Engineering issues at flood detention reservoirs

A.J. BROWN, Jacobs, Leatherhead, UK
D. A. BRUGGEMANN, Jacobs, Leatherhead, UK,
J. D. GOSDEN, Jacobs, Croydon, UK

SYNOPSIS. The paper describes a number of engineering issues relating to flood detention reservoirs including structural problems with the embankment due to it normally being dry, design issues with hydraulic structures and use of transportation embankments to detain floods. The commentary highlights key differences between flood detention and water storage reservoirs, including discussion of where additional research or development is warranted to improve reservoir safety management.

INTRODUCTION

Flood detention reservoirs (FDR) in England and Wales now comprise a total of 170 reservoirs classified under the Reservoirs Act 1975, comprising some 9% of the stock of large reservoirs in England and Wales. They are also the most common form of new reservoirs with several built each year.

Historically design of flood alleviation schemes, including FDR, has been largely a separate discipline from engineering of water storage reservoirs, with guidance developed separately. Guidance for Flood Storage Works comprises Chapter 10 of the Fluvial Design Guide (Environment Agency, 2010) and earlier CIRIA Design of Flood Storage Reservoirs (Hall et al, 1993), although for geotechnical aspects reference is also made to CIRIA Report 161 (1996). Guides on design of large reservoirs are summarised in the Guide to the Reservoirs Act (ICE, 2000)

This paper explores some of the dam engineering issues which arise in engineering new FDR, contrasting FDR with water supply reservoirs, and where appropriate makes recommendations in order to stimulate debate on what constitutes good practice. It complements the papers presented at the British Dam Society (BDS) Seminars on FDR in London in April 2008 and in Manchester in November 2008, with presentations available on the BDS website and written up in the July issue of Dams and Reservoirs (Brown, 2008, Harding, 2008).

EMBANKMENTS – STRUCTURAL ISSUES

Watertight element

Historical practice for the watertight element of UK dams was a relatively narrow puddle clay core, constructed by addition of water to a local clay to provide an undrained shear strength as low as 10kPa (Johnston et al, 1999). This generally works well, as once the reservoir is filled most of the puddle clay is below reservoir level and therefore kept wet by seepage from the reservoir. Modern practice would be to provide a wider core using a local clay compacted by machine, but again seepage will maintain the clay in broadly the condition in which it was placed. In both cases a high plasticity clay would provide the ideal core, in having significant flexibility and being resistant to erosion if any cracks did develop.

FDR vary from this in that once placed they will remain dry most of the time, occasionally filling for short periods in extreme floods. On the one hand it can be argued that as the loading is transient and steady seepage through the body of the dam is unlikely to established, the watertight element can be to a lower specification. On the other hand it can be argued that a higher specification water tight element is required as

- the likelihood of undetected cracks being present is higher, and
- that loading is likely to occur when access for surveillance is difficult, such that if a structural problem developed it would be unlikely to be detected in time to allow action to be taken to avert failure
- structural loading of the dam by the reservoir is likely to occur relatively fast as the reservoir fills from empty in a few hours, such that any cracks do not have time to self heal by swelling

Table 1 compares the properties of CH and CL clays; it could be argued that the latter would be preferred for use in flood detention dams because of its reduced risk of desiccation, provided increased susceptibility to other factors can be accommodated.

Table 1. Comparison of characterises of high and low plasticity clays

Property	CH Clay	CL Clay	Source
Piping Resistance	Greatest	Intermediate	NAVFAC, 1986, Figure 1 pp 7.2-42 – 7.2-43
Cracking Resistance	High	Low	
Ease of working	7	3	NAVFAC, 1986, Table 2, 1 best 14 worst, pp 7.2-40
Permeability	10^{-9}m/s	10^{-7}m/s	Head, 1981
Seismic Susceptibility	Low	Intermediate	
Risk of dessication	High	Low	

Desiccation

Desiccation cracking occurs on the crest of unprotected embankments and flood banks, with an example in Figure 1. As the fill dries out it shrinks and negative pore pressures (suction) may develop. When the tensile force due to the suction exceeds the lateral confining pressure, vertical cracking or fissuring develop below the surface. Vertical and sub-vertical fissures tend to propagate downwards from the drying surface. A few horizontal cracks may propagate inwards from the initial vertical cracks and result in the separation of the upper desiccated layer from the layer below (Dyer et al, 2007).

Figure 1. Example of desiccation cracking on flood detention reservoir

The occurrence of such features is important to dam safety because transverse cracks create a zone for seepage through the crest and downstream face, and horizontal cracks can lead to lifting of individual blocks during impounding events (Dyer, 2005). This contributes to slope instability and breaching which occurred in the failure of the east coast flood embankments in 1953 (Cooling et al, 1954), and in 1994 in failures of Mississippi levees (Frith et al, 1997).

Guidance on management of the risk of desiccation in flood banks is given in the Earth Embankment Fissuring Manual (Frith et al, 1997), with more recent research in Dyer et al (2007) and mentioned in Section D of Morris et al (2005) in respect of maintenance of flood embankments. Options of measures to make good the effects of desiccation are presented as replacement of clay to the depth of fissuring (typically 1.2m to 1.5m); addition of a landward stability berm; replacement with hoggin; impermeable membrane; sheetpile cut-off wall; granular crest and geotextile. Measures in design of new works additionally include reducing placement moisture content, increasing freeboard and/or crest width. A suggested freeboard to allow for fissuring ranges from 300mm to 900mm, depending on the tendency to fissure and the site sensitivity (Table 5.1 of Frith et al, 1997).

In contrast current guidance for water storage dams does not comment on the management of desiccation in the crest of earth dams. It is of relevance to safety under extreme floods, when the reservoir level rises above normal levels. It is also important when considering options of how to increase the standard of the design flood at a dam. Using the existing wave freeboard to pass the larger flood increases the risk of failure along desiccation cracks. It is suggested that improved guidance is required for Panel Engineers in relation to management of desiccation cracking in dams.

Filters

Although filters are routinely provided in water storage reservoirs (ICOLD, 1994) current guidance for FDR (Fluvial Design Guide, Environment Agency, 2010, Sections 9.8, 10.5 and CIRIA, 1996) does not mention them. Filters are important in sealing cracks through embankments and their foundations and thus preventing internal erosion under hydraulic load. Although it is accepted that for FDR the duration of impounding may not be sufficient to establish steady state seepage, this does not apply to the foundation which is normally below groundwater level and thus as soon as a differential head is established seepage will be initiated. It is suggested embankment and foundation filters should be considered in the design of all new FDR, and as a retrofit during periodic safety reviews.

It is suggested that provision of filters to FDR should be determined following a site specific risk assessment, and that preliminary criteria for when a filter should be provided in FDR would be when any one, or more, of the following applied

- All FDR where the flood wave resulting from a breach is of such a depth and velocity that it is likely to lead to significant loss of life (say > 10 lives)
- Where the foundation is erodible and the gradient under design water level is greater than the critical gradient for piping (e.g. as defined in Figure 2 of Bridle et al, 2010; or USACE ETL-2-569, 2005)
- The clay used to form the embankment is dispersive, or likely to have desiccation cracks to below the design water level

The site specific review of incorporation of sand filters in high consequence small dams became standard practice in the US Soil Conservation Service in 1985 (Talbot et al, 1985).

CONTROL STRUCTURES

Conveyance through watertight element

Control structures at most FDR vary from those at water retaining dams in that they are along a watercourse with streamflows in channel, with the reservoir typically being dry and used for agriculture, or recreational uses. The hydraulic control is normally upstream of the core. As the conveyance through the core is therefore not under pressure, it is normal practice to have water flowing in the conveyance, rather than in a pipe within a culvert which would be the normal arrangement in water storage reservoirs.

There is often debate about the form and size of this conveyance where it passes through the watertight element of the dam. Where the dam is of modest height, say less than 4m above the flood plain, then good practice would be to provide a flume to minimize fragmentation of the aquatic environment and avoid culverting, which both contravene Environment Agency policy and the Water Framework Directive. In all cases it is good practice for the structural invert to be below hydraulic bed level, and to provide a gravel or other substrate in the invert of the conveyance, to encourage the continuity of habitat for fish and other aquatic life.

However, on higher FDR a culvert or pipe is unavoidable, and the debate is then the size that should be provided. Functional requirements are likely to include some or all of

a) a small pipe which just provides free surface discharge at the design flood

b) adequate access for long term maintenance, say 2m diameter culvert

c) capacity to pass flood during construction

Adoption of pipes increases difficulties of adequate compaction of fill around the pipe, maintenance of the river channel which flows along the base of the pipe and long term inspection (although the latter could be mitigated by CCTV survey). The disadvantages of a culvert include increasing construction cost, risk of differential settlement between the structure and adjacent fill and entry by vandals. The authors suggest that good practice would be to provide a minimum 1.5m high conveyance, to allow periodic inspection.

Internal erosion along outside of conveyance

One of the most common modes of failure of embankments retaining storage reservoirs is erosion along the interface between the concrete structure and adjacent fill. Although historically concrete collars were provided, it was realised some time ago on water storage reservoirs that the increased difficulties of compaction outweighed any benefits (De Mello Rankine lecture, 1977), with US practice at the Soil Conservation Service changing in 1985 (Talbot et al, 1985). Good practice therefore now comprises battering the sides of the structure at no steeper than 8V:1H, using sand filter collars (Fell et al, 2007, Figure 13) and providing adequate width for machine compaction of the backfill to the excavation. It is suggested that practice in FDR should follow good practice in water storage reservoirs.

Risk of blockage of outlets

A significant issue in the design of FDR is the risk of blockage of the operational outlet, which normally comprises some form of orifice, with typical sizes varying between 0.3m diameter and 2.0m diameter. It is now normal practice to provide a steel screen upstream of the control, which both acts as a security screen to prevent unauthorised access and prevent large debris blocking the outlet. The Environment Agency has a well developed Guide for Design of Trash Screens (2001), with the trash screen typically having an area of 10 to 30 times the area of the orifice. One of the modes of failure is complete blockage leading to structural overstressing of the screens, which then collapse, releasing the debris which then blocks the outlet. It is therefore a dam safety requirement to design the screens to not fail under full hydrostatic load when completely blocked.

A further measure that is often used on FDR to reduce the risk of blockage is to install coarse trash posts upstream of the intake to prevent large scale debris reaching the screens. This is similar to water storage reservoirs, with Wearing et al (2008) , reporting on model tests to optimise the spacing and plan layout of such posts. The structural design will depend on the size and velocity of floating timber in a major flood, and has some similarities to the design criteria for debris impact onto piers of highway bridges (Highways Agency, 1994).

Emergency drawdown capacity

An issue that often provokes debate in design of flood detention reservoirs is whether a second outlet structure should be provided, with possible reasons summarised in Table 2. Items 2 and 3 are largely peculiar to FDR and can be within the Intake structure, whilst Item 1 is also a common issue with water storage reservoirs and requires a separate structure. As for water storage dams it is suggested that the need for a second outlet would be determined following a site specific risk assessment.

Table 2 Possible reason to provide a second outlet in FDR

	Purpose of outlet	Comment
1	To increase rate of drawdown, so that reservoir can be emptied rapidly in an emergency	There are no nationally agreed criteria on what drawdown rate is required. The only published criteria are those by Hinks (2009)
2	To provide independent means of drawdown, in case the main orifice is blocked	It is unlikely that complete blockage would occur, such that the reservoir would drain down slowly.
3	To provide independent means of drawdown if trash screens are blocked	a) Risk of blockage could be reduced by adoption of coarse trash posts upstream of Intake structure. b) Where the screens extend up to dam crest level it should be relatively straightforward to remove the trash on a screen by screen basis and thus empty the reservoir c) Second outlet should be sufficiently separate to ensure not affected by trash screen blockage

TRANSPORTATION EMBANKMENTS

<u>Adaptation to form flood detention reservoirs</u>

In some cases a flood detention dam could be created by adding a throttle on the upstream end of the culvert under a transportation embankment. Careful attention needs to be paid to the possible need for structural works to the transportation embankment to ensure that the FDR is adequately safe, with potential failure modes and structural works including those in Table 3.

Table 3. Possible failure modes of transportation embankments used to detain flood water

	Failure mode	Possible structural works to mitigate
1	Piping in embankment	Clay lining to upstream face and/or filter blanket to downstream face
2	Piping along outside of culvert	Filter collar around downstream end of culvert
3	Structural collapse of culvert	Reline culvert
4	Scour at downstream end	Energy dissipation and/or armouring of bed
5	Overtopping	Reinforce downstream face; provide spillway

The authors are involved with a safety review of an example of this, termed Reservoir X, where a 19m high disused railway embankment, built of sand, which crosses a watercourse with a catchment of 3.5 km^2 has been converted by addition of a 7m high drop shaft upstream of the 1.2m brick diameter culvert. The culvert was relined with gunite spray which marginally reduced its diameter, but no other structural works were carried out. One of the concerns over the safety of the reservoir was that no spillway was provided in the original conversion. Checking estimates of PMF inflow using conservative application of current good practice, including a range of storm durations and including a frozen catchment confirmed that in all cases the storage volume upstream of the embankment was sufficient to store the PMF, such that no spillway was necessary, and this conclusion was accepted. However, it leaves a residual risk, that if practice for flood estimation varies in future, as knowledge and possible impact of climate change develops, it is possible that flood volumes may increase, leading to the need to retrofit a spillway over the disused railway embankment.

In a second case, termed Reservoir Y, the authors are designing a FDR formed from a 10m high disused railway embankment. Structural works carried out in this instance to ensure the safety of the FDR include

a) provision of a concrete reinforced grass spillway at one abutment to discharge extreme flows;

b) sheetpile cut-off through the embankment which comprises highly variable and generally permeable fill material;

c) removal of trees from the upper part of the embankment near the spillway, to reduce head loss on approach to the spillway crest (trees are left in place on the remainder of the embankment to minimise landscape changes);

d) replacement of the culvert (lining the existing 900mm diameter culvert was considered unsafe).

The authors are also involved at Reservoir Z in working with the designers of a new road bypass upstream of a town, to design this to also function as a FDR, by including a control structure on the watercourse and appropriate amendments to the road embankment.

Discontinuance as flood storage reservoir

A separate issue that arises with the use of transportation embankments as flood storage reservoirs, is what work is required if in future it was wished to discontinue them.

At Reservoir X there were over 13 badger sett entrances in the faces of the dam embankment, leading to concern over the risk of interconnected burrows providing a major leakage path through the dam. One of the options considered to mitigate this defect was discontinuance, and there was some debate over whether removing the throttle was sufficient, or whether the dam had to be breached, which would have had major landscape and ecological impacts.

There are similar issues for the risk posed by transportation embankments, which may incidentally temporarily hold more than 25,000m^3 during extreme floods and which is not normally considered by Highways Authorities. It is suggested that the following three tests should be applied to establish whether incidental temporary impounding constitutes a reservoir:

a) What volume is the transportation embankment designed to hold?

b) Is it “incapable of holding” more than 25,000m^3?

and a third test to assess whether incidentally impounded water poses a risk to life:

c) For extreme flood events with a low probability (<0.1%/ year as defined in PPS25 (DCLG, 2006)), is the risk of water, accidentally detained by the transportation embankment, causing failure of the embankment leading to release of the water as low as reasonably practicable?

For most transportation embankments the answer to ‘a’ will be nil, and the answer to ‘b’ that water will be accidentally detained by the abandoned railway embankment, but it is not designed to be held. Test ‘c’ is therefore the critical test.

For Reservoir X the response to test ‘c’ after removal of the hydrobrake and intake shaft was that the maximum flood depth in a flood with 1 in 1000 annual chance, after routing, would be 6 m. At this peak level, after steady state seepage had become established, the hydraulic gradient across the railway embankment would be 7%, which was considered reasonably low. To reduce this further would require removal of a section of the full height of the railway embankment, which would require temporary relocation of badgers and major impact on the landscape and was therefore considered disproportionate. It was therefore accepted that discontinuance could be achieved by simply removing the upstream intake shaft and returning the system to culvert control.

However, it is likely that there are some existing transportation embankments which would not pass this test, and could therefore be considered a risk to the public.

CONCLUSIONS

This paper has highlighted the differences and similarities in the engineering of flood detention reservoirs, and water storage reservoirs, commenting on where best practice on one type of dam should be applied to the other type, to reduce the overall risk of reservoirs to the community. Particular issues where improvements could be made in reservoir engineering include

a) more specific consideration of the risk of the type of clay used, and desiccation of the upper part of clay barriers

b) use of filters as crack stoppers on a more consistent basis

c) improvements in detailing of hydraulic structures

Transportation embankments are being used for economical development of flood detention reservoirs. Issues to be considered in assessing the need for structural works are discussed. The risk of accidental impounding behind transportation embankments has been noted, and the need for consideration of potential of dam break type failures due to the pressure of this floodwater.

REFERENCES

Brown AJ (2008) *Flood detention reservoirs: Geotechnical aspects of design and construction*. Dams and Reservoirs Vol 18(2) July, pp71-78.

Bridle, R, Fry JJ, Brown AJ (2010) *Internal Erosion at Existing Dams: an Outline of a Proposed ICOLD Bulletin*, in Managing Dams: Challenges In A Time of Change, Thomas Telford, London

Cooling L F and Marsland A (1954) *Soil Mechanics of Failures of the Sea Defence Banks of Essex and Kent*, ICE Conference on the North Se Floods of 31 January / 1 February 1953

CIRIA (1996) *Small embankment reservoirs*. Report 161. 447pp

DCLG (2006) *Planning Policy Statement 25 Development and Flood Risk.*

De Mello VFB. (1977) *Reflections on design decisions of practical significance to embankment dams*, 17th Rankine Lecture. Geotechnique 27 (3) pp 281-354

Dyer M, Utili S and Zielinski M (2007) *The Influence of Desiccation Fine Fissuring on the Stability of Flood Embankments*, FRMRC Research Report UR11

Dyer (2005) *Further tests on the fissuring of clay fill at the Thorngumbald flood embankment*, Proc. Int. Symposium on advanced experimental unsaturated soil mechanics, Trento, Italy, Taylor and Francis

Environment Agency (2001) *Trash screens Design and operations Manual*. R&D Contract W5A-01 (updated version in press)

Environment Agency (2010) *Fluvial Design Guide*. Available at http://evidence.environment-agency.gov.uk/FCERM/en/FluvialDesignGuide.aspx

Fell R, Wan CF, Foster MA (2007) *Assessment of the likelihood of erosion in embankment dams*. In Internal erosion of dams and their foundations – fell & Fry. Pub Taylor 7 Francis. Pp 71-102

Frith CW, Purcell AM and Powell AS (1997) *Earth embankment fissuring manual*. Environment Agency R&D Technical Report W41.

Hall, M J, Hockin D L and Ellis, J B (1993). Book 14: *Design of flood storage reservoirs.* Construction Industry Research and Information Association and Butterworth-Heinemann.

Head K H (1982) *Manual of soil laboratory testing. Volume 2: permeability, shear strength and compressibility tests*. Pub Pentech Press

Highways Agency (1994) *Design manual for Roads and Bridges. Volume 1 Section 3. Part 6. BA 59/94 – The Design of Highway Bridges for Hydraulic Action*

Hinks JL (2009) *Low level outlets 1: Formula for target capacity,* Dams and Reservoirs 19(1) March pp7-10

Harding (2008) *Maintenance of flood storage reservoirs,* Dams and Reservoirs Vol 18(2) July. Pp79-84

ICE (2000) *A Guide to the Reservoirs Act*. Thomas Telford, London.

ICOLD (1994) *Bulletin 95. Embankment dams granular filters and drains*.

Johnston TA, Millmore JP, Charles JA, Tedd P (1999) *An engineering guide to the safety of embankment dams in the United Kingdom*. BRE Report BRE171.

Morris M, Dyer M and Smith P (2007) *Management of Flood Embankments, A good practice review*, R & D Technical Report FD2411/TR1, Defra / Environment Agency

NAVFAC (1986) *Design manual DM 7.2 Foundations and Earth Structures*, https://portal.navfac.navy.mil/portal/page/portal/NAVFAC/NAVFAC_DOCS_PP

Talbot JR and Raslton DC (1985) *Earth dams Seepage Control, SCS Experience.* In Proc ASCE Goetch Conf Seepage and leakage from dams and impoundments. Conf. Denver, Colorado pp 64-55

US Army Corps of Engineers (2005) *Design Guidance for levee underseepage.* ETL 1110-2-569. 01 May 2005

Wearing MJ, Baker R and Carter I (2008) *A method of mitigating tree blockage to bridges on a spillway,* in Ensuring Reservoir Safety into the Future, pp 157-163, Thomas Telford, London