Leakage investigations at Lower Carno dam

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SYNOPSIS. Lower Carno reservoir is situated 3 km north of Ebbw Vale. The 27 m high dam, completed in 1911 to the designs of GF Deacon, has a central puddle clay core supported by shoulders of clay and stony material. The dam has had a history of leakage and a succession of remedial works has been carried out.

In January 2005 operations staff, who visit the reservoir on every working day, notified the supervising engineer of increased flows in the toe drains. After investigations to trace the source of the flows were unsuccessful and the rate of leakage increased rapidly, it was decided to empty the reservoir.

This paper describes the history of the reservoir, indicators of the leakage that were observed, the conclusions reached to date on the pathway of the leakage and the ground investigation being undertaken to confirm potential remedial options.

DESCRIPTION OF RESERVOIR

Introduction

The reservoir was completed in 1911 and is impounded by an earthfill embankment dam built across the headwaters of the River Ebbw. The capacity of the reservoir is 800,000 m^3 and the direct catchment area of the reservoir is 5.39 km^2. The catchment is generally moorland. The town of Ebbw Vale is a short distance downstream and the dam is Category A.

On 20^{th} January 2005 operations staff notified the supervising engineer of increased and turbid water flows in the toe drains. The previous inspecting engineer of the reservoir was consulted and it was decided to empty the reservoir. During further investigations more significant flows started to emerge from the area at the downstream toe of the dam. The flow was estimated to be 200 l/s with a significant (1%) silt content.

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IMPROVEMENTS IN RESERVOIRS

Black & Veatch were retained by Dwr Cymru (Welsh Water) to carry out a literature review and visual inspection of the dam to determine the potential cause of the leakage event. The study identified possible mechanisms for the leakage and recommended intrusive investigations to provide more information for establishing the leakage path and for the design of remedial works.

Dam details

The dam, which has a maximum height of 27 m and is 180 m long is formed by an earth embankment with a puddle clay core. The crest level is nominally 394.8 mODN. Figure 1 shows a typical section of the dam.

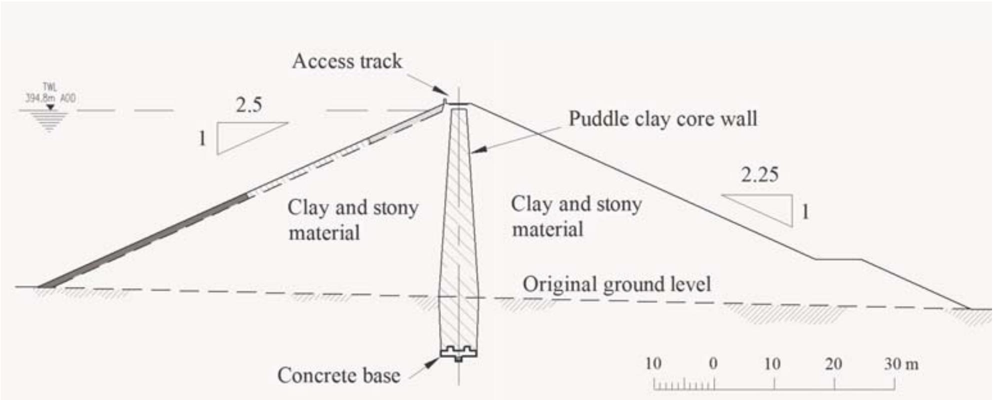

Figure 1. Typical cross section of Lower Carno Dam

The majority of the dam is founded on the Lower Coal Measures of the Westaphalian Sequence which consist mainly of mudstones and siltstones. Glacial Till overlies the Coal Measures but has been eroded away in the valley, which has alluvium along the river course. No faults underlie the reservoir basin or dam.

The puddle clay core is supported by shoulders of clay and stony material. The shoulder fill is of variable composition. Generally it is a heterogeneous firm sandy gravelly clay and mudstone/siltstone gravel with some cobbles. Zones of stonier material adjacent to the core are thought to be present.

There are no drainage blankets or filter zones in the dam but the River Ebbw was filled with a stone product along its course under the embankment.

The clay core is extended down into the foundation as a cut-off trench which has a concrete key at the base. The trench cut-off extends 78 m into the right abutment and 43 m into the left abutment.

The upstream face steepens from the bottom to the top and averages 1 in 2.5. The slope of the downstream face also increases from bottom to top and averages 1 in 2.25. The downstream slope is mainly grassed.

Instrumentation

The locations of all instrumentation on the dam are shown on Figure 2. These installations include 24 standpipe piezometers, toe drain flow measurement, 12 wave wall settlement measurement points, 8 crest settlement points and reservoir level measurement.

Figure 2. General arrangement of Lower Carno Dam

Draw-off arrangements

There is a concrete culvert under the upstream shoulder, with a reinforced concrete approach channel and a 'dry' concrete culvert under the downstream shoulder, the latter being sealed by a brick and concrete plug where it passes through the puddle clay core. The section of the culvert passing through the puddle clay core trench is supported on (and enclosed within) a concrete foundation cast into the base of the cut-off trench.

A 450 mm diameter scour main and a 300 mm diameter supply main were laid in the dry culvert, with control valves at the base of what was originally a dry shaft located just upstream of the puddle clay core. These valves were operated from the top of the shaft. This shaft has been filled with water to reservoir level since the outlet arrangements were modified in 1933, after serious leakage started to take place into the shaft. At that time the original supply outlet main was permanently sealed and a completely new draw-off system constructed through the hillside upstream of the right abutment of the dam. The original 450 mm scour pipe through the culvert remains in use.

HISTORY OF LEAKAGE PROBLEMS

There have been many modifications and remedial works undertaken, many to reduce rates of leakage. These are described below:

1911- On first filling in 1911 a flow of 9 l/s was observed leaking through the fissured rock and coal seams which form the left abutment of the dam. The designer decided not to attempt to seal these leakage paths unless the maximum leakage exceeded the statutory compensation flow of 10.8 l/s. Within 18 months the leakage rate had fallen to 2.5 l/s.

1915- A few years after the completion of construction in 1911, unsuccessful attempts were made to reduce the rate of leakage in the left abutment. The designer of the dam concluded that the rate of leakage, which was less than the specified compensation water, caused no threat to the integrity of the dam or the safety of the reservoir. It is not recorded what these remedial works included but injection grouting may have been used.

1933- Strong leakage from the upstream shoulder into the valve shaft via voids in the base of the tower was identified during a diver’s inspection. The voids had been formed by disintegration of the concrete in the side walls of the shaft. The diver also noted that significant outflows from the tower were visible. After prolonged attempts to locate the source of leakage and to seal the flow by grouting, it was decided to abandon the valve shaft. The new outlet works were constructed on the right side of the reservoir and the bottom of the old valve shaft was sealed with a concrete and brick plug.

1987- A small amount of leakage into the culvert 1.5 m downstream of the plug on the line of the puddle clay core was identified in 1985. This leakage was sealed by pressure grouting.

1996- A significant leakage emerged from a point about two-thirds of the way up the left abutment of the embankment in April 1996. The source of the water was traced to the underside of the new concrete section of the sloping spillway channel where water was seen to emerge from the stony backfill placed in this area, the soil matrix evidently having been washed away. It was also noted that about 250 mm of settlement of a small area of stone pitching laid on backfill immediately adjacent to the new overflow weir had occurred. The valve shaft was drained to determine that the issue of water was not caused by leakage out of the shaft and thus not through or under the body of the dam embankment. To prove conclusively that the flow was not linked to the valve shaft a tracer test was carried out. No dye was found in the leakage water. Additionally, the water level in the shaft was varied to determine any variation in the leakage flow. None was evident. Conductivity testing of the reservoir water and leakage water confirmed that it was the same water. The flow of water was estimated as 5 l/s. When the reservoir level had dropped to about 8.3 m below TWL the leakage ceased. Pressure relief holes were drilled at an inclination of 30^o to the horizontal through the spillway channel floor to release some of this water, and the remainder was piped down the lower part of the mitre to rejoin the original leakage water in a chamber near the downstream toe.

SUMMARY OF THE RECENT LEAKAGE EVENT

On 20th January 2005 site operatives informed the Supervising Engineer of increased and discoloured water flows in the toe drains. Investigations were carried out to locate the source of these flows, but without success. Contractors were employed to clean out the manholes and V-notch chambers but the source of water was not found. As a precaution, flow from Upper Carno was diverted past the reservoir using the adit and the scour was opened to lower the water level.

During the week ending 6th February 2005, two drains (one being the discharge from the 1996 installed V-notch and the other being an unidentified drain leading towards the right abutment) had lifted to the west of the stilling basin. Flows were seen discharging from this area (marked on Figure 2) over the ground and into the stilling basin. The previous inspecting, engineer was informed and, on a site visit on 8th February, instructed that the unidentified drain should be traced back towards the reservoir.

During the investigation more significant flows started to emerge from the area to the west of the stilling basin. A channel was cut to contain the flow. The flow was estimated to be approximately 200 l/s with a significant (1%) silt content. The rate of lowering of the reservoir level was increased and the leakage at the toe of the dam substantially stopped with the water level at 373 mODN, 20 m below top water level.

Instrumentation response

Prior to the discovery of the leakage, neither the boreholes in the left abutment nor the V-notch flow showed any abnormal behaviour. All of them have a damped response to reservoir level rather than to seasonal fluctuation in ground water levels. It is concluded that there is a small but not insignificant amount of leakage in the area of the left abutment. It is probable that this seepage is not connected to the severe leakage at the toe of the dam.

There was no visible crest settlement prior to drawing down the reservoir. Settlement occurred suddenly and quickly during the course of emptying the reservoir but this settlement is not associated with a rapid drawdown failure. The most recent settlement measurements indicate that the dam has settled by about 250 mm since 1990 at monitoring points E2 and WW5, as shown on Figure 3. Increased settlement is noted along nearly the whole length of the dam and is significant over a length of 70 m. The width of the settlement trough is as would be expected for ground loss at the depth of the culvert or base of the cut-off trench.

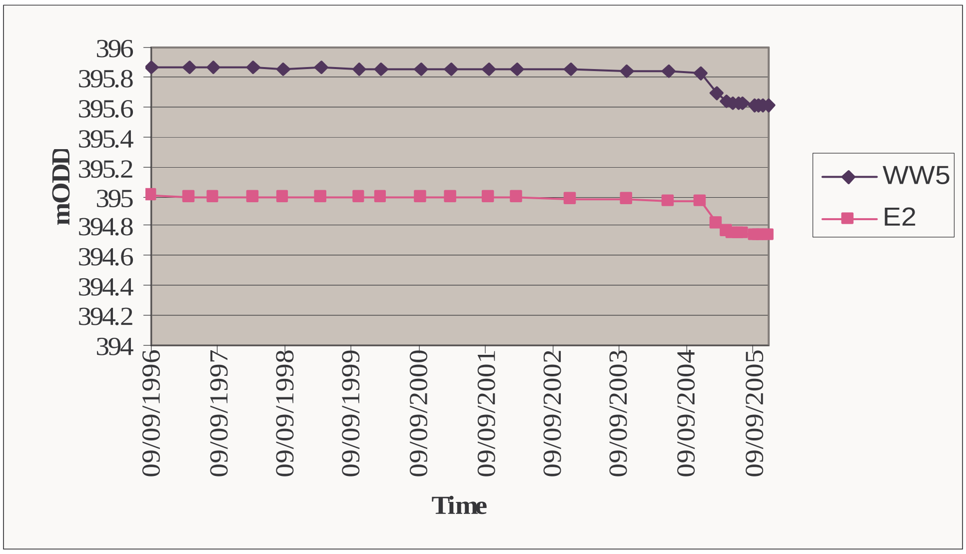

Figure 3. Settlement measuring points E2 and WW5 1996 to 2005

The crest pin monitoring records show that, during the period 1990 to 1996, crest pin E2 and wave wall pin WW5, both close to the line of the draw-off culvert, settled at an average rate of 5.3 mm and 5.8 mm a year respectively. Between 1996 and 2002, the average rates of settlement reduced to 3.1 mm and 2.4 mm a year. Inspection of the plots of crest level against time show that the readings taken in December 2002 suggest an increase in the rate of settlement. Subsequent readings show this trend continuing and the average rates of settlement between February 2002 and November 2004 were 6.2 mm and 8.0 mm a year for the crest and the wave wall. These represent a slight increase over the long term average. Adjacent pins show a similar pattern of settlement. The amount of annual reservoir draw down has not changed significantly and it is possible that this small change in settlement rate was an early indication of the leakage problem.

PRELIMINARY ENGINEERING ASSESSMENT

Lower Carno Reservoir has a long history of leakage events. From the initial filling of the reservoir through to the present day, significant seepage has occurred. However, it is not uncommon for old dams to experience a number of seepage events during their lifetime. This section reviews the likely cause of the leakage scenarios and anticipated future investigations required to determine necessary remedial repair. It is worth noting that mining related subsidence has been ruled out as no deep mining is catalogued in the vicinity of the reservoir.

Shallow mining related voids

Potential cause of leakage: Prior to 1901 a trial coal adit was excavated into the left abutment of the dam at a level of approximately 385 mOD just upstream of the core. The coal deposits outcrop upstream of the dam and seem relatively fissile. Additionally, the leakage through the left abutment does seem to cease once the reservoir level drops below 384 mOD. The recent leakage flow at the toe of the embankment did not significantly reduce until the reservoir water level was at 373 mOD. Thus the leakage through the left abutment is unlikely to be related to the flow path associated with the recent leakage incident.

Further investigation and remedial option: The investigation is designed to assess the need and lateral extent of any positive cut-off to minimise the flow through the left abutment to ensure that further problems do not arise in this area in the future. In the left abutment rotary coring and packer testing will be carried out to determine the presence of any significant leakage pathways in the abutment.

IMPROVEMENTS IN RESERVOIRS

Leakage through the concrete support to the culvert in the core trench

Potential cause of leakage: In September 1932 leakage into the culvert downstream of the core increased significantly. A diver was sent down into the valve shaft and reported strong leakage into the shaft from the upstream side and heavy seepage out of the shaft to the downstream side. The seepage was occurring through voids in the concrete sides of the shaft and existing culvert plug. In 1933 a grouting operation was carried out to reduce the flow into the culvert. Water samples taken in 1953 from within the culvert indicated that the sediment in water discharging to the culvert was practically completely soluble in acid, indicating that it was not a clay-based product. In 1987 a further grouting exercise was carried out to minimise inflow.

It is possible that the concrete below the culvert in the puddle clay core trench has also deteriorated with time resulting in a seepage path developing below the culvert. The seepage could possibly have entered the Alluvial Gravel downstream of the core or gravel filled former river course, eventually emerging at the embankment toe.

Further investigation and remedial option: The proposed investigation will include core sampling of the concrete surround to the culvert. Visual examination of the samples will allow the level of deterioration of the concrete to be determined. Additionally, packer testing will be carried out within the concrete via rotary drillholes to determine the permeability of the in-situ concrete. Where the concrete is found to have deteriorated significantly a grouting exercise from the surface and possibly from the culvert could be undertaken.

Leakage through the puddle clay core

Potential cause of leakage: The puddle clay core sits on the concrete surround to the culvert. The sides of the surround are quite steep, between 30-60º. Prior to remedial works in 1988, comprising enlargement of the upper part of the spillway, restoring the crest level of the dam and constructing a wave wall, it was noted that the crest of the dam had settled approximately 600 mm in the centre of the valley since construction. Where these relatively large settlements occur adjacent to a rigid inclusion, such as a concrete culvert or plinth, fracturing of the puddle clay core adjacent to or at the concrete interface may occur. This would result in the opening of a leakage path through the core. Hydraulic fracture may also have caused the initial leakage path but significant internal erosion has occurred since resulting in the crest settlement and milky discharge observed.

Further investigation and remedial option: Fully cased light cable tool percussion boreholes will be sunk from the crest of the dam through the core. Permeability tests will be carried out at close intervals to determine the presence of leakage paths or voids in the core. Additionally, near continuous undisturbed sampling will be carried out to allow visual examination of the puddle clay. It is also expected that the casing and/or boring tools will drop on locating voids and this will be noted by drillers and the consultant's geotechnical engineer supervising the investigations. Consolidation grouting may be required to fill voids in the shoulder fill and core. A positive cut-off trench could then be excavated through the puddle clay core over the length and depth of core affected by any fracturing.

PROPOSED GROUND INVESTIGATION

At the time of writing this paper, the ground investigation works are programmed to start April 2006. They are designed to determine which of the hypothesized scenarios, defined above, is the most likely cause of the recent leakage event. Between 10 and 15 light cable tool percussion boreholes will be sunk through the puddle clay core and 10 may then be extended by rotary means to allow the concrete culvert surround and dam foundation materials to be sampled and tested.

The upstream and downstream shoulder fill is more problematic to investigate. A section of the reinforced concrete wave wall will require removal to allow staging to be constructed over the upstream face. Additionally, inclined rotary holes may be drilled from the crest of the dam. The presence of a temporary operational 500 mm diameter raw water main on the downstream edge prohibits access onto any staged exploratory holes from the adjacent crest area over the downstream fill. However, a light cable tool percussion rig may be able to be winched up the slope. The extent of any grouting exercise would be determined as part of the grouting works.

The foundation is not thought to be a likely cause of the recent leakage event. However, to confirm that this is the case, rotary coring and packer testing of the foundation will be carried out to confirm the depth of any cut-off wall and confirm the absence of high permeability layers or zones.

CONCLUSION

In retrospect the evidence of the embankment crest settlement readings could infer that the leakage began before August 2002, although the actual changes were very small and there were no other indications of problems in the piezometer or drainage monitoring readings. The leakage accelerated in January 2005 apparently causing considerable internal erosion of the dam and wash-out of fines from the fill.

IMPROVEMENTS IN RESERVOIRS

The design of the dam comprising a central puddle clay core supported by shoulders of clay and stony material is typical of the Heads of the Valleys reservoirs and there was nothing different in the design of Lower Carno to suggest that it would be more vulnerable to leakage and internal erosion than other dams of the type. However, there is some evidence that stones picked from the core may have been placed close to the core rather than in the outer part of the shoulders as planned. It is not possible to determine whether this has contributed to the history of leakage problems. At present more weight is being given to the proximity of the leakage path to the outlet culvert.

The position of the resulting settlement trough which developed at the dam crest and the position of the emergence of the leakage suggests that the erosion was largely confined to the core and probably occurred close to the western side of the outlet culvert. The proposed ground investigations will determine whether a suitable remedial option can be designed to allow the reservoir to return to operation. Discontinuance of the reservoir has not been ruled out.

Once again the importance of regular, vigilant and effective surveillance and of prompt communication with those qualified and empowered to take appropriate and immediate action has been proven. Delay in detecting the leakage and taking immediate action could have resulted in a major disaster.