Ulley Reservoir and high velocity spillway flows

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SYNOPSIS. In the small hours of Tuesday 26 June, 2007 Rotherham Metropolitan Borough Council requested the evacuation of areas downstream of Ulley Dam and the closure of the M1 motorway because of fears about the safety of the dam. The danger arose because of the failure of the masonry walls of one of the original spillways at the dam during a flood with a return period of about 200 years.

This paper discusses the background to the incident, the problems associated with high velocity flows in masonry spillways, the handling of the emergency and plans for the restoration of the dam.

INTRODUCTION

Ulley reservoir is located about 5 km to the south-east of the town of Rotherham in Yorkshire. The dam, which is earthfill with a puddle clay core, was completed in 1873 and was originally used for water supply. In 1986 it was sold by the Yorkshire Water Authority to Rotherham Metropolitan Borough Council for £1 plus outstanding debts. Since then it has formed the centrepiece of the Council's Ulley Country Park.

92.4 mm of rain (measured at the Maltby raingauge) fell on 24 and 25 June, 2007. This caused flooding in the Borough, most notably at Catcliffe, and also led to significant spill from Ulley reservoir. At 19.00 on Monday, 25 June the Manager of the Country Park visited the dam and decided that there was a risk of erosion adjacent to the south bywash channel that might endanger the dam. The site was then visited the same evening by officials of the council and by the Supervising Engineer.

At 01.20 on Tuesday 26 June the Chief Executive of the council requested that areas downstream be evacuated and that the M1 motorway be closed in both directions downstream of the dam. The total number of people evacuated was about 1,000 although it is not possible to say exactly how many of these were evacuated as a result of the flooding already being experienced and how many were evacuated as a precaution against the possible failure of Ulley dam.

Responsibility for the enforcement of the Reservoirs Act, 1975 in England and Wales passed to the Environment Agency on 1 October 2004. Since then, their Reservoir Safety Section based in Exeter, have been active in promoting various initiatives aimed at improving reservoir safety. One of these is their Post-Incident reporting system for UK dams which has been developed on their behalf by Halcrow Group Limited. The final report setting up the system was submitted in February, 2007.

Under the relatively new Post-Incident reporting system the Environment Agency requested Jonathan Hinks and Peter Mason to prepare a review report on the Ulley incident with the objective of ensuring that any appropriate lessons were learned by those responsible for reservoir safety in the UK. This report, which was submitted in November 2007, did not cover future actions to be taken to ensure the safety of the reservoir. These matters were addressed in a report under Section 10 of the Reservoirs Act prepared by Mr.J.Claydon (Independent All Reservoirs Panel Engineer engaged by Ove Arup & Partners Ltd. as a sub-consultant).

Figure 1 - Works in progress filling scour hole

BACKGROUND

Ulley dam has a puddle clay core, a crest length of 205 m and a maximum height of 16 m. It impounds a reservoir with a capacity of 580,000 m^3.

The catchment area to the north-east, east and southeast is 11.86 km^2. The reservoir has a surface area of 0.12 km^2.

The dam is located on sandstones of the Middle Coal Measures of the Upper Carboniferous period. Mine workings are known to have taken place in the area in at least eight seams. During the twentieth century mining within the area of influence of the reservoir is known to have taken place as follows:

Barnsley Seam in 1927 at a depth of 434 m
High Hazel Seam in 1953 at a depth of 357m
Thorncliffe Seam in 1964 at a depth of 677 m
Wathwood seam in 1967 at a depth of 300 m

In each of the above seams an area of coal is said to have been left unworked to protect the dam from the worst effects of subsidence, although the design of such pillars may not in all cases have been based on present day understanding of the real effects of mining subsidence.

In addition to the above an unspecified seam was mined in 1935. A proposal to purchase a pillar in this seam was turned down by Rotherham Council who preferred to let the dam settle before building the new spillway in 1943.

There was damage to the scour tunnel and pipe in 1968 which may possibly have been associated with mining in the Wathwood Seam the previous year. However this is not certain since a pillar is believed to have been purchased in the Wathwood Seam.

As originally constructed the dam had narrow spillways down both mitres with masonry retaining walls on either side. These narrow spillways take the form of cascades with a series of plunge pool type stilling basins to dissipate energy. In 1943 a new concrete spillway was constructed at the south end of the dam to discharge, via a chute, to a short stilling basin adjacent to the stream. It is remarkable that resources were allocated to the construction of a new spillway in the middle of the Second World War.

Figure 2 - Flow down 1943 spillway and original south spillway during the incident. Original south spillway is on extreme right of photograph.

The hydraulics at the south end of the dam are complicated with water entering two spillways at different levels, in one case round a sharp right-angled bend.

	2006 survey (m AOD)
Previous TWL (southern bywash)	51.75
Morthern Weir	53.56
1943 weir	52.98
Peak WL in 2007 flood	53.55

It will be seen from the above that the lowest of the three weirs was that at the top of the southern bywash channel and that the 1943 weir was 1.23 m higher. The Morthern (sic) weir was still higher and did not actually discharge any significant amount of water in the June 2007 flood.

Total outflow in the spillways during the incident is thought to have been about 10.1 m^3/sec (6.1 m^3/sec down the old masonry channel and 4.0 m^3/sec down the 1943 spillway). The table below suggests that the flood had a return period of about 200 years.

The following table is based on calculations by Jeremy Benn Associates of Skipton presented in their report of November 2006. Adjustments have, however, been made to the assumed discharge coefficients and the results related to the datum used for the 2006 survey.

Return Period (Years)	Peak Water Level (m AOD)	Peak Outflow (m3/sec)	Wave freeboard (m)
FEH 150 year	53.25	7.00	1.95
FEH 1,000 year	53.61	14.44	1.59
FSR 1,000 year	53.47	11.24	1.73
FSR 10,000 year	53.98	26.32	1.22
FEH PMF Summer	54.95	71.56	0.25
FEH PMF winter	54.69	57.99	0.51

The above figures show that the peak flow in the incident was only about 14 % of the PMF and 38 % of the 10,000 year outflow.

Figure 3 - Scour hole photographed on Tuesday 26 June, 2007

There is a low level outlet with its intake near the right abutment of the dam. The control for this is now at the downstream end of the tunnel. The capacity of the low level outlet is given as 18,000 m^3/day (0.21 m^3/sec) in the Prescribed Form of Record.

LESSONS LEARNED FROM THE INCIDENT

It would appear that the erosion of the downstream embankment shell was initiated by the collapse of the masonry chute running down the left mitre. Mechanisms proposed for this collapse have included:-

- high turbulence flows in the chute 'plucking out' the masonry blocks or pushing them out by water pressure from behind.

- overtopping of the chute walls eroding fill behind the walls as well as, perhaps, causing some backpressure on them.

Figure 4 - Turbulent Flow in Spillway channel

The chute in question was not simply stepped but comprised a series of separate plunge basins formed by low walls across the chute at each step. Not only was the hydraulic action in these basins extremely turbulent, as evidenced by photographs, but there would have been a mix of turbulent high pressure and low pressure zones, the former caused by flow impact from the basin above.

In conjunction with this the wall facing blocks were, in effect, open textured. That is to say although there were remnants of mortar pointing, the facing blocks did not seem well bedded in mortar. Furthermore these outer facing blocks were backed only by rubble mortar with no keying between the two parts. There would have been little to prevent individual blocks being removed by pressures from high turbulent zones feeding as back-pressure behind facing blocks in lower pressure zones.

Had the chute been sited across natural ground any collapse and erosion of adjacent soil would simply have been a matter of rebuilding. The incident was compounded in this case by the chute being sited at the toe of the embankment. It is also clear from photographs taken at the time that debris from the initial collapse caused enhanced turbulence on the chute and deflected flows in such a way as to further enhance embankment erosion.

Figure 5 - Local hydrodynamic stone removal. Note also general condition of wall.

Calculations carried out since the incident suggest that ‘skimming flow’ would have set in and that the peak flow velocity probably exceeded 8 m/sec. The high velocities and turbulent nature of the flow in the channel would appear to have been quite sufficient to generate internal pressures within the masonry sufficient for stones to be extracted. Near the upper end of the chute a number of carefully shaped rectangular stones were seen to have been plucked out of the wall. This was probably by high water pressure behind the stones although suction from in front may also have played a part.

The hydrodynamics of flows in stepped spillways are further discussed in the paper by Mason and Hinks in the March 2008 issue of Dams and Reservoirs

EMERGENCY RESPONSE

The response to the emergency at Ulley was impressive and illustrates a number of key lessons for reservoirs in general. Once the crisis was identified the Rotherham Metropolitan Borough Council (RMBC) Emergency Planning Procedures were invoked. The Council already had such procedures in place following the requirements of the 2004 Civil Contingencies Act and the duty of County Councils to establish Regional Resilience Forums.

Under the emergency procedures already existing, a Bronze (Operational) Command centre was established at Ulley reservoir. This comprised appropriate on-site expertise able to identify immediate needs and resource requirements, such as pumps, plant and ballast. These requirements were passed upwards to Silver (Tactical) Command.

Silver Command was sited at a local district police centre with the purpose of resourcing any requests from Bronze and arranging, for example, required plant and material to be taken to the affected site.

Gold (Strategic) Command sits above this and operates at county level, monitoring crises in different areas, adjudicating the relative seriousness of conflicting requirements and deciding strategically on orders of precedence in terms of response. For a number of reasons, the resources needed to mitigate the potential failure of Ulley reservoir were given precedence by Gold Command over other flooding elsewhere in Rotherham.

Figure 6 - Repaired scour hole after incident

RESERVOIR DRAW-DOWN CAPABILITY

It is not normally practicable retrospectively to provide permanent low-level outlet facilities capable of drawing down reservoir levels in the event of major flood events. In fact the draw-down facilities provided at Ulley had served to lower reservoir levels on previous occasions sufficiently to allow maintenance work to take place. Nevertheless, their sizing would appear to be rather low. Their capacity is quoted in the Prescribed Form of Record as being 18,000 m³ per day. Given the area of the reservoir this constitutes a draw-down rate at maximum reservoir level in the order of 150 mm per day, which is less than is desirable for a dam where human life is at risk (a figure of the order of 500 mm/day being desirable in our opinion).

The 2007 report under Section 10 of the Reservoirs Act recommended replacement of the scour pipe with a larger diameter pipe discharging to the channel downstream of the dam.

ACTIONS TAKEN SINCE INCIDENT

Within a very short time of the incident being declared the erosion hole in the downstream shoulder of the dam was filled with stone and the old south spillway was closed off temporarily with a loaded skip. Subsequently it was permanently closed off with a concrete wall. Water level in the reservoir was lowered using temporary pumps.

The Section 10 Inspection which had been called for by the Supervising Engineer made several recommendations in the Interests of Safety. These included, *inter alia*:

- Changing the Dam from Category C to Category A, a review of the flood hydrology and construction of spillway capacity to pass the PMF.
- A site investigation, which has shown that the core raising carried out in 1967 using plastic concrete was brittle and crumbling.
- Filling in the Morthern bywash channel with stone to support the toe of the embankment.
- Increasing the size of the draw-off pipework in the tunnel

Discontinuance of the reservoir was considered and rejected by the Undertaker and at the time of writing options for repair are being considered.

POSSIBLE RESEARCH ISSUES

The incident at Boltby in June 2005 and the Ulley incident both point to a need for research into the hydraulic conditions that can be withstood by masonry walls of various types. Superficially the masonry walls beside the southern bywash spillway at Ulley appeared to be in reasonable condition. However, events showed that they were unable to withstand the hydraulic conditions to which they were exposed.

Figure 7 - Damaged spillway at Boltby in 2005

Peak flow in the southern bywash spillway at Ulley has been estimated at 6.1 m^3/sec. The width of channel is given as 1.83 m so the discharge was 3.33 m^3/sec/m width. Obviously this was too high although the form of the spillway, comprising a series of stepped plunge pools, probably exacerbated the situation.

With UK dams averaging about 110 years in age there are very many masonry channel walls at UK dams which play a vital role in ensuring the stability of the structures. It is thought that the deployment of resources to study this problem, and provide advice to Inspecting Engineers, would be well justified.

CONCLUSIONS

The incident was most unfortunate and many people were severely inconvenienced including those evacuated from their homes and those delayed as a result of the 40 hour closure of the M1 motorway. However the situation was very well controlled by the prompt and efficient action of Rotherham MBC, the emergency services and J.N.Bentley Ltd. who were a framework contractor to Yorkshire Water. The threat to the security of the dam was posed by the collapse of the masonry spillway walls. This, in turn, was caused by high velocity 'skimming' flow down the old spillway whose sill was set 1.23 m lower than the sill of the more modern concrete spillway built in 1943.

Similar failures are known to have occurred at not less than nine other masonry spillways including Toddbrook in 1985 and Boltby in 2005. None of these have led to the failure of a dam but they highlight the risk particularly where the spillways run close to the toe of the dam. The authors of this paper believe that Inspecting Engineers should be made aware of the risks and that research should be promoted into possible failure mechanisms. There were two high pressure (37 bar) gas mains of 1.22 m diameter just downstream of Ulley Dam of which the last Inspecting Engineer was not aware. Such infrastructure should be identified and taken into account when assigning a category to a reservoir.

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