite limit.

As a result, the site search was quickly refined to the river reach between the village of Cropredy and the M40 crossing of the valley; that is between about 2km and 6km north of the town centre. The primary constraints within this reach were:

- the Oxford Canal running along the west side of the valley;
- the A361 running along the east side of the valley, partly within the natural floodplain;
- the village of Cropredy, which must not be influenced by the maximum 'backwater' resulting from the impoundment; and

- farm and other buildings within or close to the storage reservoir.

Flow control structures

The Hardwick and Huscote flow control structures (Figures 1 and 3) are identical. Each structure consists of three sections, which taken in the direction of flow are:

- the passive flow control devices;
- a trough section, which gradually widens, whose sidewalls form the primary spillways, when the reservoir storage is full; and
- a bridge and abutments section, which forms an opening through the flood embankment.

Figure 3. Huscote flow control structure, looking upstream

The Environment Agency was keen that the control of discharges passed downriver from the flood storage reservoir should occur automatically, with no requirement for attendance by their operatives during floods. It was also considered desirable to place no reliance on power supplies or remote operation of the flow control structure. If practicable, a structure with no moving parts was therefore preferred. These objectives led to consideration of the design concepts embodied in the baffle distributor devices that have been used for many years in irrigation systems.

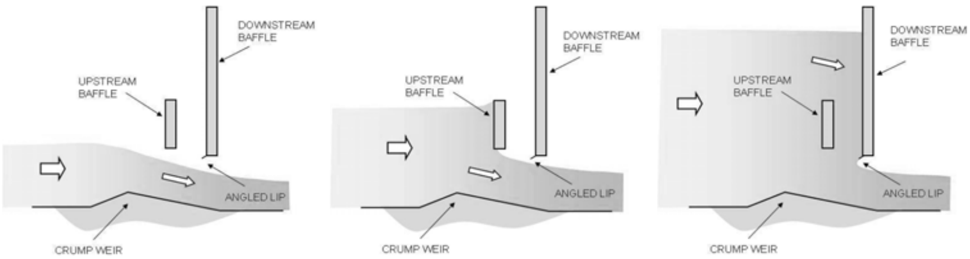

Figure 4. Three flow modes for the Banbury double-baffle orifice device

Performance information on these devices – which are designed to achieve a nearly fixed discharge out of a parent irrigation canal over a range of operating levels – is given in several references. Two forms of the device are described, one comprising a single baffle and the other a double baffle, with the latter selected for physical model testing and development for the Banbury scheme (Ackers *et al*, 2004). Figure 4 shows the three flow modes for the adopted design.

Each of the two flow control structures incorporates twin 30m long primary spillways, which are arranged in the form of sideweirs over the walls on either side of a reinforced concrete trough (Figure 3), within which the requisite energy dissipation can take place before the flow continues downriver. Figure 5 gives the stage-discharge relationship for each of the two flow control structures. The lower part, up to a head of 4.45m, comprises the throttled flows passing down river when the reservoir is impounding. When the storage is filled, at a head of 4.45m, the primary spillways are overtopped and the flows passed down river increase.

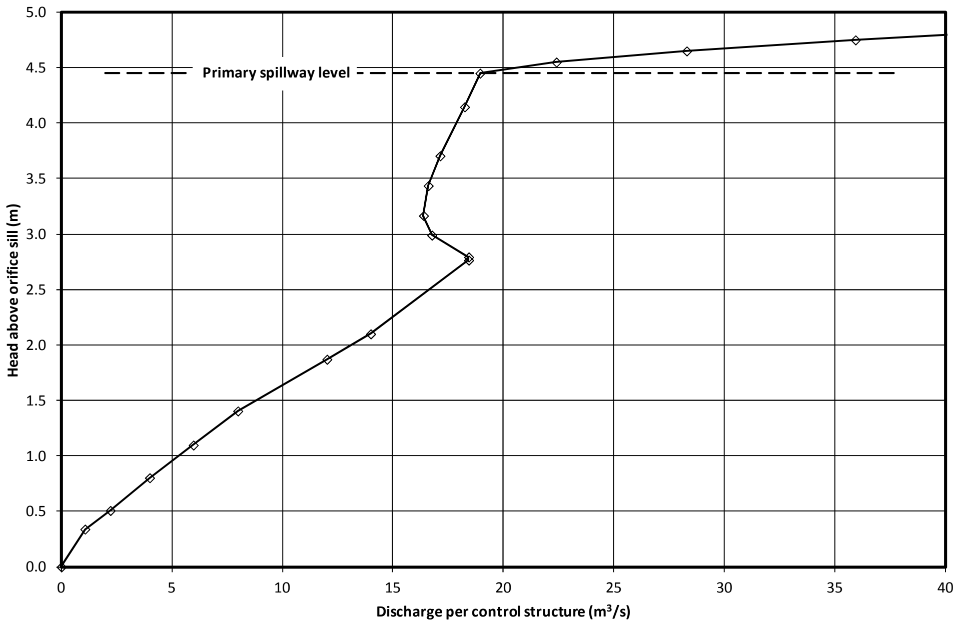

Figure 5. Combined orifice and primary spillway rating for each structure

It may be noted that the rating curve shows an almost uniform flow of about $18m^3/s$ per structure over a head range of about 2.5m to 4.5m above the crest of the sill. This range of heads takes in 90% of the available storage capacity in the reservoir.

<u>Emergency spillway</u>

The emergency spillway comprises a 267m long section of the embankment, located between the two flow control structures, that has a lower crest level than the rest of the 2.9km long embankment. Its initial crest level is 600mm higher than the crest of the primary spillways and, if the full design settlement occurs, it remains 400mm above the primary spillways. Because of the provision of primary spillways, the emergency spillway will operate only in extreme events, with a return period in excess of 500 years even after the occurrence of the full amount of settlement allowed for.

The primary spillways start to overtop in about the 150-year flood and have a combined discharge capacity (together with the orifice devices) of about 90m^3/s before the emergency spillway (at its post-consolidation crest level) is overtopped. It may also be noted that this combined discharge capacity is equivalent to that which would occur if a 100-year flood were to occur when the flood storage reservoir is already full.

One of the reasons for adopting the two-stage approach to spillway provision on this scheme is to ensure that, before the emergency spillway operates, the water level on its downstream side is high enough to limit the velocities that are reached by the accelerating flow passing down the downstream face of the embankment. This minimises the erosion risks – for the embankment itself and for the ground at its toe – and also means that there is no need to provide a stilling basin or other energy dissipation measures at the toe of the emergency spillway.

<u>Flood performance</u>

The scheme was developed on the basis of a target design flood event with a return period of 200 years, as that was found to be economically justified. The flood modelling undertaken to establish the performance of the scheme over a range of return periods (two to 1000 years) was based on:

- inflow hydrographs at the upstream limit of the impoundment such that the 100-year flood without the reservoir in place produced a close match to the April 1998 flood hydrograph at Banbury gauging station;
- larger and smaller flood inflows scaled according to growth factors derived from the flood frequency analyses;
- a digital terrain model of the extended floodplain forming the flood storage reservoir, based primarily on 2002 aerial photogrammetry;
- the stage-discharge ratings for the two flow control structures; and
- flood modelling using a linked 1D/2D ISIS/TUFLOW model.

Figure 6 provides a simple illustration how the scheme works for the 150-year flood. The dashed line represents the flow entering the flood storage reservoir and the continuous line shows the total flow leaving it through the twin control structures.

It was found that the flood storage reservoir would be filled to the crest level of the primary spillways in a 150-year flood, rising to about 0.2m higher in the 200-year flood, with a minor fall-off in flood protection between the 150-year and 200-year floods due to the additional flow passed over the spillways. Consideration was given to a minor rise in the spillway crests, which would cause a further rise in the peak flood level, but this was dismissed because of the increased flood risk that would be caused to adjoining properties.

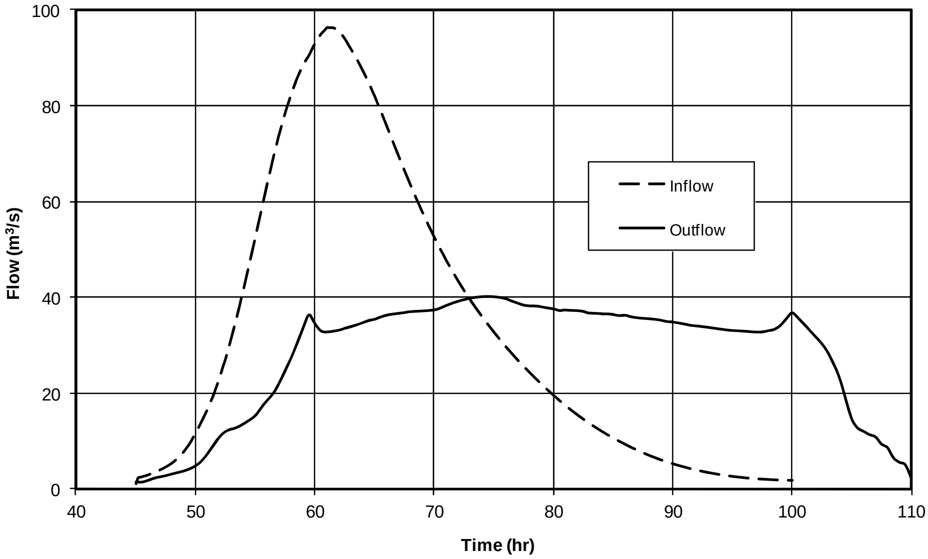

Figure 6. Flood routing through flood storage reservoir for 150-year flood

EMBANKMENT DESIGN

Geology

The solid geology beneath the site and its surroundings comprises a sequence of Lias rocks of Jurassic age which are predominantly over-consolidated clays with some shales and some thin limestone bands. The reservoir is underlain by Lower Lias clays typically about 100m thick. The surrounding hills, outside of the reservoir, are capped by Middle Lias clays that include some harder siltstone bands.

Superficial deposits are generally absent, with outcrops of the weak rocks at the surface. The Lower Lias outcrop is generally weathered to depths of 2m to 3m. Throughout the floodplain, the Lower Lias is typically overlain by highly variable river deposits comprising alluvial clays, silts, sands and gravels 1m to 5m thick. Lenses of organic clay up to 2m thick are present, resulting from changing channel locations within the floodplain. The gravels are usually at the base of the alluvium, resting on rockhead.

The alluvium was probably deposited in late glacial times by a river that conveyed much greater flows than the Cherwell does now. The gravel content is mainly flint and quartzite derived from glacial deposits. The soft alluvium is mainly formed by the infilling or silting up of abandoned river channels, and the highly organic layers represent local marsh development. The alluvium is weathered throughout. The clays are mottled in colour, generally brownish orange and grey, but have a uniform brown or reddish colour due to iron-enrichment in the desiccated layer.

Site investigations

Site investigations for the design of the flood storage reservoir used a staged approach, with desk study followed by intrusive investigations along the preferred embankment alignment and in the potential borrow areas for construction materials. Earlier investigations of the site in 2000, and report work done for the adjacent M40 motorway, were also referred to in compiling the site design information.

The flood storage reservoir site was initially investigated as part of a feasibility study. This work included 44 window samples taken to a maximum depth of 5.2m and four trial pits with eight piezometers installed. A limited amount of testing was done. For the design of the embankments and associated works, additional intrusive investigations were done. The main investigation comprised 29 boreholes, typically to depths of 10m to 13m, and 42 trial pits.

An additional investigation was done of the borrow area (Figure 1) in 2003, to assess the quality and quantity of material available. This investigation comprised 13 trial pits up to 5m deep. Several pits were abandoned due to the presence of hard mudstone or limestone. As the borrow area is close to the M40 motorway embankment and the Birmingham–Oxford railway line, the stability implications of excavating slopes for the borrow area were checked.

Foundations

Along much of its length the embankment is constructed on weak alluvial soils with only the topsoil removed. The exception is the left abutment where the foundation is formed by Lias clay. Along most of the length, the alluvium appears to rest directly on unweathered Lower Lias clay. Between ch1850 and ch2150 the alluvial clays are underlain by weathered Lower Lias which has a thickness of up to 2m.

The superficial deposits of alluvium are up to 5m thick, overlying the Lower Lias beneath the footprint of the embankment. Granular soils typically 0.5m to 2m in thickness are usually present at the base of the alluvium, immediately overlying rockhead.

A cutoff is provided through the alluvium in the form of a clay-filled key trench beneath the centre of the embankment. This cuts through any land drains that might be present and through fissured or permeable horizons within the alluvium.

Where areas of particularly weak foundations are present, the ground is improved by the use of a drainage blanket to enhance consolidation. The full drainage blanket extends under the bulk fill and under some sections of the landscape fill.

At Hardwick flow control structure, in order to avoid excessive differential settlement between the structures and the embankment, the alluvial material underneath the structure was removed and replaced with compacted clay. The transition between the embankment foundation and hard structures is graded at a maximum 1 on 2 slope to reduce the differential settlement between hard and soft structures.

Stability calculations and embankment zoning

The spillway and embankment crest levels are defined by the design criteria for flood defence levels. The basic embankment design is an earthfill embankment with side-slopes of 1 on 3, the crest a minimum of 3.5m wide to allow vehicular access, and a maximum height of 4.5m. There are two distinct embankment designs – one zoned earthfill and the other homogeneous – but there are a number of variants of the zoned design, depending on the ground conditions, whether it serves as the emergency spillway, and the type of crest road or access.

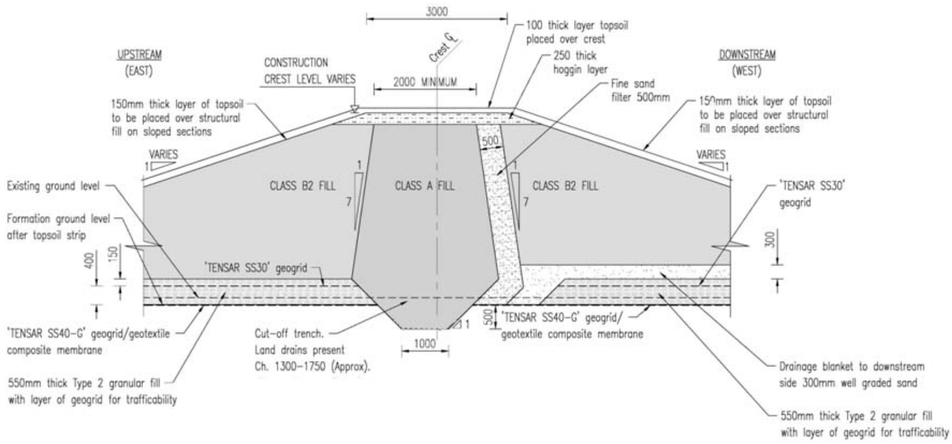

Figure 7. Zoned embankment

The zoned construction of the embankment consists of a clay core supported by bulk fill. The use of the central core zone and its thickness are determined by the limited available quantities of suitable clay material from local borrow pits and the limits imposed by the working width required for appropriate compaction plant. The core is therefore 2m wide at the top where it is narrowest. Batters to the core are 7 vertical to 1 horizontal and the core is supported by the bulk fill on either side. The clay core has a filter layer against its downstream face, connected to a drainage blanket beneath the downstream shoulder. A granular blanket was also used where the foundation was soft. This was reinforced with geo-grid so that it could be used as the haul road.

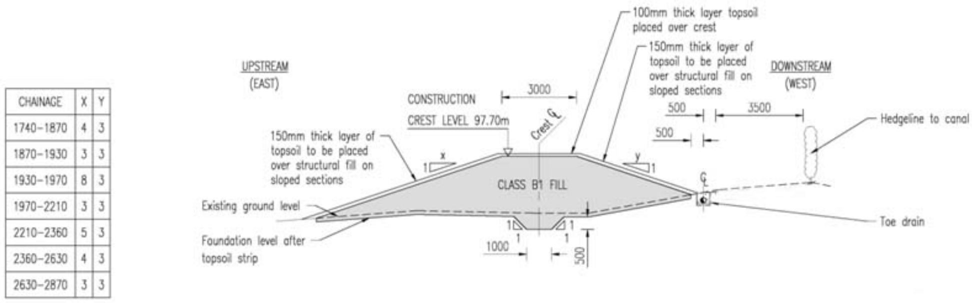

Figure 8. Homogeneous embankment

The section of embankment between the flow control structures, which includes the emergency spillway, has 1:3 side slopes. Elsewhere, however, the embankment slope varies for aesthetic reasons, becoming significantly flatter in many places and producing an undulating surface, through the addition of various amounts of ‘landscape fill’ to the bank shoulders.

The emergency spillway section of the embankment is 267m long and designed to pass the most extreme floods. To assist accommodate the difference in crest elevation between the emergency spillway and the adjacent embankment sections, the crest width is increased to 4.0m along the spillway section. The crest and downstream face of the emergency spillway section are protected by Armorflex cellular concrete blocks.

The embankment is constructed from material taken from a local borrow area, on the west side of the flood storage reservoir between the canal and the railway line (Figure 1). The material used for the embankment is Lias clay, with both Middle Lias and Upper Lias being present in the borrow area. The amount of material available in the borrow pit was estimated to be about 210,000m³, which is only marginally more than was needed to construct the embankment.

The amount of good quality clay suitable for rolled clay fill was limited and was planned to be sourced from weathered Lower Lias in the borrow area, which produces a more plastic uniform material suitable for compaction into an impermeable core. Other clay fill materials come from the Lower Lias and Middle Lias deposits in the borrow area. The alluvial materials and material found unsuitable for clay fill from the borrow area were used in landscape fill.

Table 1. Fill parameter

Soil type	Fill parameters		
	c_u	c'	φ'
Core	60	2	25
Bulk	60	2	25
Landscape	40	2	25

For the purposes of analysis, the soil parameters for the compacted Lower Lias were used as representing a conservative case for the core, bulk fill and homogeneous embankments (Table 1).

Table 2. Foundation soil parameters

Soil type	Foundation parameters		
	c_u	c'	φ'
Alluvial clay	17-48	0	30
Alluvial silt	10-25	0	30
Very high plasticity clay	17-48	0	26
Very high plasticity silt	10-25	0	25
Alluvial sand/gravel	0	0	32
Weathered Lower Lias	40-105	0	28
Lower Lias	80-209	0	30

Sands and gravels for use in filter layers and drainage layers were imported to site for construction, as no suitable materials were available on the site. Hoggin material for use on the embankment crest was originally planned to be imported, but limestone from the borrow pit was crushed on site and used instead.

The stability of the embankment cross section was analysed for a variety of load conditions likely to be experienced. The factor of safety against the formation of a slip circle that reduces the embankment height during a flood event is greater than 1.6. The factor of safety against the formation of a slip circle that reduces the embankment height during rapid drawdown of water within the flood storage area after flooding is greater than 1.4.

Settlement allowances

Ground investigations found weak and compressible alluvial deposits in the foundations that are likely to be subject to significant amounts of consolidation settlement. Back-analysis of settlement records for the M40 embankment, which was built with a 600mm thick drainage blanket at the base and a grid of wick drains at 1.3m spacing in the foundation soils, resulted in the following settlement parameters being estimated for the alluvial deposits:

$C_v = 1.51\text{m}^2/\text{yr}$; $m_v = 0.321\text{m}^2/\text{MN}$

The foundation settlement calculations for the flood storage reservoir embankment were undertaken using the coefficient of volume compressibility and Newark solution, adopting the above parameter values. No specific allowances were included for settlement of the underlying Lower Lias clay, or for consolidation of the embankment fill itself.

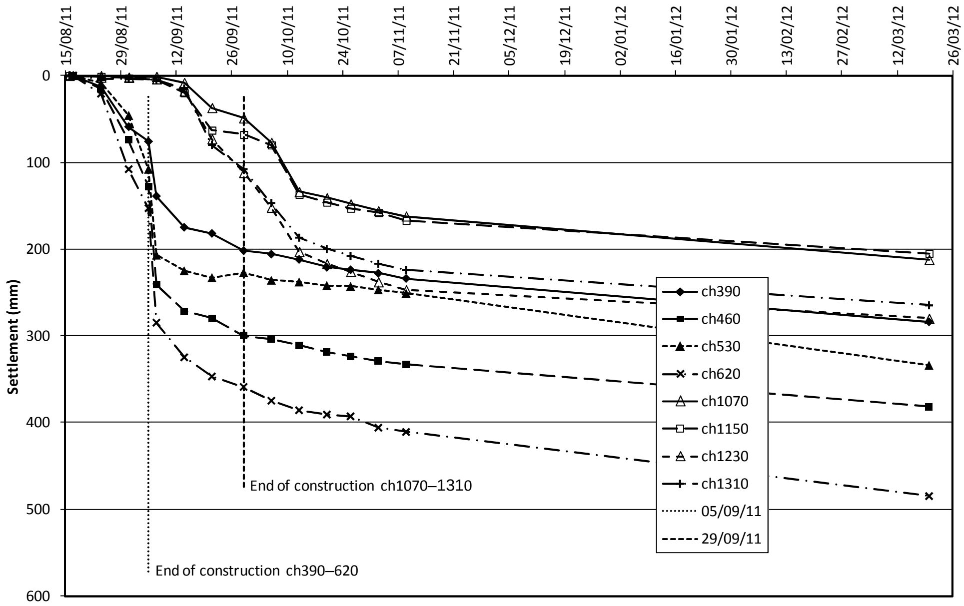

Figure 9. Foundation settlement in areas of soft foundation

Settlement allowances varied between 200mm, where there was no alluvium present, up to 450mm for chainages 1036–1370, where the foundation was particularly soft. In view of the large settlement estimates made for chainages 1036–1370, it was decided to introduce a 12-week waiting period after completion of the engineered embankment section and prior to the placing of the topsoil in this area. This waiting period was, however, eliminated during construction to remove a significant impact on the programme, and was replaced with an additional settlement allowance of 150mm. The 12-week waiting period was also applied to the section of embankment that includes the emergency spillway, in order to reduce its susceptibility to differential settlement occurring after the installation of the cellular concrete blockwork.

CONSTRUCTION

Programme

Construction commenced in March 2011, although vegetation clearance had been started earlier, prior to the bird-nesting season. With the long linear site, two river realignments and a borrow pit on the opposite side of the canal, access provision was key to timely progress. Initial activities focused on the construction of Huscote control structure, which could be constructed off the line of the river, and provision of access to the borrow pit.

Figure 10. Embankment, Hardwick control structure and borrow pit (09/11)

Access to the borrow pit for light vehicles was available by mid-May, enabling the contractor's soil investigation of the borrow pit for detailed material assessment to start. Topsoil stripping and initial ground works were also able to commence. Main embankment construction started in late June when it was possible to obtain material from the borrow pit. Trials of the two embankment types were carried out as part of early embankment construction to confirm the methodology and specification.

The contractor initially planned to provide access to the furthest end of the embankment and then construct the embankment working back. This was later modified due to access constraints at various locations such as river realignments. The upstream river realignment was completed in mid-July, which allowed access to construct the northernmost section of embankment.

Hardwick control structure construction commenced in late July after the river had been temporarily diverted along a realigned link channel upstream of the embankment. The river channels were reinstated through the structures in mid-October (Huscote) and early December (Hardwick).

The structural embankments were substantially completed in December 2011 – allowing the scheme to become operational and the first preliminary certificate under the Reservoirs Act 1975 to be issued – but the onset of wet weather meant that final completion of the finishing and landscaping works was delayed until the ground had dried out in the spring of 2012.

Borrow area and materials

The contractor's materials assessment of the borrow pit identified that there was adequate weathered clay for the core and homogeneous embankment, but it was stratified with silty clay (only suitable for the zoned shoulders of the embankment or landscaping) and with rock beds. It was also difficult to differentiate visually between the different weathered strata. However, trials identified that the unweathered Lower Lias, which insitu was a mudstone, was suitable – with the addition of water, working and compaction with the heavy plant being used – for use in the core and for the homogeneous embankment. This material was grey in colour compared to the orangey brown of the weathered clay. Minor modifications of the specification were made to accommodate the use of the unweathered clay, as it had a higher clay fraction than found in the weathered material.

The original site investigation and testing had indicated that the clay may need to be conditioned prior to placing, as its insitu moisture content might be above the optimal range. On site it was found that water generally needed to be added.

It was originally anticipated that hoggin used as a capillary break on top of the core would be imported. It was found that limestone blockstone found in the borrow pit, when crushed and graded, produced a suitable alternative. The blockstone was also used, as an alternative to gabions, for some of the river bank protection works, proving much easier to place insitu with water in the river.

Temporary works

Two Bailey bridges were installed to provide access across the two arms of the river. Access into the borrow pit was provided by strengthening the deck of an existing brick-arched canal bridge. This involved the installation of a separate reinforced concrete arch – which is being left in place on scheme completion – over the existing deck to enable access by heavy construction plant. This ensured that the scheme had no impact on canal traffic.

A shallow, normally dry, link channel historically connected the two arms of the river upstream of the M40. This channel, whose alignment coincided with the footprint of the embankment, was reinstated directly upstream of the embankment. It was widened and deepened to suit its utilisation as the river diversion during the construction of Hardwick control structure. This larger link channel has been retained for the finished works, but with environmental enhancements including the provision of gravel riffles.

The deep excavation for the foundations of the Hardwick control structure was protected by the provision of temporary sheet pile walls at each end of the excavation to exclude the river. Sump pumping of water ingress to the excavation was found to be adequate, as the alluvial gravel was found to be predominantly in a silty matrix.

Embankment

Old stream channels and very soft areas under the embankment were cleaned of very soft and organic material before being backfilled with compacted clay. After topsoil removal a vee trench was cut under the centre of the embankments using a purpose-built trenching bucket. The primary purpose of this was to ensure that all land drains had been severed. The trench was backfilled with clay in 150mm thick layers and compacted with a small sheepsfoot roller.

The core and shoulders were placed in 250mm finished thickness layers and compacted with a sheepsfoot roller. The chimney filter drain was installed by first placing up to 500mm of clay core and shoulder material, then excavating through the clay to expose the previously laid filter, then backfilling the trench with the filter sand, which was lightly rolled.

Control structures

The control structures at Huscote and Hardwick are identical. Huscote was constructed first, as it was close to the site compound and could be constructed off-line. It was also founded on Lias Clay. The main construction issue was the overhead 132kV EHV powerlines that traverse the inlet of the Huscote structure. Due to the nearby constraints of the river Cherwell on one side and a public footpath on the other side it was not possible to accommodate a crawler crane's minimum boom length and maintain a safe clearance from the overhead powerlines whilst lifting formwork. Instead a 40t tracked excavator that could work close to the structure, with its short boom and dipper arm, was used to lift the formwork. Elsewhere on the structures a 70t crawler crane was used to lift materials.

Hardwick control structure is located on the line of the main river channel in the floodplain. Prior to its construction the river was temporarily diverted through the realigned link channel and temporary sheet pile walls constructed at each end. The design required similar foundation characteristics for both structures, with the aim of achieving similar settlement. Options of insitu soil improvement by the addition of cement or removal and replacement by compacted clay were allowed in the specification. The contractor opted for removal and replacement. This proved a good choice, because groundwater was not found to be a major issue and less material needed to be removed than originally anticipated.

Environmental enhancements

The river was realigned in two locations as well as the link channel being relocated. These new channels were designed to replicate natural geomorphology, with enhancements such as the provision of gravel riffles and remnant ponds.

Wildflower mix is being used for the landscaped parts of the embankment. Landscaping works are being carried out, including extensive tree planting, hedgerows and wetland features. A country park is planned, with enhanced public access, encompassing the borrow pit area and the southern part of the embankment.

ACKNOWLEDGEMENTS
The authors would like to acknowledge the colleagues – too numerous to list here – whose contributions have led to the successful implementation of the Banbury flood alleviation scheme, of which the flood storage reservoir forms the principal component.

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