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7793 DISCUSSION

Cow Green dam and reservoir

M. F. KENNARD & R. A. READER

This Paper was discussed jointly with 'The design, construction and performance of Cow Green embankment dam', by P. R. Vaughan, H. T. Lovenbury and P. Horswill, *Géotechnique*, 1975, **25** (3) 555–580.

Mr M. F. Kennard

The most interesting features of the scheme arose because of the geology of the site. All sites have unique geological features, but the close proximity of the Whin Sill, the buried channel, the exposed clay slope and waterfall at the dam site, the limestone and shale alternating strata in the reservoir basin and the extensive mine workings make this site especially unique. The special geological aspects led to it being the first site in Britain where, I believe, an engineering geologist was employed full-time as a member of the Resident Engineer's staff.

103. An earthfill embankment across the valley, a combination of earthfill with rockfill, concrete gravity or concrete buttress section would all have been feasible choices of dam. The final choice of a gravity section on the rock foundation and earthfill on the clay foundation led to the simplest form of construction for this remote and high site. That construction was completed within the contract period of 3 years and impounding commenced as programmed shows that the original programme, phasing in the diversion with the concrete and earthfill construction, was well conceived.

104. The embankment section was an example of the 'design as you go' principle. However much site investigation is carried out beforehand, it cannot compare with the information that becomes available during construction when in addition to drilling, open excavation, field testing and site laboratory testing can be carried out, supervised by a full site staff. The construction phases allowed for this fuller investigation to be undertaken before the river was diverted through the concrete dam and before any earth moving could take place. This enabled the detailed design of the embankment and foundation to be developed and checked as the work proceeded. The investigation of gravel deposits at the same time enabled gravel to be placed instead of boulder clay in the shoulders. The close control in raising the bank to the full height and control of impounding because of the slow rate of consolidation of the foundation and the deformations was a continuation of the design principle to the end of construction. In an embankment of this type, including the foundation, it is not possible, or even desirable, to have everything cut and dried beforehand. If it is, it would be a much more overdesigned and expensive structure.

105. The promotion of this scheme involved prolonged hearings before select committees of both Houses of Parliament, as well as debates and divisions. The private bill procedure, instead of proceeding with a water order and a subsequent bill because of common land, led to a successful outcome, but involved a much more searching technical inquiry than usual in such proceedings. This in depth investigation is I think a good

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thing, but it is frustrating at the time, when generalizations by the petitioners have to be fully answered by facts put forward immediately following the technical evidence given by the petitioners without prior discussion among the engineers.

Dr P. R. Vaughan

Our Paper covers many of the problems involved in designing and constructing embankment dams. Two are perhaps of the most general interest.

107. The first concerns the design of a filter to ensure that a clay core is self-sealing even when cracks form in it. Since the design of the Cow Green filter the same principles have been applied at several other British dams. Some general points have emerged. Flocculating conditions seem to be usual, and the average floc size which may arise during internal erosion, which represents the minimum particle size which must be retained by the filter for it to be fully effective, may be related to the salt content of the water flowing through a crack. In pore water, flocs arise in the size range 2–6 μm, increasing to about 10 μm when the concentration of calcium and magnesium salts reaches about 10 mEq/litre and thereafter remaining constant with increasing salt concentration. Sodium salts may give smaller floc sizes, or cause complete dispersion. The size of floc retained by a filter is probably best related to the permeability of the filter rather than to its grading, and the limited amount of data currently available suggests a relationship of the form

$$k = 4 \times 10^{-6} . \delta^2$$

where k = coefficient of permeability of filter (m/s)

δ = floc size (μm)

The use of permeability to quantify the effective pore size of a filter may be valuable in the design of filters generally.

108. For a filter to be effective in causing cracks to seal, it must be non-cohesive and so be unable to sustain an open crack with water flowing through it. It has been found that a simple site test to check that a filter material is non-cohesive is to form a compacted sample of the moist filter material, place it in a tray and carefully flood it by pouring water into the tray. If the sample slumps to its angle of repose it is non-cohesive. Compacted samples may be stored before testing to check whether cohesion may develop with time.

109. The second problem is the non-brittle behaviour of sandy clay fills in undrained shear. It has been suggested elsewhere[5] that this type of behaviour in intact unfissured clays may be related to the drained brittleness index as determined in the ring shear apparatus. Based on tests on clays with a mainly illite clay mineral content and with an activity around unity, the brittleness index is found to increase sharply when the clay content exceeds a critical value, equivalent to a plasticity index of about 25%. This change probably differentiates between the non-brittle undrained behaviour of the sandy clays and the brittle undrained behaviour associated with more plastic clays.

110. It is also suggested that it may be unwise to rely on plastic, non-brittle undrained behaviour in monitoring the behaviour of in situ sandy clays, first if they are cemented or, second, if they contain fissures or other discontinuities along which the drained strength is lower than the drained strength of the intact clay. If such discontinuities are present, it may also be unwise to base the assessment of ultimate undrained strength on remoulded test specimens, as described in the paper on the Cow Green embankment.[3] The cores obtained from the Cow Green foundation were carefully examined for such discontinuties at the time of the site investigation, and none were found.

Professor J. L. Knill, Department of Geology, Imperial College

In 1964 I was asked by the Consulting Engineers to assist in the geological studies for the Cow Green reservoir. There was a background history of effective condemnation of the site on geological grounds but there was some evidence to suggest that the

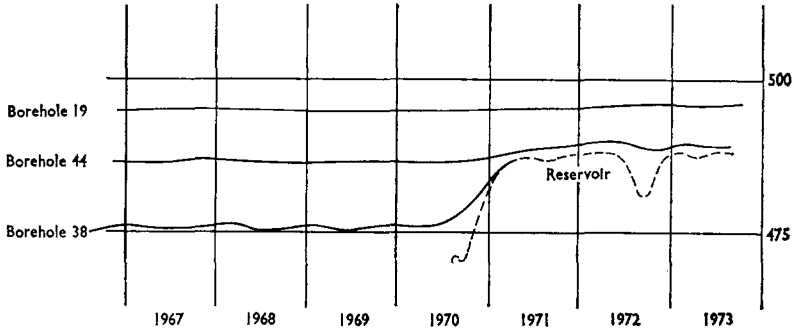

Fig. 17

arguments which had been presented previously were incorrect. The reservoir bed is underlain by the thick Whin Sill dolerite which is overlain by a limestone–sandstone–shale sequence. The lowermost, massive limestone is contact metamorphosed to a saccharoidal limestone which weathers very readily to a calcareous sand which characterizes the biological conditions of the site. There are small sink holes at the edge of the limestone outcrop where solution has taken place. At that boundary there is also outflow of water associated with springs. What was convincing in 1964 was that surface water was flowing over limestone with no sign of it disappearing into the ground, as might commonly have been expected. Above top water level, water discharged at the boundary between the limestone and the top of the Whin Sill. This was a clear but limited demonstration of a water-table well above the proposed top water level of the reservoir and this provided evidence to suggest that this condition might be more widespread and so there was a case to proceed with a site investigation. The basic geotechnical argument was concerned with water levels and the distribution of groundwater pressures at depth as reflected by the results of individual boreholes, on which a vast amount of work was carried out. Against a very difficult time-table, a sound case for building the reservoir was made.

112. It was suggested in the presentation of evidence in support of the petitioner's case to the House of Commons Committee that the reservoir could leak; that certain geological conditions in the area had not been given full consideration, and that any reservoir built on the Cow Green site would require extensive grouting measures. I would like to ask if the technical experts for the petitioners have now withdrawn the views they put forward in 1966 and 1967?

113. Some data has been put together on water-table measurements from three of the boreholes, 38, 44 and 19 (Fig. 17). Of these, borehole 38 was drilled in mine workings. In general terms, boreholes in mine workings intersecting the reservoir showed continuity between the water level in the borehole, the groundwater, and the rise in reservoir level. Effectively from 1971 onwards borehole 38 and the reservoir have responded together. Borehole 19 is in limestone about 45 m from the edge of the reservoir; so far as one can tell, there has been a mean increase in the water level of about 0·5 m after impounding the reservoir. Borehole 44 is very interesting. The piezometer is below the base of the Whin Sill and about 100 m below the top water level. The original water level in borehole 44 was below the top water reservoir level, and subsequently it has risen; in other words, the whole groundwater system has been modified to considerable depth by the presence of the reservoir.

114. I was of the opinion that the concrete section of the dam should have been built in masonry and so simulated the characteristic pillared structure of the Whin Sill which

is typical of the area. The earth embankment could have been sculptured far more effectively into a moraine-like form, and with careful landscape treatment, one could have produced a feature which, although wholly artificial, would at relatively low cost have simulated the natural environment into which the whole structure is built. I should like to inquire whether it is something that the designers would give some closer consideration to nowadays?

115. Passing to the paper by Vaughan *et al.*, I wonder whether the Authors could give their views on the geological causes for the strength with depth relationship shown in their Fig. 6.

Dr A. D. M. Penman, Geotechnics Division, Building Research Station

It is pleasing to see that the Institution has included a paper from *Géotechnique* for discussion with the one in the *Proceedings*, but in fact this is a trilogy which is complete only if it includes the paper by Vaughan and Kennard.[4]

117. The importance of Cow Green reservoir is well illustrated by Table 1 of Paper 7743 which shows it to be almost as large as the other five reservoirs in the Tees valley put together. According to § 9, one of the reasons it was not developed before was because of the geotechnical problems. A site investigation was made in 1956, but the site was turned down as being too difficult. The fact that the reservoir has now been built reflects developments in geotechnical engineering, particularly as applied to embankment dams, during the past 20 years.

118. Engineers have been saying for several years that it is not enough in dam design to provide a factor of safety against complete collapse, but that a dam should be designed to suffer only acceptable deformations. One might expect that the lower the factor of safety, the greater the movements that will occur and it is interesting that in the paper by Vaughan *et al.* the authors suggested that the performance of this dam supports the view that constructional stability may best be monitored by measurements of deformation. Table 8 compares the movements of 10 dams. It is difficult to draw a true comparison between the behaviour of different dams because of the large range of variables, but the values shown are those of the greatest rate of horizontal movement caused by the addition of 1 m of fill to the dam when it is almost at its full height, divided by its height. This is a form of deformation modulus; deflexion over height representing a strain, while a metre height of fill added is a stress increment. From Table 8 it can be seen that Cow Green is the most advanced of the stable dams; Galisteo was in a state of balancing equilibrium and Muirhead undoubtedly failed.

Table 8. Maximum rate of horizontal movement of ten dams

Dam	Movement, mm/m rise of fill in relation to height of dam in metres
Derwent	0·028
Scammonden	0·057
Backwater	0·070
Gepatsch	0·085
Blowering	0·089
Llyn Brianne	0·22
Chew Stoke	0·39
Cow Green	0·68
Galisteo	1·10
Muirhead	15

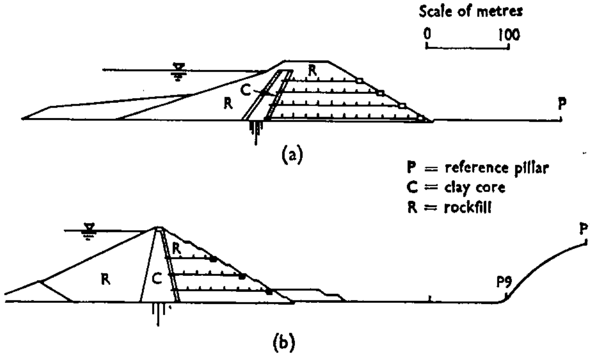

Fig. 18. Major sections of (a) Scammonden and (b) Llyn Brianne, showing positions of horizontal plate gauges and reference pillars

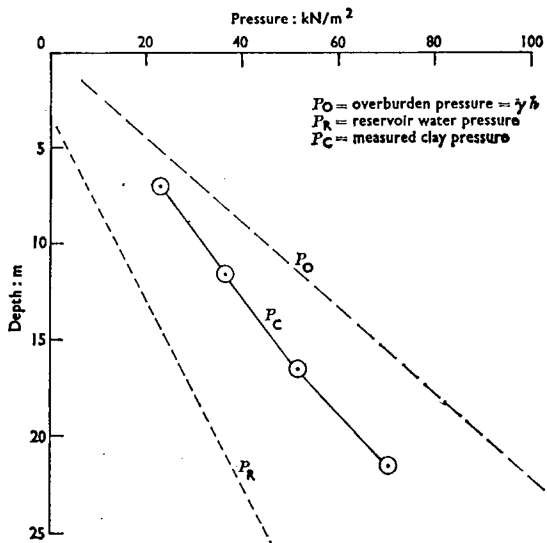

Fig. 19

A limit for this rate of deflexion in terms of millimetres of horizontal movement per metre rise of fill over the dam height may well be unity.

119. A common misconception is that the action of filling the reservoir pushes the clay core downstream against the downstream shoulder. That this idea was used in the design of Cow Green is shown by the 1 in 9 slope on plan of the end of the concrete dam. Vaughan and Kennard[4] admit that this is a debatable feature since the potential increase in contact pressure with downstream movement of the core would be reversed if the core moved upstream and they state 'Such upstream movements are known to occur'.

120. In measuring the movements of dams using the horizontal plate gauges as shown in Fig. 18 the Building Research Establishment has been able to measure the horizontal movements of several points on the downstream edge of the clay cores of two dams with

an accuracy of ± 4 mm: it was found that there was virtually no movement caused by impounding. This behaviour is readily explained when it is appreciated that the pressure from the clay against both the upstream and downstream shoulders is greater than the pressure from the reservoir water. This means that when the reservoir is filled the water pressure on the clay reduces its thrust against the upstream shoulder, but the downstream shoulder is unaware that the reservoir has been filled.

121. The pressures imposed by the clay at Cow Green have been measured with BRE type earth pressure cells manufactured under licence by Soil Instruments Ltd and the results are given in Fig. 19. They show that the clay pressure is proportional to depth, is approximately equal to the expected intermediate principal stress, σ_2, and is comfortably above reservoir water pressure at all depths. This result agrees with the findings of no downstream movement of the core on impounding.

122. With regard to the best shape for the concrete face in contact with the clay, there is clearly no advantage in a slope on plan to oppose downstream movements of the whole core. The balance of pressure between the clay and the shoulders controls movements of the interfaces: initially, as pore pressures dissipate and the total pressure on the shoulders decreases, the interfaces move inwards towards the centre of the core, but in time creep in the shoulder material might allow some outward movements. Since the clay pressures are well in excess of the reservoir water pressures, there is probably no merit in providing any slope in plan for the concrete face. The softer the clay, the higher the pressures to be expected. Was the use of much wetter clay—something approaching a puddled clay—considered?

Dr J. A. Cooper, Imperial Chemical Industries Ltd

The dam is part of a post-war saga which started in 1949 with the first dam, Selset. The demand by the Water Board at that time was 24 mgd compared with the latest forecast for Teesside for 1984 of 180 mgd. The domestic consumers will need 28 mgd by 1984 and the rest is for industry. The Selset, Balderhead and Cow Green dams have been largely required for industry and a further dam (Kielder) will be required by 1980. The reliable yield of these dams is respectively 18·5 mgd, 28·5 mgd, 35·0 mgd and for Kielder 200 mgd. Fortunately the cost of the dams per mgd in Northumbria becomes cheaper in real terms as each succeeding dam is built, although in many parts of Britain no doubt the reverse is true. The major consumers are the steel and chemical industries. The reason for this enormous consumption of water is the use by industry on a very large scale of heat-producing materials such as oil, natural gas and coke. Recirculation of water in cooling towers is regarded as an essential economy measure. The Cow Green dam was a source of controversy at the time but the care given to environmental considerations produced, it is hoped, the best compromise solution. Mr Jeffcoate, for the opposition, suggested the sinking of a number of boreholes in the Teesside area as a temporary solution to the threatened water shortage. The underground water supply has now in fact been exploited, but quality considerations would in practice have limited the use of underground water for industrial purposes.

124. There has always been a period of apprehension before each reservoir has been built, largely because of the speed with which new industrial plants can be built compared with reservoirs: 1949, 1959 and 1969 were each years of greater or lesser anxiety. The year before Kielder is completed, namely 1979, is the next year in the sequence, although after 1980 it is expected that supplies will be safe for at least 20 years.

Mr A. L. Little, Binnie & Partners

I was associated with this project through Binnie and Partners' consultancy to ICI. Sandeman, Kennard and Partners, as they then were, freely discussed their problems with Binnie and Partners and made available to them all test results, field observations and calculations.

126. The Authors have said that the embankment design was determined principally

by the foundation conditions. This laconic statement covers several months of intensive measurement, calculations and discussions. Although the subject has been dealt with more fully elsewhere,[3, 4] it may perhaps not be out of place to discuss it briefly here. Anyone dealing with soils will know that the selection of parameters for calculating a factor of safety is not easy. Indeed, it is questionable whether the safety of so complex a structure as an embankment dam can be represented by a single number. Perhaps the best way of treating a factor of safety is as an index to behaviour and economy of design.

127. Calculations were made for various assumptions of foundation drainage and shear strain. Using ultimate strengths and taking into account the long-term effect of sand drains at a typical section gave a factor of safety of 2. Mobilization of the ultimate strength would have involved large shear strains. Limiting the strain to 2% meant that a little less than half of the shear strength could be mobilized; under these conditions, without sand drains, the factor of safety fell to 0·8. Even with the effect of sand drains, the factor of safety at the end of construction was only 0·95. Results for other sections were similar.

128. Although these latter calculations are somewhat artificial, sand drains were clearly necessary and there was also an important relation between shear deformation and dam safety. Inclinometers were installed to monitor dam movements, so that the deformations could be studied, and taken into account in the calculations. One such inclinometer, in the downstream area of the foundation sand drains, is shown in Fig. 14 of the *Géotechnique* paper.[3] The maximum foundation displacement is about 150 mm, roughly half this having occurred between readings on 3 June 1970 and 18 June 1970 at the end of fill placing, when the final 9 m were placed in 2 months. At this point the factor of safety of the slopes had dropped to about unity, partly because the rate of dissipation of pore pressures was less than hoped. From pore pressure observations, the average c_v lay between 1·1 and 1·4 m^2/year compared with a design assumption of 2·25 m^2/year. As a consequence the r_u value in the sand drain zone was 64% instead of the design value of 40%.

129. As can be imagined, these movements and pore pressures caused some concern at the time and there was careful consideration before a decision was made to proceed with impounding in stages; the decision seemed courageous at the time but the subsequent satisfactory performance of the dam and the 27% increase in safety factor (compared with 30% forecast) has shown it to have been correct. I wonder if the engineers would have been so happy if they had known the things Dr Vaughan has since discovered.

130. Bearing in mind the 'soggy' behaviour of the boulder clay fill coupled with the weather conditions, which at times were appalling, the situation at Cow Green perhaps represents the limit for construction of an earth embankment. Do the Authors agree?

131. Finally, I should like to congratulate the Authors, on the engineering insight and courage which they showed in bringing this remarkable scheme to a successful conclusion.

Mr M. R. H. Dunstan, South West Water Authority

My remarks refer to the concrete dam rather than to the embankment. The incidence of cracks in the concrete dam at Cow Green seems to be typical of cracks that have occurred in the majority of mass concrete dams in the UK in recent years. These have been reported at Spelga, Clywedog and Meldon, among others. Although the cracks in the majority of cases have no structural significance, they can become very unsightly or, as in the case of Cow Green, be expensive to seal.

133. Similar cracks were discovered in the lower lifts (those below ground level) of the Upper Tamar dam on which I was Resident Engineer. A detailed investigation is reported elsewhere.[6] I believe that both vertical and horizontal cracks are caused by restraint due to thermal problems, and not due to shrinkage of the constituents of the concrete. It would be useful to analyse the formation of horizontal cracks which seem

to have caused the most trouble at Cow Green to confirm whether or not the results at Upper Tamar are typical.

134. It seems that general practice in the UK on concrete dams is to leave a lift for some time so that heat generated within it can be dissipated. Thus a minimum exposure time, usually 7 days, is specified. However, at Tamar it was found that horizontal cracks formed when the difference in temperature across a horizontal joint was over 6–7 degC (that is, the difference between the maximum temperature in the subsequent lift, which will be at about one third to one half lift depth, and the regenerated temperature in the previous lift which will be near or on the surface of that lift). Thus the subsequent lift has to be poured fairly quickly and not all the heat is lost from the previous lift.

135. The results of the thermo-couple study suggest that cracks could be avoided in most concrete dams with a little extra specification and the cost of concrete dams could probably be considerably reduced.

136. It would be helpful if the Authors could produce an analysis of the cracking, both horizontal and vertical, against exposure time and the month of the year. The latter would give some idea of the maximum temperature generated in concrete.

Mr N. J. Ruffle, Northumbrian Water Authority

Although the Cow Green scheme was approved after detailed Parliamentary examination, the strength of the anti-reservoir lobbies undoubtedly had its influence on the deliberations which were even then under way on the further augmentation of water resources in the north of England. By 1970 the Water Resources Board was recommending a major new source at Kielder in North Northumberland, and an aqueduct 40 km long to carry water from the Tyne to regulate the rivers Wear and Tees. This aqueduct, mainly in tunnel, is now under construction.

138. Industrial development on Teeside is expected to cause the curve of consumption shown in Fig. 1 to continue its steep rise after a lull in the first half of the 1970s, to reach 9 cumecs by 1985, i.e. a 50% increase in 10 years. As the water from Kielder to be transferred from the Tyne to the Tees will be subject to an expensive pumping lift of 200 m, there will be an economic incentive to make the optimum use of the Tees reservoirs, to minimize pumping, and it will not be long before the arrangements at Cow Green will have to come under scrutiny to devise means of drawing off water at a greater rate than the present capability.

139. The reservoir is a pleasing addition to an otherwise rather featureless landscape. But the concrete dam, although an admirable structure, seems to me to intrude to an unfortunate extent as it towers above the Cauldron Snout waterfall. In contrast the earth embankment is scarcely noticeable, and if the whole structure had been of earth it would have blended much more sympathetically with the landscape.

140. The Authors give reasons (§§ 24–28) for their choice of a composite structure, but one is left with the impression that it would be difficult to prove any significant economic advantage over a dam composed wholly of embankment.

141. Although the embankment part of the dam is the minor length it is certainly a subject of interest. Following the troubles at Balderhead it was right and proper to exercise particular caution to avoid recurrence, but I wonder whether in retrospect the Authors would now see some of the extra precautions as over-reaction. To remove (or to make every endeavour to remove) all stones over 75 mm size from a rather thick core does seem unnecessary. Having secured a plastic core by placing the clay wetter than Proctor optimum, the compactive effort was surely sufficient to squeeze clay around stones. I would suggest that only stones down to 100 mm, being two thirds of the layer thickness, which are visible on the surface, together with those which have cracked under contact with a roller or bulldozer, need be removed.

142. The purpose of the filter behind the core is appreciated, but it must inevitably constitute an expensive complication in bank building. Do the Authors think it

necessary always to provide such a feature with a rolled clay core, even in a dam of similar modest dimensions?

143. The three dams in Northumbria, Selset, Derwent and Cow Green, and the papers on them[7-11] constitute a series recording the developing techniques of building earth dams under close control. One of the notable geotechnical features of the Cow Green dam is the reduction of the factor of safety of the embankment to 1·0 at completion, thus demonstrating that a factor of safety of 1·0 in terms of effective stress is not synonymous with collapse.

144. At the completion of bank building in 1959 Selset was reported to have a factor of safety of 1·5; in 1965 at Derwent it was 1·3; in 1970 at Cow Green it was 1·0. Perhaps after all the engineer's concept of $F=1$ is only what the sports writers would refer to as a psychological barrier and, as engineers are becoming increasingly adept at controlling embankment construction, it is interesting to speculate on this trend!

Mr G. M. Thompson, *Northumbrian Water Authority*

As the Authors indicate, there were interesting and unusual problems in this continuing development of the resources of the River Tees to meet the phenomenal growth of industrial demand for water for the chemical and steel making industries. They indicate that the site of Cow Green had been considered for many years topographically as a valuable reservoir site because the valley widened out upstream of a restricted section of the valley, and the upstream river gradient was comparatively gentle for almost 4 km. This meant, of course, that a shallow dam would retain a large volume of water. However, geologically it was considered unsuitable until the investigations indicated that the groundwater level in the col between the valleys of the Tees and Harwood Beck would always be above the water level in any proposed reservoir in the Tees basin.

146. The Authors discuss (§§ 4 and 5) the problems relating to the Parliamentary Bill. As is indicated, the scheme was indeed subject to an exceptional technical investigation extending over many months, and upon the granting of the Royal Assent the closest possible liaison was established between the Water Board, the designers, the botanical interests and Imperial Chemical Industries Ltd, who were understandably anxious not to curtail any existing botanical research programmes. In furtherance of this liaison the Board appointed a Site Liaison Officer, whose value became more apparent as time went on. By the time the dam was completed it was clear that the creation of such a post had greatly enhanced the smooth running of the project.

147. By the time all the objections had been heard and the Bill enacted, a great deal of time had elapsed. In order to be able to meet the demands on the water undertaking the dam had to be completed to a very restricted timetable indeed. The Authors were so confident that they would be able to complete the project in time that they established their site offices below top water level, though it must be conceded that *all* temporary works were carried out below final water level so as to reduce to the very minimum the damage to the botanical interests of the site.

148. The completion and implementation of the reservoir has enabled the Water Authority to meet all the water demands forecast. In the face of the very large industrial and domestic demands yet another source had to be sought and the Northumbrian Water Authority is now developing the Kielder scheme.

Mr M. F. C. Thorn, Hydraulics Research Station, Wallingford

My remarks are personal and should not be construed to be the opinion of the Department of the Environment. Since the Authors themselves raise the issue of 'amenity' it is perhaps pertinent to consider the wider issues of amenity and reservoir promotion raised by Cow Green. I first visited Cow Green in 1954 and I have felt an affinity with that area ever since. Although my speciality is civil engineering hydraulics, I would not agree that the amenity of Cow Green and Cauldron Snout as a wild and beautiful

Pennine landscape has been totally preserved, but I am thankful that the visual intrusion of the dam and reservoir is relatively small.

150. Designers and planners seem curiously insensitive to the need to minimize disturbance to valuable landscape, and too often confuse amenity with the provision of a townsman's trappings of car parks, picnic areas, recreation centres, wide roads and smooth footpaths, which themselves destroy what was worth preserving. Perhaps some lessons have been learned at Cow Green (although even here the tarmac surface incongruously laid over the rough moorland track to Cauldron Snout shows the hand of the tidy-minded amenity planner). I should be interested to know whether the limitation of the construction area and the construction of the access road below top water level resulted in any real cost to the Client, or whether this is something which could easily be considered for future reservoir schemes.

151. The Engineers and Contractors are to be complimented upon their ultimately positive approach to the environmental objections to the scheme, with which I originally found sympathy. If this kind of approach were to be emulated, and made clear from the inception of such projects, perhaps they would be more sympathetically received by a public that is suspicious of the restriction of access and the destruction of the character of wild landscape by insensitive reservoir development. The environmental guidelines and standards now being applied by the US Bureau of Reclamation to its construction projects deserve close consideration on how similar criteria might be applied to civil engineering construction in the United Kingdom.

Messrs M. F. Kennard and R. A. Reader

The petitioners have not publicly withdrawn their views. The reservoir is now satisfactorily retaining water as designed, thus showing that the doubts about leakage due to the limestone and mine workings expressed by the petitioners were wrong. One of the principal developments that has occurred in thinking about reservoirs in Great Britain in recent years has been the attention given to groundwater conditions and this has been partly due to the Cow Green scheme.

153. **Dr Penman** referred to the junction of the concrete and earth fill sections. We consider that a sloping face has the feel of being correct and we would be reluctant to omit this feature.

154. **Mr Ruffle** referred to stones in the clay core and whether it was necessary to remove them. On site, the effect of having some form of inspection and perhaps overstrict specification on this aspect is largely psychological. In constructing a clay core, which is a quality article made out of a rather common constituent, it is necessary to try and impress on everybody that they are doing something rather special. Maybe one could argue that taking all the boulders out is not strictly necessary, but, on the other hand, that would have the effect on site of people thinking that any old thing would be alright. Some form of fussy specification like that used on this site points out to everybody that things are not as easy as they may think. Certainly to leave the clay core with 25% of boulders seems excessive. This quantity looks excessive when seen on the ground. One gets the impression that it is all stones with some clay in between. There was some difficulty in compacting the shoulders of the core where we did not take boulders out. There is a tendency for the roller to bounce over the top of the stones rather than to compact the clay.

155. The reference by **Mr Little** to the situation at Cow Green representing perhaps a limit for construction of an earth dam is an interesting point. If this dam had been built more than 25 years earlier, it is most likely that a failure would have occurred as the foundation conditions and the significance of consolidation would not have been appreciated. Now it is possible to build successfully on such sites, and if the conditions can be determined in advance or during construction, then an embankment can be designed. Worse conditions could have been dealt with by means of flatter slopes, and another season for construction.

156. The appearance of the dam and the form of construction was raised by **Professor**

Knill, Mr Ruffle and **Mr Thorn.** From the aesthetic point of view, there is much in favour of an embankment dam, but there were reasons against this (§§ 25–28). The problems of earth fill, involving boulder clay under the Cow Green climatic conditions, should not be underestimated. The appearance of the embankment is considered to be satisfactory, but additional fill could have been placed to modify the slopes at additional cost. On reflexion the concrete section could have been modified by mounding of fill adjacent to the downstream face and by apparently reducing the length of exposure of the concrete section. Professor Knill's suggestion of simulating the pillared structure of the Whin Sill is not considered to be a satisfactory or economical solution. In fact, the outcrop of whinstone does not go quite as far as the dam itself. There is a soil cover at the dam site. Photographs have been published of Cow Green dam which do not show half the structure; this is because they ignore the earth dam. This shows that an embankment is often not noticed and therefore creates little interest. There are references which imply that Cow Green dam consists only of the concrete dam.

157. It is impossible to assess the real cost of the construction of the access road below top water level, as asked for by Mr Thorn. Each reservoir and dam is unique topographically and certain works and costs are an integral part of the cost of that site. Temporary works below top water level are not considered to have added to the cost. The tarmac surface of the moorland track was felt to be necessary to ensure access at all times. The appearance is not considered to be unsatisfactory.

158. Mr Ruffle mentions the forecast of demand and **Dr Cooper** referred to the demands of ICI Ltd. The diagram of yield (Fig. 1) was based on the information at the time of the promotion of Cow Green, which was nine or ten years before. Industrial demand occurs to a much quicker time-table than domestic demand and makes it very difficult to forecast accurately in such cases.

159. Dr Cooper mentions the apparent reduction in real cost of the schemes in Northumbria over the years. One of the reasons for this is the concept of river regulating reservoirs. Selset was for direct supply, Balderhead was part direct and part regulating and when Cow Green was first considered in 1956 it would have been a direct supply reservoir with an expensive pipeline from Cow Green to Tees-side. The Kielder scheme is for regulating of the River Tyne, and also makes use of the River Tees. That is the principal reason for the reduction in cost over the period. The river regulating concept dates back to the late 1950s from schemes such as the Porth reservoir scheme in Cornwall, and has developed through Balderhead and Cow Green (and others) to such bigger schemes as Kielder.

160. **Mr Thompson** mentions the value of the site liaison officer. Mr Reader as resident engineer agrees entirely. On a site such as this where great public interest was generated the presence of a site liaison officer prevented the engineering staff being diverted from problems needing their attention.

161. The concrete problems are referred to by **Mr Dunstan** who specially pointed out the effect of present day cement compared with the coarse ground ordinary Portland cement, not necessarily low heat cement, used some 20–25 years ago, especially in the North of Scotland Hydro Electric Board dams. The cement industry has concentrated very much on cement for the precast concrete industry and for structural work.

162. The conclusion that reduced times between pours of concrete in the monoliths tended to reduce horizontal cracking along the lift joints was not reached on site till near the end of the contract, and consequently careful analysis was not possible. The effect of a prolonged exposure time between pours does appear to cause the exposed pour to curl up at the corners, producing a horizontal crack beneath it, and the subsequent pour tends to crack beneath, presumably because of the excessive temperature difference across the joint.

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Professor Knill raised the question of the geological deposition of the boulder clay foundation and its relationship to the observed increase in strength with depth. The strength profile shows great local variability, yet with strong evidence of consolidation of the clay under its own weight. Two conclusions can be drawn directly from the soil mechanics evidence. First, the clay must have been deposited with widely varying water contents. Second, the properties of this sandy clay when consolidated under low stresses are such that any preconsolidation pressure applied during and after deposition must have been small and of the order of 100 kN/m².

164. **Dr Penman** discussed the design of the junction between the earth and the concrete dam. The formation of a batter on plan to the end face of the concrete is debatable, and it would be dangerous if the dam moved upstream during impounding, as sometimes happens with dams with upstream granular fills which yield during flooding. The clay placed right against the concrete face received extra watering to ensure that a good contact was obtained during compaction. A wider wet zone would have produced an inhomogeneity in the core and the effect on the contact stresses, which are the most important points, would be difficult to predict. The incremental ratio of horizontal movement to embankment height discussed by Dr Penman is an excellent indicator of embankment performance. However, the way in which it increases with height is a function of the types of soil involved and their brittleness, of drainage conditions and of creep just as much as it is of safety factor, and this makes generalizations potentially dangerous.

165. One of the pleasures of working on the Cow Green project was the opportunity for frequent technical discussions with **Mr Little** and his colleagues. The conditions at Cow Green certainly approached the limit for the economic construction of an embankment from non-free-draining fill. However, with modern plant this limit is probably controlled by the all-weather performance of the haul roads which can be constructed economically, and this will vary from site to site. The design of the sand drains at Cow Green presented two particular difficulties: first, how to decide on the depth they should reach, since there was no horizon at which there was a major gain in undrained strength; and second, how to allow for the fact that only a relatively small increase in strength was required. With hindsight, an estimation of the decrease in water content due to consolidation and an estimate of the increase in undrained strength following this is probably as good a method as any. The failure of the sand drains to be as efficient as anticipated remains something of a mystery which deserves further investigation.

166. **Mr Ruffle** commented on the removal of stones from the core, and on the filter design. In practice, a specification requiring the removal of stones above a certain size results in a decrease in their number, rather than their total exclusion, unless factory methods of fill preparation are used. Large stones may have two effects. If they are numerous so that the fill is effectively gap graded, large voids may be left between them. This is relatively easy to avoid. Secondly, large stones cause local stress perturbations which may facilitate the formation of cracks. This is a matter which requires further examination. The provision of filters meeting the requirements set out in the paper[3] is not necessarily very expensive, even if the required grading has to be manufactured. While further research into the mechanics of cracking and filtration of clay cores is required, the present state of knowledge of these matters suggests that the provision of a 'perfect' filter has much to recommend it. Such filters may eventually allow economies to be made in the processing and treatment of cores.

167. The stability of the Cow Green embankment has been commented on by Dr Penman, Mr Little and Mr Ruffle. The engineering meaning of a factor of safety depends on the way in which it is defined and the circumstances in which it is employed. A reserve is required against slipping, which in brittle soils may occur when deformations are small. A reserve is also required against unacceptable deformation, in which there is rather more room for error. Deformations rather than slipping are likely to be the limiting factor in non-brittle soils and probably in fully drained, relatively homogeneous situations. What, perhaps, is most required is a means of safely classifying problems so that appropriate methods and factors are used, and research in this

area is continuing. In the event, the approach used at Cow Green worked. Subsequent work[5] has indicated that the Cow Green foundation may have been close to the boundary differentiating non-brittle behaviour and brittle behaviour. How close cannot be established without further site investigation. On a future site it would be possible to establish this with much greater certainty. The consequences of movement at Cow Green could have been rectified within the construction programme. Thus the choice was between spending money when the evidence available showed this to be unnecessary, and accepting the risk of having to spend rather more money later if the decision proved to be wrong.

168. Professor Knill, Mr Ruffle and Mr Thorn have all discussed the appearance of the dam. This is largely a matter of opinion, but it seems to involve two questions. Is it pleasant to look at? This involves matching the appearance of the dam with that of the surrounding countryside, the proportions of the dam itself and of the dam in relation to the valley, and the appearance of surface finishes and details. The second question, which only arises with embankment dams, is can and should the dam be made inconspicuous, so that it appears a natural rather than a man-made feature? To look like a natural feature an embankment dam must meet five main conditions:

(*a*) embankment slopes must not be significantly steeper than those of the valley;
(*b*) plane surfaces, which are rare in nature, must be avoided or disguised;
(*c*) surface finishes and vegetation must match those in the valley;
(*d*) a straight, level crest must be avoided;
(*e*) spillways and other hydraulic structures must be hidden.

All these requirements cannot be met except at enormous cost. However, the lower slopes of an embankment can often be made inconspicuous, so making the embankment appear lower than it really is. This will often improve the final appearance, and it was done at Cow Green. The Cow Green dam is fortunate in that it is pleasantly proportioned and small in relation to its valley. One can only express a personal opinion, which is that the final structure looks like a dam, but one which is quite pleasant to look at, and that this is the best thing to aim for.

169. A final point concerns the contract organization of a project such as Cow Green, where design changes may be considered necessary or desirable after the contract has been let to meet changed or unexpected circumstances, to improve the final structure, and even to achieve economies and to make things easier to build. Such a situation requires frequent, relatively informal consultation between Engineer and Contractor, and it also requires that the adjustment of rates be discussed at the same time as technical details. This requires, in turn, that the technical and financial control of the work should be in the same hands. The Cow Green contract perhaps was fortunate in that all these conditions were met. At a time when construction periods are shortening and when contracts seem to involve more and more complex design and supervisory arrangements, with a tendency for separation of technical and financial control, these requirements should be considered if a contract is contemplated which may involve a 'design as you go' approach to the extent to which it was succesfully adopted at Cow Green.

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