Remedial drainage to Laggan and Blackwater gravity dams

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SYNOPSIS. Alcan’s 48m high Laggan Dam and 26m high Blackwater Dam have both been reassessed for extreme floods and seismic loading, and stability at both was found to fall short of modern guidelines. In the case of Laggan Dam the critical load case was the PMF, which would overtop the substantial masonry walls of the spillway bridge. Blackwater Dam stability was found to be marginal under normal conditions and unsatisfactory under both extreme load cases because of its slender section and serious doubts that it could carry tensile stresses, particularly at the foundation contact. An assessment of alternatives found that remedial drainage provided the cheapest satisfactory solution at both dams. At Laggan Dam this involved drilling from the dam crest to intersect the gallery and from the gallery into the foundation. At Blackwater Dam, which has no gallery, the solution involves inclined holes from the downstream face to intersect the dam/foundation interface.

The paper sets out the studies, investigations and design of the remedial works, and implementation of the work at Laggan Dam. Implementation is still to take place at Blackwater.

ALUMINIUM IN THE SCOTTISH HIGHLANDS.

The British Aluminium Company was formed in 1894 with the aim of developing the new process of electrolytic reduction, which depends on the availability of cheaply produced electricity for the commercial production of aluminium. The company’s first hydroelectric power station was built at Foyers on Loch Ness in 1896. It produced 3MW of power and was capable of satisfying one tenth of the world demand for aluminium, which at that time stood at two thousand tons per annum; this compares with over 18 million tons today.

The Company expanded their facilities in the Highlands with an aluminium smelter in Kinlochleven in 1907 and Lochaber Smelter in Fort William in 1929. Both of these are powered by their own hydroelectric schemes with Kinlochleven generating 20MW and the Lochaber Scheme 65MW. These schemes were each massive engineering undertakings in their day with a combined catchment area of 940sq km.

The Foyers Smelter was closed in 1967, although the hydropower scheme was taken over and redeveloped by Scottish Hydro Electric. In 1981 the British Aluminium Company was taken over by Alcan. The smelter at Kinlochleven was closed in 2000. However its hydropower scheme was retained and refurbished to produce supplementary power for the Lochaber Smelter. Lochaber smelter and hydropower scheme are still in operation. It is impressive that the original hydropower developments have stood the test of time, both being largely still in operation in their original form.

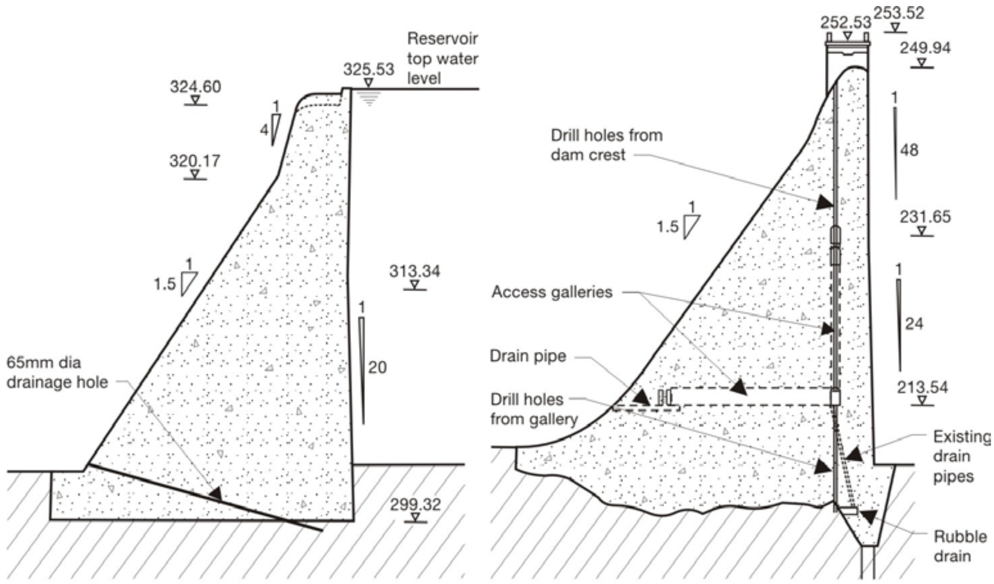

Figure 1 Sections of Blackwater and Laggan dams (not to scale)

BLACKWATER DAM

<u>Background</u>

Blackwater Dam impounds the main storage reservoir for the Kinlochleven Hydro Electric Scheme. The dam is situated some 70 miles north of Glasgow on the west side of Rannoch Moor. Access to the dam is via a 5 mile long rough track suitable only for small 4WD vehicles. The reservoir supplies water to the power station in Kinlochleven, 8km from the dam, via a covered free-flow channel and surface penstocks. Francis turbines and AC

generators were installed in the power station following the closure of the aluminium smelter in 2000, replacing the original 1908 DC Pelton units.
The 26 meters high concrete gravity dam was completed in 1909. It is 948 metres long and 503m of the crest, ie more than half the length of the dam, is overflow spillway at an elevation of 325m aOD. The dam section is shown on Figure 1. There is a central valve tower on the upstream face from which water is drawn-off through pipework in the base of the dam. The reservoir is 12 kilometres long and holds 111 million cubic metres at top Water Level. At the time of construction the reservoir was thought to be the largest in Europe. Reservoir levels often reach spill level during the winter months and are typically drawn down twelve to fifteen metres during the summer. The dam has been in continuous service since it's construction.

The dam is composed of a mass concrete matrix in which are embedded heavy granite displacers. Hearting concrete in the dam was a 1:5 mix with up to 50mm aggregate and a slightly richer 1:4 mix with 19mm aggregate used for the facings. Rock was quarried locally to the site but much of the sands and gravels were imported from a gravel bank in the tidal loch near Kinlochleven. The rock foundation was excellent with almost no fissures being found in the foundation area. The maximum depth of excavation to sound rock was only 4.6m. Cement mortar 50mm thick was laid on the rock foundation with a further 25mm thick layer placed prior to the placing of the concrete by derrick cranes. Large granite displacers weighing up to 10 tons were embedded in the concrete with many of them bridging the lift joints. Further details are given in the 1911 ICE construction paper [7].

The section of Blackwater dam is slender [Figure 1] and stability has always been recognized as marginal. The narrow section was commented on in the discussion following presentation of the construction paper in 1911 [7] in relation to other dams of the period. This appears, with hindsight, to be because uplift was not properly taken into account in the design. Moreover, at some time after this, the top water level was raised by about 0.9m by infilling the lower parts of the crest in the original stepped spillway.

The vertical cracks found in the dam shortly after completion were of great interest to the civil engineers of the time and may well have been influential in the inclusion of vertical contraction joints in subsequent dams. Interestingly a small water supply dam built shortly afterwards in the valley below has vertical joints. There were seven main cracks which opened up to 2.4mm wide. Water wept through the cracks and attempts to seal them using silicate solution and fine grout were largely unsuccessful. Subsequent treatment using peat introduced into the water on the upstream face of the dam were more successful. Practically no water was leaking through the dam by 1910, the cracks having apparently having been sealed either by sediments and peat in the water or by leached free lime from the cement. This built up as a hard white deposit on the downstream face dam and still builds up today, particularly below any small leaks and weeps.

The first inspections under the 1930 Act in 1933 and 1943 reported that the leakage through the contraction cracks was small, but stability was investigated in 1935, which included taking cores from the dam.

In 1963 the deterioration of the upstream side of the horizontal construction joints was considered to be a problem. Significant effort was put into sealing the upstream face of these joints and the vertical cracks by breaking out unsound mortar and concrete and refilling with mortar overlain with bitumen reinforced with a fiberglass mat. This significantly reduced the amount of leakage through the dam. Periodic maintenance of the upstream face sealing has been carried out since 1963.

In 1979 the stability of the dam was reassessed using information gathered from new core holes and piezometers, following which the frequency of inspections increased to five and then ten years. This work was recorded in an 1982 ICOLD paper [9].

Leakage readings are taken every two months from six fixed points downstream of the dam and also from the base of the draw off tower.
Foundation piezometers are read twice a year at high and low reservoir levels. In recent years some have tended to show a rising trend, and their condition has deteriorated, making readings less reliable. Tower plumb bobs are monitored annually. Movement stations are surveyed every four years.

Recent studies and investigations

Blackwater Reservoir lies above the town of Kinlochleven and is Category A to the standards in Floods and Reservoir Safety [2]. Following the 1993 periodic inspection, a hydrological assessment was carried out in 1995 [10] based on the Flood Studies Report [1]. This calculated a peak PMF outflow of 1043m^3/s, compared with the original design flood of about 377m^3/s. Calculated maximum flow depth over the 503m long spillway in its present configuration was 1.09m. This is within the height of the wave wall, although deficient in the recommended wave freeboard. A subsequent check has shown that the water level produced by a 1:10,000 year flood based on the Flood Estimation Handbook [5] is less than this.

A Flood Stability Assessment [11] of the dam was carried out in 1996 for the revised PMF design flood level. No provision for foundation or dam body drainage was included in the design, but uplift pressures are measured at the six piezometers installed in the 1970s. The gravity method stability analysis concluded that Blackwater Dam relies on tensile strength on the lift joints to provide the recommended factors of safety under both normal and PMF conditions. If tensile strength is ignored and cracks exist on lift joints in the upstream face, the factor of safety against overturning is about 1.15, as against a recommended value of 1.5 in the Engineering Guide to the Safety of Concrete and Masonry Dam Structures in the UK [4], and could drop to as low as 1.03 under PMF conditions. Both were considered unacceptably low. The main recommendations of the report were:

- that an investigation of the vertical tensile strength of the lift joints in the dam be carried out; and
- that the performance of the dam under seismic loading be included in the review.

These recommendations were reviewed and endorsed in 1997 in a Section 10 Inspection report, which also recommended that any unacceptable deficiency in stability should be remedied.

Historical research revealed that formation of the lift joints is described in the construction paper [7] as follows:
"Before concreting a new layer the surface of the old one below it was thoroughly cleansed, roughened, and covered with 1 inch of cement mortar, upon which, while still fresh and soft, the new concrete was deposited. This was done to ensure a sound and watertight seam between layers.
In this connection mention may be made of a particular characteristic of the rotary cement. A fine, brown scum formed on the surface of the concrete, and, if left, set hard with a skin like glass, this making it difficult to obtain a sound joint with the next layer. It became necessary, therefore, to destroy this skin by brushing the surface when partly set and thereby leaving it rough. Care was taken to have this done always."

The hearting of the dam was constructed incorporating large granite displacer blocks, weighing up to 10 tons. The extent of these is clear from the construction photographs [Figure 2]. Particular care was taken to include these across lift joints, and they have a significant influence on the tensile strength at the dam body. Inspection of the joints at the upstream and downstream faces, however, suggested that the concrete material in the joints is significantly weaker than the rest of the dam concrete [Figure 3].

Records of borehole investigations of the dam in 1935 and 1978 were examined, as were details of the 1978 investigation given in the 1979 Stability Report [8] and ICOLD paper [9]. However neither of these considered the tensile strength of the lift joints.

Figure 2 Displacer blocks on lift joints at Blackwater Dam

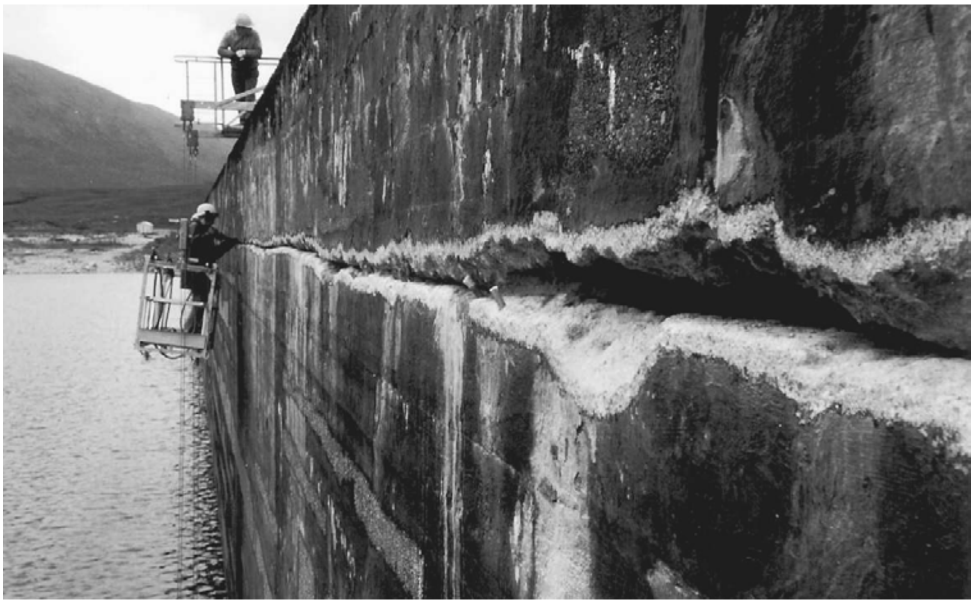

Figure 3 Raked-out joint in upstream face at Blackwater Dam

Alcan awarded a site investigation contract to Exploration Associates in July 1998 for drilling horizontal cores at joints and vertical cores through the dam and subsequent laboratory testing. Work commenced on site in August

1998 and was completed in October 1998. The factual report covering the drilling and testing was submitted in December 1998 [12]. Few of the lift joints were recovered intact and significant areas of honeycombing and poor joint bonding were found in the cores.

A further Stability Review [13] taking the collected data into account, concluded that, while concrete tensile strength could not be expected at lift joints, the rock displacers provided an acceptable degree of tensile strength across lift joints in the dam body. However unacceptable cracking could still occur at the dam foundation/rock interface. The cheapest option to remedy this was found to involve drilling inclined holes from the downstream face to intersect the foundation contact and so relieve uplift pressures.

An initial pseudostatic seismic analysis based on the UK Seismic Guide [3] had indicated tensile stresses at the dam heel likely to produce excessive cracking, leaving the post-seismic cracked section only marginally stable. However a lower 1:10,000 peak horizontal ground acceleration of 0.2g was derived from the Application Note to the Seismic Guide [6] and confirmed against site-specific seismic accelerations calculated for Scottish and Southern Energy dams in the area [15]. A more detailed 2-dimensional dynamic analysis using EAGD-SLIDE [14] subsequently demonstrated that, with the drainage works required for flood stability in place, direct seismic failure is most unlikely, although cracking may still occur, and that post-seismic stability is sufficient that any damage caused can be assessed and, if necessary, can safely be dealt with after the event.

Implementation

Design drawings and Tender documents for the recommended remedial drainage works at Blackwater Dam were prepared in 2003 and the works are planned for construction in 2004 and 2005.

LAGGAN DAM

Background

Laggan Dam impounds 40 million cubic meters for the Lochaber Hydro Electric Scheme. The dam is situated some 100 miles north of Glasgow at an elevation of 250m in Glen Spean, west of Spean Bridge. Access to the dam is via a short road immediately off the A86 trunk road. Now owned by British Alcan the reservoir supplies water via Loch Treig to the power station at the aluminium smelter in Fort William.

Completed in 1934, the dam is a conventional mass-concrete gravity dam some 48m high between general foundation and spillway crest level. It is slightly curved upstream in plan, but was designed as a purely gravity structure. The whole crest of the dam is a free-overflow spillway except for a central block housing siphons and gate control equipment. The spillway crest is broken into 29 bays by piers, supporting bridge arches. The upstream and downstream faces of the bridge consist of massive masonry wave walls. Six siphon pipes embedded in the dam concrete supplement the crest spillway discharge. The siphons make and break automatically at pre-set reservoir levels using a system of air valves.

The dam was built in 7 blocks with both copper strip and hot poured asphalt water stops in the joints. The bulk of the dam body is constructed of mass concrete with a nominal 15N/mm^2 characteristic design strength. However recent testing of cores from the dam has shown average strengths of 28.5N/mm^2, and a peak strength of 36N/mm^2. Higher strength concrete was used in the external faces. The dam concrete contains about 5% of granite displacers. The dam foundation rock is fresh or slightly weathered granite. After the dam was completed, gunite was applied to the upstream face to reduce leakage through any contraction cracks that appeared. The gunite was applied in two layers onto a wire mesh fixed to the face of the concrete.

The dam is generally in excellent condition with practically no leakage or signs of movement. The original gunite facing has not been a success and can be seen lifting away from the face of the dam at low reservoir levels. Until the remedial drainage works, completed in 2001, no works of any significance had been required on the dam since construction.

The total leakage from the foundation drains into the gallery is monitored. Leakages are small and increase with increasing reservoir level. The foundation drainage system is tested annually by forcing water by means of a packer into each drain pipe in turn and noting connections to adjacent pipes. This monitors the integrity and porosity of the rubble drain system.

Recent Studies and Investigations

Laggan Dam is situated upstream of Roy Bridge and Spean Bridge and is considered as Category A by the standards of Floods and Reservoir Safety [2]. Following the 1993 periodic inspection, a Flood Hydrology report [10] was prepared in 1995 using the Flood Studies Report [1]. This calculated the routed PMF outflow through the siphons and over the free spillway on the dam crest as 2073m^3/s with a corresponding flood rise of at least 3.07m. This compares with the original design flood of 396m^3/s and corresponding flood rise of 0.87m above spillway crest given in the 1937 construction paper [16]. This assumes that the spillway discharge is unrestricted. Taking the effect of the arches into account, the peak PMF outflow is restricted to 1620 m^3/s but the peak flood level rises to 4.09m above spillway crest level, or 0.54m above the top of the masonry wave wall on the dam crest bridge. A check has shown that the water level produced by a 1:10,000 year flood based on the Flood Estimation Handbook [5] is less than this.

Halcrow carried out a Flood Stability Assessment of the dam [17] in 1996 for the revised flood water level. The highest sections of Laggan Dam contain a foundation gallery and copper drain pipes are provided between the gallery and a rubble drain on the foundation at the back of the cut-off trench, but the dam body above the gallery is undrained, and drainage of the section below the gallery into the copper pipe drains is doubtful. The construction paper [16] reports that only 50% uplift pressure was allowed for in the original design of the dam. This was justified by the inclusion of the gunite layer.

The stability analysis concluded that the dam body stability relies on tensile strength at the lift joints to provide the recommended factors of safety under both normal and PMF conditions. Under normal conditions the dam structure requires a tensile strength of 0.3MPa at undrained lift joints to meet recommended factors of safety against tensile failure but would remain stable should cracking occur. Under the PMF the vertical strength at the lift joints to provide the recommended factor of safety of 2 against tensile cracking would need to be 0.7MPa. Should the upstream face fail in tension and a crack develop, the dam would become unstable against overturning under PMF conditions, although this assessment ignores the moderate arch shape of the dam. The main recommendations of the report were:

- that an investigation of the dam concrete and in particular of the vertical tensile strength of the lift joints in the dam be carried out; and
- that the performance of the dam under seismic loading also be reviewed.

These recommendations were endorsed in a Section 10 Reservoirs Act report in 1997, which also recommended that appropriate measures be taken to ensure adequate stability of the dam.

Alcan awarded a site investigation contract to Exploration Associates in July 1998 for drilling vertical cores from the dam and subsequent laboratory testing. The report was submitted in December 1998 [18]. Over 70% of the lift joints in the cores were found to be intact, and some of those broken were fresh, having been broken in the drilling process. Average tensile strength at intact joints tested was 0.7MPa.

A further Stability Review [19] was undertaken in 1999 using the data on the dam concrete from the drilling investigation. Higher than previously expected concrete density of 2450kg/m^3 improved the results, but not to an acceptable extent. Stability at PMF was acceptable in the upper third of the dam, at the drained foundation and where the section was drained by the gallery, but was unacceptable in the lower two thirds of the dam where the section was undrained. Pseudostatic seismic analysis showed that the seismic load case was less critical than the PMF, and that, while the dam section could be expected to crack under extreme seismic loads, post-seismic stability was acceptable, particularly when subjectively taking into account the curvature of the dam in plan.

Consideration of remedial options concentrated on providing adequate drainage to the dam section, and it was concluded that this was best done by drilling from the dam crest to intersect the gallery, and from the gallery into the foundation. This included both vertical and inclined holes. The layout of these was complicated by the curvature of the dam in plan, the need to drill holes down through bridge piers and across the spillway openings and the presence of siphon outlets, a bottom outlet and associated equipment embedded in the dam body. A new survey and 3-d AutoCAD model of the dam were prepared by RBJ Surveys Ltd of Glasgow at a cost of £15,000 to confirm the setting out of the holes.

Implementation

The drainage design required drilling: -

- 980m of minimum 65mm diameter vertical and inclined open drain holes from the dam crest up to 40m deep to intersect the gallery.
- 350m of minimum 50mm diameter vertical and inclined open drain holes from within the gallery to intersect the rock foundation.

In total there are 66 holes spaced at nominal 3m centres, but adjusted where necessary for reasons of access and to avoid built in parts such as the siphon pipes. All holes drain into the 0.9m wide by 1.8m high gallery. All of the holes were technically challenging due to the accuracy required to intersect the gallery or the very cramped conditions within the gallery.

The contract was put out to tender to six contractors and four competent tenders were submitted. The successful contractor was Ritchies Ltd of the Edmund Nuttall Group who successfully completed the works within the 16 week contract period in summer 2002. The contract value was £170,000.

The main Health and Safety hazard identified in the risk analysis was working in the gallery where access was via two small vertical shafts. Most importantly a rescue procedure was developed with the aid of the Mines Rescue Service. This was tried out in a full mock rescue. Rope access personnel were trained and retained on site in case a rescue was required. Other systems developed included those for communication, noise and dust control and movement of materials and drilling equipment.

Environmental control adjacent to a major watercourse was of prime importance. Great care was taken to reduce the risk of spills of oils and fuels and emergency procedures were developed. On the dam crest drill stems were shrouded and vented to a dust collection system with the cement and rock dust being disposed of off site. Dust suppression in the gallery was achieved using water mist injection into the compressed air.

All holes were drilled using down the hole percussive hammer techniques. A crawler mounted rig was used for vertical and inclined holes on the dam crest roadway. The contractor elected to drill at 95mm diameter in order to reduce drill string deflection with the top 3metres of each hole being cored and cased to aid directional control through the rubble filled piers and the "air gap" between the underside of the roadway bridge and the curved spillway below. The drilling system drilled well through light reinforcement and rock displacers in the concrete. At the final count only three out of 30 holes drilled from the dam crest just missed the gallery, this was likely caused by the drill head "glancing off" embedded steelwork. However all three were later located using a vibrating tool and intersected from the gallery. A special drill rig was fabricated to work in the confines of the gallery and used successfully to drill 50mm diameter holes inclined and vertically upwards and downwards. However progress was slow and a rock drill with an air leg was used to increase production rates on some of the shorter inclined holes.

Figure 4 Drilling equipment at Laggan Dam crest and gallery

CONCLUSIONS

Both Blackwater and Laggan Dams are historic concrete gravity dams of their period, constructed before modern design criteria were established. Both have served, and continue to serve, the original function for which they were designed. Despite the differences in their designs, remedial drainage to relieve uplift pressures has been adopted as the most appropriate and economic measure to improve stability at both dams to upgrade them to meet modern standards.

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