

The long term performance and remediation of a colloidal concrete dam.

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SYNOPSIS. Within Scottish and Southern Energy plc's (SSE) stock of concrete dams a small but nevertheless interesting subset is colloidal dams. SSE own three dams that are part formed using this technique. A brief history of colloidal dams is given followed by detailed information on particular problems at Loch Dubh Dam. Babbie Group (BG) is currently conducting studies leading to remediation proposals.

INTRODUCTION

Colloidal concrete or Colcrete depends on the production of a colloidal grout that is stable but highly fluid and can be injected into pre-laid aggregate. The aggregate, from which all material below 1.5 inch must be excluded, is placed in position independently, and the grout is either poured over it and allowed to penetrate downwards, or introduced near the bottom through grouting pipes or channels and allowed to fill upwards. If correctly adopted the method ensures that the aggregate has point contact in all directions. The voidage is therefore less, and proportionately less grout, and therefore less cement, is required to fill it; thermal stresses are reduced, and cumulative contraction is prevented. Cement shortages were a significant issue during the early hydro development period and any reduction in use was sought.

This is a rare form of construction with known shortcomings in terms of performance when compared to conventional mass concrete, mainly due to the high water cement ratio required for placing.

LOCH DUBH DAM

Loch Dubh Dam is situated approximately 10 km north east of Ullapool and was completed in 1956. The dam is a concrete gravity structure of conventional profile, as shown in Figure 1 and set in a small steep-sided valley. It can be described as a medium sized dam in UK terms, due principally to its height of 20m (from lowest foundation). Much of the

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Figure 1: General View of Loch Dubh Dam

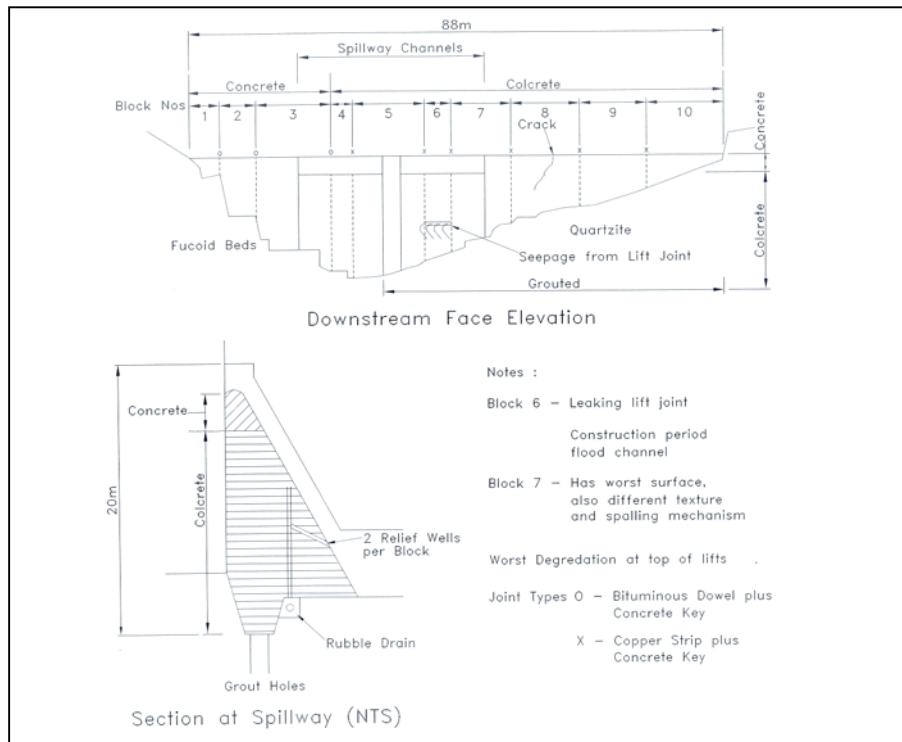


Figure 2: Principal Features

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structure acts as the spillweir. The most remarkable feature of the dam is the method of construction using colloidal concrete. An associated feature that is equally unusual is the use of conventional mass concrete for a small number of monoliths on the right abutment. The reason for this decision is not clear although there is reference to a change in foundation rock type as a contributory factor (Refer Figure 2).

Where the dam is founded on quartzite, it is formed in Colcrete with a grout mix of 2 parts of sand to one part of cement by volume and aggregate in the range 37 mm to 225 mm. The overflow sill (upper 1.67 m) is formed in conventional structural concrete (19mm coarse aggregate).

Where the dam is founded on fucoid beds, the main body is formed in mass concrete (100mm coarse aggregate). The upstream and downstream faces have structural grade concrete 0.61 m thick, cast concurrently with the core.

OTHER COLLOIDAL DAMS

During construction of Mullardoch, which is a mass concrete gravity dam, changes in the economics of the day led to the design top water level being lowered and then raised again. The impact of this required a rather unique problem to be solved to thicken that portion of the dam already completed and to restore the 6.1 m removed from the original height. The method adopted for the thickening stage involved casting a slab over the downstream face of the dam, resting on precast concrete ribs on the sloping face but separated from it by a 0.91 m slot so that no bond could form between the two masses. After most of the contraction in the new concrete had taken place, the slot was filled with Colcrete, which was chosen as the material best suited to meet the requirements of minimum shrinkage coupled with good bonding qualities and, to a lesser extent, of high strength and high quality.

Difficulties were not surprisingly experienced during construction and rather than the more traditional form of Colcrete construction the coarse aggregate and grout were placed by "shooting" it into the slot through elephant trunking. Pre-mixing prevented the stones from breaking up and minimised the wear on the trunking. The water cement ratio of the grout was maintained at 0.9 with grout of 3:1 sand/cement mix and the coarse aggregate was crushed rock graded 89 to 63.5 mm. Test results on 57 cores taken demonstrated equivalent average cube strengths of 21.6 Nmm^{-2} and a density of 2387 kgm^{-3} . Current experience would suggest that although there are isolated areas of seepage and deterioration they are no more than those seen at other more traditional concrete gravity structures.

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Tummel Bridge Aqueduct was substantially extended during 1957-1959 with the addition of a smolt bay using conventional concrete gravity construction and extension to the existing spillway portion of the aqueduct by buttressing. Colcrete techniques were adopted to form these sections which were formed directly on top of existing concrete gravity wall sections. Subsequently additional drainage holes have been drilled in an attempt to relieve water build up within the structure and to drain the interface between the concrete types. Deterioration of external surfaces due to freeze thaw action and spalling has progressed to an extent where localised concrete repairs should be carried out. The extent of this is perhaps greater than seen on conventional concrete gravity structures.

HISTORY & PERFORMANCE OF LOCH DUBH DAM

Over the years the structure of the dam has exhibited a range of defects. Some of these were not unusual on gravity dams while others were less common. Although disfiguring the external appearance none of the defects were judged immediately critical to safety, although regular monitoring was stipulated by Inspecting Engineers over the period.

The visual defects were surface breakdown and joint leakage while instrumentation revealed high pore pressures. Almost immediately these defects were attributed to the use of colloidal concrete.

The underlying process was believed to be a combination of high seepage through the mass concrete, poor drainage at the downstream face and the north facing aspect of this surface in an area prone to freeze thaw conditions.

These problems were obvious early in the dam's life, if only superficially, by the loss of surface finish. By 1964 the rate of surface erosion was causing concern and measures were put in hand to monitor the areal extent and depth of concrete degradation. These concerns increased during the 1970's and a limit of 75mm loss was set as a trigger for re-facing but by 1984 there was evidence that the process was slowing and to date the maximum loss is only locally at that limit.

Piezometers were first installed in 1968 (18No) as part of a research project into uplift pressures and revealed high levels in the downstream zone that indicated that enhanced drainage was required. The piezometers are simple standpipes. Many of them have been lost over the years and there are now only 6 in service. Although some isolated information is available from the early years the most consistent period of readings comes from the 1990's.

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The trend of piezometer readings is not conclusive but shows signs of stabilising after increasing effective drainage in 1971.

Broadly speaking, the drainage gives an immediate drop in uplift of about 5m at full reservoir head (30%) with further dissipation towards the toe. The original series of vertical and horizontal holes have been reamed out where possible and supplemented with inclined connections. There is a possible link between improved drainage and decreased degradation of the surface although this is only a perception over time rather than a measured outcome.

Leakage from a lift joint, low in one of the central blocks, has been observed from the beginning. Accurate measurement of flow is not practical as it sits just above the drowned stilling basin and extends the full length of the joint. The rate of leakage is reported to be increasing.

There is a reasonable photographic record of the appearance of the dam from the 1960's to the present time (1961, 64, 66, 71, 72, 75, 81, 84, 2000 and 02) and this represents one of the best indicators of change in the degradation of the structure. Figure 3 shows a picture of a typical section of degraded face.

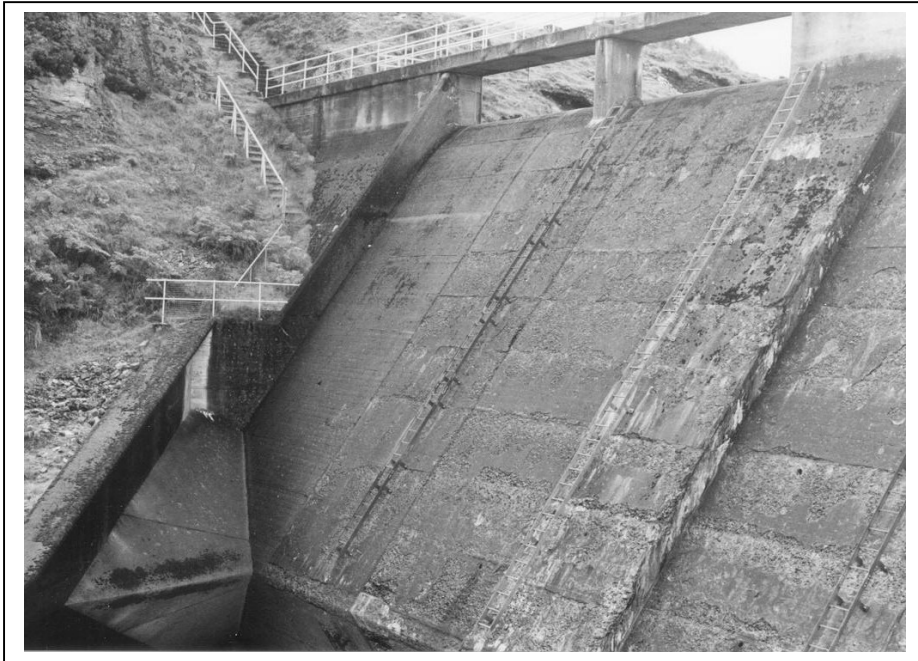


Figure 3: Varying face degradation, blocks 3, 4 and 5

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The structure is routinely surveyed for settlement and lateral movement. There are no unexpected trends and the dam performs as would be expected of a gravity structure of this size.

The upstream face of the dam has been historically coated with a bitumastic paint although recently this has been allowed to degrade (in the expectation of an enhanced sealing coat).

While the possibility of making good the degradation of the downstream face by applying a finite surface thickness has been mooted it has always been accompanied by a concern that it might worsen the drainage/pore pressure regime even if a suitable application method could ensure adhesion and finish.

The current study has been triggered by the need to set a clear direction for the future maintenance of the asset.

DISCUSSION OF INDICATORS/INFLUENCES

The foregoing section on history describes the noted defects in general terms but as part of the current study the individual drivers were considered and analysed for likely impact. The principal indicators are as follows:

- Leakage
- Surface spalling
- Internal pore pressures
- Cracking

These physical outcomes are driven by a wide range of influences related to the design, construction and performance of this particular dam, namely:

- Colloidal concrete
- Acidic water
- Freeze thaw
- North orientation
- Construction sequence/standards/varying aggregate
- Porosity
- Face saturation
- Movement

The use of colloidal concrete is the first and most obvious deviation from standard gravity dam construction and is thus the prime suspect for poor performance. Although used on several dams in the UK and in the US during the 1950's the use of this technique was not sustained and it is now

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recognised as having poor strength and impermeability, factors that are likely to affect durability, particularly in an impounding function within a testing climatic environment. Thus the use of colloidal concrete might be expected to contribute directly to leakage and internal pore pressures. A secondary combination of saturation and weakness could also be contributing to the surface spalling. However, cracking is not likely to be a feature of this technique as it was recognised as reducing shrinkage effects.

Being an upland reservoir, acidic water from peaty soils is an influence with a known deleterious effect on cementitious matrix, the more so on weaker mixes. This might be expected to have an impact on the surface finish, particularly etching of the upstream surface but might also be impacting on conditions along discontinuities e.g. open lift joints.

The exposed surfaces of gravity dams in the Scottish highlands are prone to spalling due to frost action, especially if constructed during winter conditions. Additionally, saturated concrete is vulnerable to surface degradation during freeze/thaw cycles, the more so if weak and porous. Although not at a particularly high elevation (190m) the North facing aspect of this dam suggests that it might face the most severe freezing conditions. This might be supported by the difference in condition between the downstream face and the south facing, and submerged, upstream face.

Consideration of the construction details and sequence also reveals potential influences on performance and durability. In general there appear to be a number of variables in the way in which the work was carried out. This included considerable variation in aggregate size, aggregate type and lift height from pour to pour. Present condition also suggests variation in matrix texture (either cement, fine aggregate or additive). Sloping shutters are always an area of construction problems and may be more so with an injected cement matrix. This could explain differences between upstream and downstream face performance. Recognising the way in which colloidal concrete was formed it is perhaps not surprising to find the top edge of lifts showing a preference for early spalling. In some cases lift heights seem to be rather shallow for the technique. The combination of these influences might account for the most severe areas of degradation appearing on the downstream face. More particularly, in common with most gravity dams, a section of the structure was left low to pass construction period floods. A check on the records reveals that this corresponds to the badly leaking lift joint on block 6. While this surface may have suffered from exposure it appears also to have been compounded by the use of a very low lift in the pour immediately below the surface.

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Although there is uncertainty over the reasons for the use of conventional concrete on the right abutment monoliths it appears to be related in some undefined way to the change in foundation rock type. However, it seems improbable that there was significant variation in loading response across the foundation thus cracking or movement due to uneven loading seems unlikely. In relation to the one notable crack (crest of block 8) it should be noted that the upper section of the dam (3.3m below crest) was constructed of conventional mass concrete throughout the length of the dam. As this was one of the wider monoliths it may be that the relatively slender block of conventional concrete suffered excessive shrinkage.

Thus it can be seen that there are a number of recognisable reasons for each of the defects indicated at Loch Dubh Dam. The key questions at this time relate to the significance of these processes and their likely progression with time.

Of the defects and processes identified the loss of mass on the downstream face was potentially the most serious in terms of safety of the dam and certainly the one that had been causing most concern over the life of the structure. The other defects (discrete leakage, pore pressures and cracking) although undesirable were not unusual and could be addressed by normal remedial works. However, all of the processes had consequences for the operational life of the structure, some with immediate impact on perceptions of care and others on long term maintenance cost.

Consideration of the above led to a programme of assessments and additional testing to determine the present impact of these processes and the likely consequences of further development. The defining indicators of current impact and future performance loss were identified as follows:

- Stability checks for assumptions of face loss
- Chemical change in seepage water
- Time dependant or event specific degradation of the surface concrete

DISCUSSION OF POTENTIAL OUTCOMES

SSE require a positive direction for future asset maintenance. This programme needs to be underpinned by a comprehensive review of the information available and a clear audit trail from adverse indicator to solution.

The key issue here was whether the defects and processes noted were largely superficial or whether there was a risk of long term erosion of safety margins or functionality. While safety is paramount, the operational

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function of a dam structure is also a serious issue for a commercial organisation.

Although possibly only cosmetic, the appearance of the degraded surface is an important issue of public perception for SSE. The impression given to senior company management was also relevant in that it reflects the level of investment and care applied to the dam stock of the company.

Upon site inspection in October 2002 and initial review of the records, an immediate impression was that the degradation process was in decline. This was very much a snap judgement and it was necessary to develop a realistic means of checking the validity. This impression did however seem to agree with the most recent periodical reviews carried out by Inspecting Engineers. Central to this was deciding whether the degradation process was time limited or time dependant.

While some information is available on concrete parameters there is nothing definitive within an advancing timeframe. Concrete cube strengths are available from construction in 1955 and there are a few core samples from the piezometer installation in 1968 that were tested for compressive strength. Together with recent tests it can be said only that strength is more than adequate for mass concrete but that there are significant variations across and through the structure (min approx. 15N/mm^2)

TESTING PROGRAMME AND FURTHER ASSESSMENT OF HISTORICAL INFORMATION

The testing programme was designed to be as simple as possible and manageable with hand-held tools.

While overall compressive strength of the mass of concrete was of interest (for comparison with construction period tests) and would serve to indicate seepage related deterioration, the more important characteristic was the durability of the surface concrete, in particular, whether surface weakness was a one off construction feature rather than a function of continuous exposure.

It was decided that tests could be made for surface hardness and repeated after treating the surface in a defined way. It was also considered possible to core into the body of the dam from the downstream face sufficient to penetrate surface effects. In addition samples were taken of leakage flow for comparison with reservoir water.

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Three test panels were exposed, each 1-2 m² in area. The approach chosen was to use a Schmidt hammer as a coarse indicator of surface hardness and to use this as a proxy for durability (it is acknowledged that this is using the Schmidt test outside its validated operating methodology). For each panel a matrix of hammer tests was carried out, firstly with the surface as found, followed immediately by a similar set after scabbling back to sound concrete. The tests were then repeated on this cleaned surface after a winter exposure.

Briefly summarising this exercise it was found that the exposed downstream panel was most degraded, followed by the upstream panel with the unexposed downstream panel least degraded. The follow-up tests on the cleaned surface revealed an immediate improvement with little deterioration between second and last tests.

The core strength tests revealed that there were variations in concrete strength but that these were not necessarily a function of seepage rather a reflection of general variability in concrete quality.

A review of stability revealed that the design section had a reasonable tolerance to loss of face material (no unacceptable reduction in FOS up to 150mm loss of material – current maximum of 75mm).

POSSIBLE / LIKELY REMEDIAL ACTIONS

There are broadly two approaches; firstly a universal upgrading of the structure that might be regarded as anticipating future problems. Alternatively, specific solutions to individual defects assuming that the extent of the problem has fully revealed itself.

The long-standing proposal has been to line the upstream face with a membrane. This would have the benefit of dealing not only with point leakage but with general porosity, the associated saturation and its link to face degradation. It would however require a full draw-down of the reservoir (although this would not be difficult as Loch Dubh does not feed direct to generating plant) and more significantly removal of sediment from the toe of the upstream face. This solution assumes that the degradation is essentially porosity/seepage driven and that loss of face material would continue without a global improvement in this characteristic.

The alternative on the upstream face is to deal with the one serious leak along the lift joint and to continue the practice of painting the exposed concrete surface. Depending on the level of the leaking joint in relation to sediment deposits the leak repair work could be carried out by diver without

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dewatering (using a mechanical clamping system with a strip membrane). Although a replacement bitumastic paint system is envisaged along with some limited concrete repairs to the upstream face, support for this solution depends on evidence that the degradation process is in decline.

In both cases the present level of degradation on the downstream face either has to be accepted or is treated in some way to reduce its visual impact.

As with many reservoir maintenance problems a definitive analysis is not possible and the chosen approach has to rely on an element of judgement.

CONCLUSION

Loch Dubh Dam has a number of visible defects that detract from its appearance and give an unjustified impression of neglect. Most of these features have been in evidence for the majority of the 48 year life of the structure. Despite concerns throughout its life that some of these defects were progressive the current assessment leads to the view that the processes are either in decline in the case of the face degradation, or can be addressed by relatively simple actions in the case of the severe joint leakage.

To be confident of the decision reached the situation has to be regarded from a number of perspectives: reservoir safety, asset performance, asset life and appearance.

In terms of reservoir safety the rate of degradation does not pose a threat to stability and the leakage is not unusual nor is it significant in uplift terms. The crack is not in a critical location and appears dormant.

As with all assets the residual life is of prime importance if the enterprise is to be sustainable. In the case of Loch Dubh Dam there is no reason why the structure should not remain effective for another 50 years even if current face degradation is doubled in extent. Routine maintenance and some remedial works are necessary to sustain that situation.

The appearance of the dam is one of perception and unless studied at close quarters does not raise any great concern. However, the philosophy of SSE is that all their structures should give an appearance of robustness and reliability even if not directly in the public eye. On this basis the current appearance of the dam does not meet the owner's criteria and some action is necessary to improve the situation.

It is implicit that the critical indicators identified here are kept under review, not only in the routine surveillance of the structure but at times of statutory

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inspections such that the current assumptions are regularly reconfirmed or alternatively that a change of conditions requiring action is identified.

At the time of writing the decision has been made to proceed with the specific actions necessary to reduce the principal defects and specifications will now be prepared for leak sealing, sealing coat and downstream face stabilisation.