

## Design and constructional features of hydroelectric dams built in Scotland since 1945

by

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Mr J. Guthrie Brown, C.B.E. (Partner, Sir Alexander Gibb and Partners; President, International Commission on Large Dams) said that his comments on the Paper would be divided into two sections. He wished to speak first as the Board's Technical Adviser, a position which he had held for 20 years. He congratulated the two Authors on producing a Paper which would prove to be of the greatest value to all engineers concerned with concrete dams and with the use of concrete. It crystallized the hard-won experience gained during the last 20 years in the design and construction

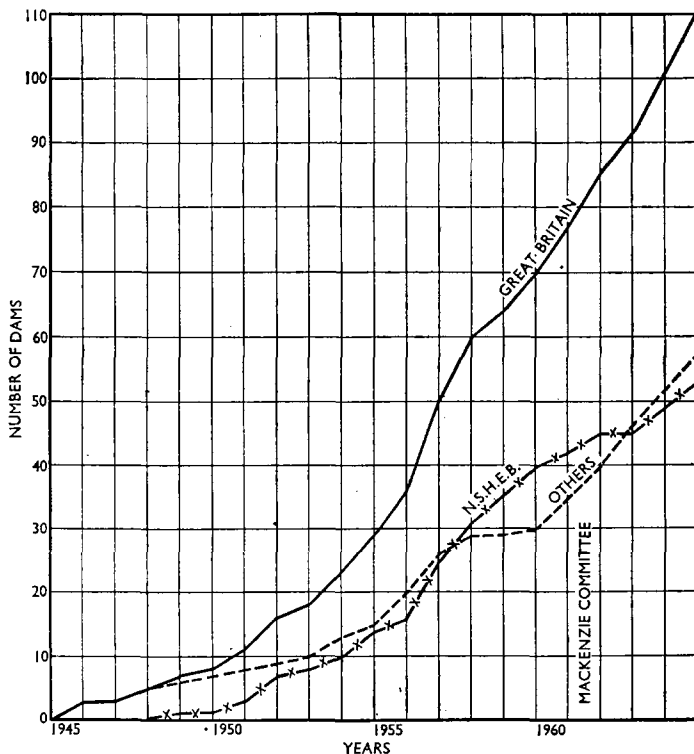


FIG. 4: NUMBER OF DAMS BUILT IN GREAT BRITAIN, 1945-1964

of over 50 dams at sites in the north of Scotland, most of which had presented many difficult problems.

83. As one of the consultants on several of the Board's major schemes, he had assumed that the Board were responsible for the majority of the dams built in Great Britain since 1945. However, this was not so: of the 110 dams of all types built in Great Britain during the past 20 years, 53 had been constructed by the Hydro Board and 57 had been constructed by other groups. Fig. 4 showed the acceleration in the construction of dams by the Board during the years 1955-1961, at which date the setting up of the Mackenzie Committee brought new developments to a halt. Construction of dams in other parts of the country showed a marked acceleration since 1960.

TABLE 6: NUMBER AND TYPES OF DAMS BUILT IN GREAT BRITAIN, 1945-1964

Types	Great Britain		Total	%
	N.S.H.E.B.	Others		
Gravity . . . . .	29	16	45	40.9
Earth fill . . . . .	3	35	38	34.6
Buttress . . . . .	9	3	12	10.9
Arch . . . . .	3	1	4	3.7
Rock fill . . . . .	3		3	2.7
Gravity and earth fill . . . .	2	1	3	2.7
Gravity and rock fill . . . .	2		2	1.8
Gravity, earth fill and buttress.	1		1	0.9
Prestressed concrete . . . .	1		1	0.9
Earth fill and rock fill . . . .		1	1	0.9
Totals . . . . .	53	57	110	100.0

84. Table 6 showed a remarkable difference in the types of dam built in Britain during these years. As the Authors had pointed out, the 29 gravity dams formed 55% of the Board's programme, whereas elsewhere in the country 62% (35) of the dams were of the earth embankment type. It was difficult to understand why, out of the Board's 53 dams, only three were of the embankment type, of which two had been dealt with by his own firm. Cement was not cheap in the Highlands and joiners were in short supply. The Authors had shown the efforts that had been made to economize in the use of cement by the adoption of additives, such as fly ash, and the attempts to overcome the shortage of joiners by using steel shuttering and precast units.

85. It was stated by the Authors in § 80 that concrete gravity and buttress types (38 out of the total of 53) seemed destined to hold their pre-eminence under Scottish conditions. This might well be so, although one would hesitate to say that Scottish conditions were unique throughout the world.

86. He was doubtful whether there was much future for the arch type of dam in Britain. Only three had been dealt with by the Board and two constructed elsewhere in the United Kingdom. In the Galloway scheme in South Scotland, however, no fewer than six arch dams were designed by his own firm in 1930.

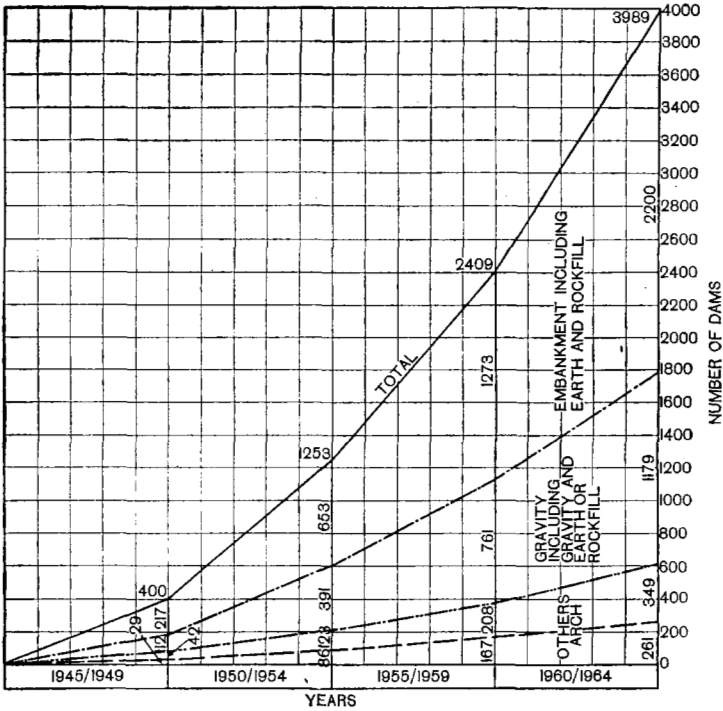


FIG. 5: NUMBER AND TYPES OF DAM BUILT THROUGHOUT THE WORLD, 1945-1964

87. Since 1945, the total number of dams built throughout the world was 3989, of which 55% were of the embankment type, either earth- or rockfill. The gravity type, including gravity plus earth- and rockfill, totalled about 30%. Fig. 5 showed that the use of the embankment type of dam had been steadily increasing, while the arch dams, which represented only about 9% of the total, had not shown such a marked increase and would appear to be gradually going out of favour.

88. In the United States of America, which during the same 20 years had built 34% of the world's total of dams, the tendency had been towards the embankment type of dam. The modern massive and highly developed earth-moving and compacting plant had emphasized this trend. It was interesting to note that during the year 1963 only 9% of the dams being built in the United States were of concrete, and of the 100 highest dams being built there during the same year only five were arch dams.

89. In view of this, he suggested that once the Arch Dams Committee had completed its studies on the design of these structures, the Civil Engineering Research Association might give consideration to the desirability of setting up a committee to carry out similar research into the many problems associated with the design and construction of embankment dams. In this way they would ensure that they were keeping abreast of modern developments and contribute useful knowledge to the prevailing world-wide trend towards the embankment type of dam.

90. The figures which he had quoted were extracted from the World Register of Dams, prepared by the International Commission on Large Dams.

Mr R. C. S. Walters (Partner, Herbert Lapworth Partners), said that to compress 50 dams into about 28 pages was a masterpiece of brevity and wit. He had no connexion with the hydro-electric dams dealt with in the Paper but he did not quarrel with anything that it contained.

92. He wished to ask some questions. Although water-supply dams and hydro-electric dams had many points in common—such as the question of the type of dam, the geological foundations, siting, the placing of concrete, matters concerning uplift, the significance of strain gauges and the all-important question of grouting—one of the points which was of concern, particularly from the water supply angle, was the question of leakage. It would be useful to know the leakages of the dams mentioned in Table 5, to compare with the gROUT table.

93. It would be of interest to know the acceptable degree of leakage from the hydro-electric angle. Was it a percentage of the loss of kW? In water supply, the only standard of which he was aware was that the leakage must be of clear water and less than the compensation water, which, of course, was self-evident.

94. In § 67 of the Paper, a figure of 100 ft was given for the depth of grouting for the 50 dams and this grouting was not generally carried further than 100 ft below the surface. During the war he had visited, with Dr Lowe Brown, a tunnel under construction which had a gradient less than the hillside. The strata were disturbed to a vertical depth of about 80 ft below the hillside. The figure of 100 ft quoted in the Paper therefore reminded him that, in very general terms, it was correct to aim at a 100 ft depth for grouting, and the tunnel experience bore out his opinion that it was as important to look after the grouting on hillsides as to pay much attention to grouting in the bottom of a valley.

95. It was stated in § 15 of the Paper that the tunnel and overflow bellmouths were not very much used and that there were complications with the bellmouth. In water supply, the bellmouth was used a great deal, because it was possible to turn the water into a tunnel which was used not only for diversion but also for putting in scour and supply pipes. The diversion tunnel, which was normally a temporary affair, became a permanent feature in water supply. In hydro-electric work, it seemed that the bellmouth was not necessarily very useful owing to gate controls.

96. The types of crest were referred to in § 10. Members might be interested to know of two types of crest in Algeria. One (Fig. 6) was known as a 'Marguerite' with a lip of petals about 400 ft in length. The other (Fig. 7) known as 'Duck bills', was equivalent to a 4000-ft weir in which the water overflowed into twenty 100-ft grooves, the whole occupying a very small space.

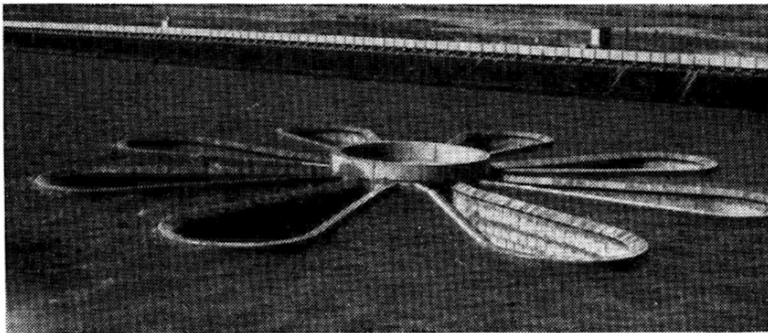


FIG. 6: THE 'MARGUERITE' OVERFLOW, SARNO DAM, ALGERIA The overflow consists of 8 'petals', 17 metres long, capable of taking a flood of 500 cu. m./sec. (Re-produced from *Waters, Dam Geology*. London, Butterworths, 1962, p. 248).

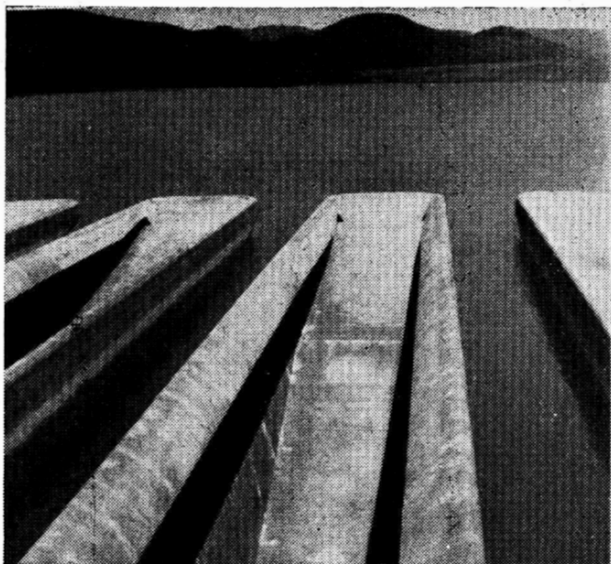


FIG. 7: 'DUCK BILLS' OVERFLOW. Water flows over the lips on both right and left sides. (Reproduced from Waters, *Dam Geology*. London, Butterworths, 1962, p. 238).

97. In § 5 of the Paper an interesting statement was made on the cheapness of concrete compared with earth fill. Briefly, the reason might be that contractors were more at home with concrete than with the modern earthen type of structures. These might involve rip-rap, rolling of rock, the rolling of a sand filter and the rolling of a core, and were subject to soil mechanics criteria, which in turn depended on the weather!

98. It would be of interest to know the approximate cost of the dams compared with the net capacity of the reservoirs. From such data, it would be interesting to estimate the cost of the dam per million gallons of yield should any of these dams ever be converted into domestic water reservoirs.

**Mr H. H. Dixon** (Partner, Howard Humphreys & Sons) said that he hoped that more papers on various specialized aspects of dams in Scotland would be presented. There must by now be a wealth of information on hydrology meriting a full length paper. Reference had been made by the Authors to over 50 major dams, whereas Table 1 contained only 18 and Table 2 only 19 dams.

100. There had already been some references in the discussion to embankment dams, and he thought that earth- and rockfill dams might have been cheaper in certain cases with methods that were available today. He drew special attention to a recently-developed American technique for rockfill dams, wherein vibrating rollers on sleds were hauled up and down the upstream sloping face, thus ensuring adequate compaction and a true face. Settlement of the rockfill under an upstream impermeable membrane was thereby reduced to a minimum.

101. Another point was that leakage or seepage need not cause concern. No dam was watertight. What had to be done was to calculate the probable leakage and make provision to get it away with an ample margin of safety. If by chance the leakage was large, it might at times be worth while to pump it back to the reservoir.

TABLE IA: NORTH OF SCOTLAND HYDRO-ELECTRIC BOARD: PROVISION FOR FLOOD DISCHARGE

Name of dam	Catchment area		Total average inflow into reservoir <i>cusecs</i>	Method of flood discharge		Maximum discharge capacity		Total discharge capacity <i>cusecs</i>	Ratio: Discharge capacity to average flow
	* Controlled <i>sq. miles</i>	Un-controlled <i>sq. miles</i>		Spillway length	Gates, valves, etc.	Spillway <i>cusecs</i>	Gates or valves <i>cusecs</i>		
Benevean	52	72	785	456 ft	6 ft dia.	13 700	1 170	14 870	19:1
Storr Lochs	1.5	5.2	30	77.5 ft	2.5 ft dia.	1 980	—	1 980	66:1
Tarsan	16.6	3.8	112	358 ft	—	2 700	—	2 700	24:1
Gaur	25	67	450	220 ft	6 ft × 8 ft	8 650	1 950	10 600	23.5:1
Luichart	298	25.4	1 523	493 ft	8 ft × 10 ft	15 205	3 050	18 255	12:1
Loch Dubh (No. 2) Meig	Nil	3	11	86 ft	—	1 625	—	1 625	150:1
Errochtly	4.3	69	370	141 ft	6 ft × 10 ft	10 510	2 775	13 285	36:1
Lairg	110	19.5	295	181.5 ft	5 ft dia.	3 520	1 200	4 720	16:1
Stronuich	42.6	188.7	819	148 ft	72 ft total	3 600	9 100	12 700	15.5:1
Cruachan	73.7	14.1	520	540 ft	6 ft square	10 900	1 520	12 420	24:1
	6.7	2.3	66	120 ft	4 ft 6 in. dia.	3 840	795	4 635	70:1 (Note: extra capacity for over-pumping)

\* Controlled means regulation of flow by either or both (a) upstream reservoirs, (b) incoming aqueducts which can be shut off completely

TABLE 2A: NORTH OF SCOTLAND HYDRO-ELECTRIC BOARD: PROVISIONS FOR DIVERSION OF WATER DURING CONSTRUCTION OF DAM

Name of dam	Uncontrolled catchment area sq. miles	Average flow at dam site* cusecs	Capacity of diversion, No. of times average flow	Method of diversion	Remarks
Luichart . . .	146	659	12	8 ft x 10 ft high ground sluice and two No. 13 ft x 11 ft high temporary openings	Max. flow 10 000 cusecs
Benevean . . .	72	455	6	Cofferdam and temporary openings. Capacity 2500 cusecs	
Lairg . . .	189	640	4	Earth cofferdams and 40 ft-wide temporary opening	
Gaur . . .	67	250	8	Mass concrete cofferdam	Overtopped once by flood of 3000 cusecs
Tarsan . . .	3.82	18.3	103	Open channels designed for 25% normal maximum flood	25% normal maximum flood exceeded in 1950
Cruchan . . .	2.3	18.3	69.4	Cofferdam and temporary opening 10 ft wide x 12 ft high	
Storr Lochs . . .	5.2	26	108	Timber cofferdams and flume with temporary opening in dam	Diversion works overtopped on two occasions
Lower Shira . . .	5.3	36.4	78 (before main dam constructed)	Diversion channel and temporary opening in dam to provide for 900 cusecs	Max. flood experienced 1700 cusecs during construction
Shin diversion . . .	193	651	7	Concrete cofferdam and 40 ft-wide temporary opening	
Lochalsh . . .	7.2	29	10	Cofferdam and temporary openings	
Lussa . . .	10.8	41.5	48	16 ft x 9 ft temporary opening	Max. flow 478 cusecs

\* Excludes diverted catchments

102. He had used colloidal concrete with success in constructing cut-offs under two earth dams, one in North Wales and one in Trinidad, in which particularly dense and satisfactory results were obtained. As the large lumps of aggregate were in point-to-point contact, shrinkage was negligible. This form of construction was particularly useful in wet trenches which could be allowed to flood before pumping in the grout.

103. The data quoted in Tables 1 and 2 of the Paper were of particular interest from the flood point of view. It was a pity that in presenting these tables, the Authors had had to amalgamate the definition of controlled catchments to include both upstream reservoirs and also diverted catchments, because the effects of the two were of a quite different nature. Moreover there were the reservoir lag effect, to which no reference had been made. Through the kindness of the Authors he had, since the discussion, received additional data which was presented as addenda to Tables 1 and 2. This information, together with the original data as given in the Paper was shown graphically in Fig. 8. The curve marked 'Normal Maximum Flood' was taken from the data presented by Allard, Glasspoole & Woolf.<sup>3</sup>

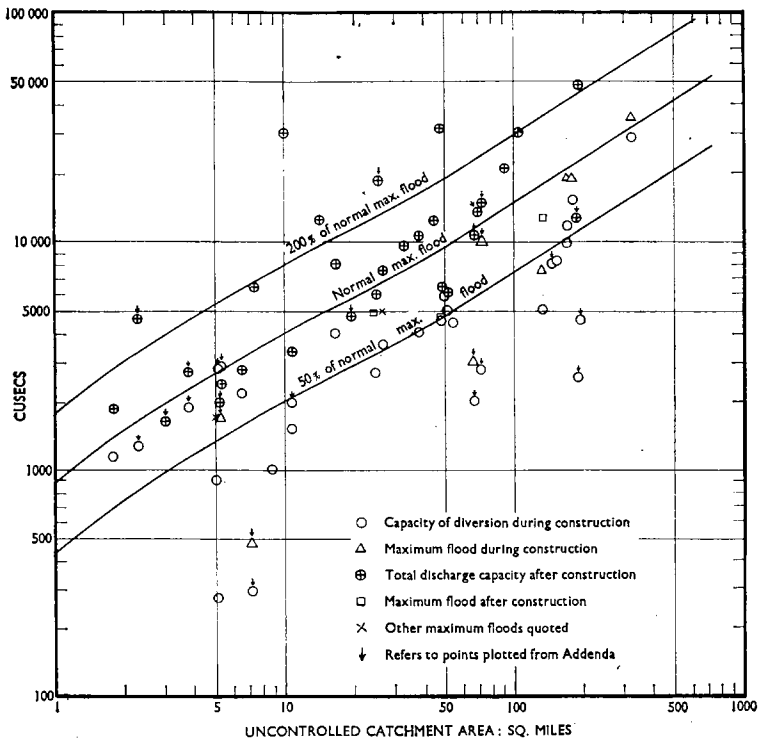


FIG. 8: PLOT OF MAXIMUM FLOOD AGAINST CATCHMENT AREA

104. Because of reservoir lag, no general conclusions could be drawn from the data as presented, as it would be necessary to make flood routing calculations in every case before some apparent anomalies could be explained. However, it might be noted that, of the points shown for total discharge capacity after construction, six lay above the upper curve on Fig. 8, twelve between the upper and the middle curves, and eleven between the middle and lower curves, none being below the lower curve. For

flood discharge capacity during construction two points lay almost on the middle curve, eleven between the middle and the lower curves, two on the lower curve, and sixteen below the lower curve.

105. He entered a plea that when hydrological data were being analysed, use should be made of statistical methods to determine the recurrence periods of the phenomena. It was more useful, for instance, to know that for a given site a flood of  $x$  cusec might be expected in one year out of ten, or in one year out of a thousand, rather than that the 'Normal Maximum Flood' had a certain recommended value.

Mr R. T. Gerrard (Partner, Binnie and Partners) said that he proposed to say a few words about the information given in the Paper on spillways. Table 1 showed that flood discharges up to about 50 000 cusec had been provided for, and it was noticed that when the discharge exceeded about 6000 cusec or what could conveniently be accommodated over a simple overflow crest, gates of one form or another were introduced to deal with the excess water. For reasons to which he proposed to refer, he suggested that in future a closer look should be given to siphon spillways before introducing gates to deal with the excess flood.

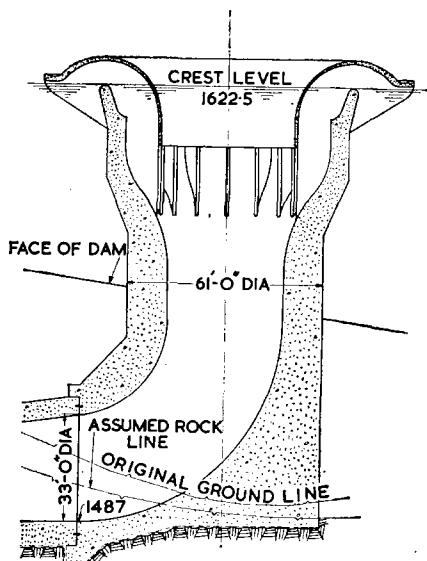


FIG. 9: BELLMOUTH SIPHON

107. In § 8 of the paper, the Authors drew attention to the desirable feature of keeping the flood rise to a minimum in order to obtain the greatest effective storage. The provision of siphon hoods over a spillway, as in the example given in Fig. 9 did exactly this. The bellmouth illustrated was currently under construction abroad. Unlike the older siphons, which ran either full or not at all, the air-regulated siphons which had recently been developed passed only the water that was offered to them and no more. They did not run full until the maximum design flood was reached. The flood to be accommodated in this case was 39 000 cusec, and was therefore within the range of the floods that had occurred in the Scottish areas. The tunnel diameter was fixed at 29 ft. The crest diameter of a plain bellmouth was 130 ft, and the flood rise 9 ft. By introducing siphons, the diameter of the crest was reduced to 88 ft

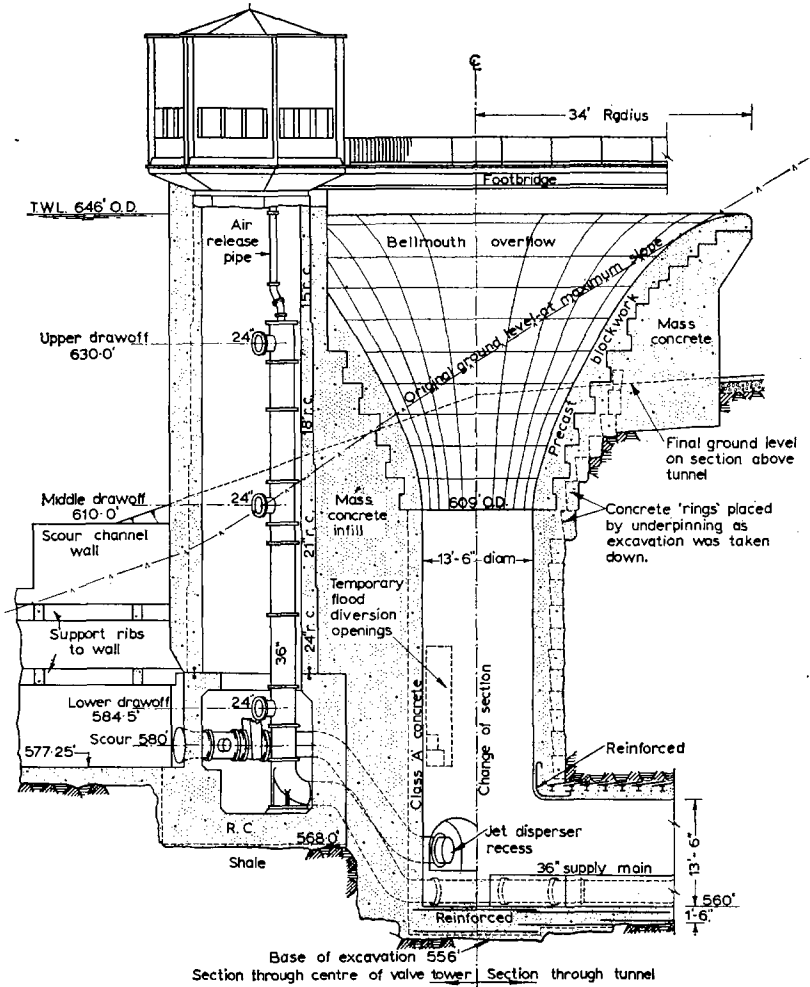


FIG. 10: BELLMOUTH DISCHARGE TUNNEL USED FOR SCOURING

and the flood rise to  $3\frac{1}{2}$  ft. The net saving was £125 000 over a plain bellmouth spillway. These siphons could of course be placed over a straight crest as well as a circular one.

108. On the score of reliability, siphons had three advantages. Hydraulic gates or the sources of power to operate them might sometimes go wrong. There was nothing that could go wrong with a siphon, which was designed to avoid cavitation and vibration difficulties. Secondly, hydraulic gates, like all machinery, cost money to maintain, whereas siphons made of concrete were practically maintenance-free. The question of reliability of labour for maintenance did not arise with siphons, and this was an important consideration in some sites. Thirdly, though when designing

a concrete dam one's first inclination was to use the dam to accommodate all the spillway arrangements rather than to build a separate concrete structure such as a bellmouth to deal with floods, economics might point to a different solution. When the flood was in the range of 5000–50 000 cusec there was commonly a considerable diversion problem during construction, and the bellmouth discharge tunnel could frequently serve for temporary diversion as well, as Mr Walters had mentioned.

109. Fig. 10 showed an example where the bellmouth discharge tunnel was used also for scour arrangements. Furthermore, the stilling arrangements at the downstream end of the tunnel were frequently more compact and cheaper than the works that were required to gather together flood water falling over a lengthy simple overfall crest.

110. Although bellmouth spillways were usually associated with earth dams and had been used at only one site referred to by the Authors, the use of siphons instead of gates to limit flood rise merited their consideration for concrete dams as well as when design floods exceeded the convenient capacity of a simple overfall crest.

Mr J. C. A. Roseveare (Engineer, Freeman, Fox & Partners) said that if he had any criticism it was that the Paper might have contained a more comprehensive list of references. It dealt with many of the Scottish dams, about which Papers had been given in the Institution and elsewhere, and it was the sort of Paper to which one would turn for references to more detailed information.

112. He had had the privilege of attending the last High Dams Congress in Edinburgh and had been impressed by the great variety of dams shown, as well as the excellence of their construction. The intricacy of the shuttering required for some of the earlier buttress designs was, however, amazing and it could well be seen how the massive buttress design with its very simple shuttering had evolved.

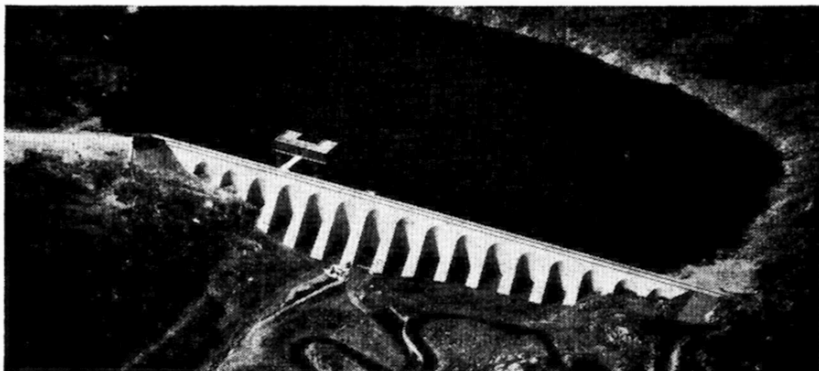


FIG. 11: FFESTINIOG: AERIAL VIEW OF STWLAN DAM

113. Another point that impressed him particularly was the watertightness of the prestressed gravity dam at Allt na Lairige. This was most significant. One could envisage improving the watertightness of many dams by this method of post-tensioning. There had been some interesting contributions to the discussion on spillway design. With the buttress type of dam this was a difficulty; Figs 11 and 12 illustrated two different ways of dealing with it. Fig. 11 showed the Stwlan dam at Ffestiniog where fortunately there was the spur at the right flank where it had been possible to put a gravity section spillway without difficulty. Fig. 12 showed another massive buttress design, the Nant-y-Moch dam of the Rheidol Hydro-Electric Development in mid-Wales. In this case there was an overfall spillway on the right bank

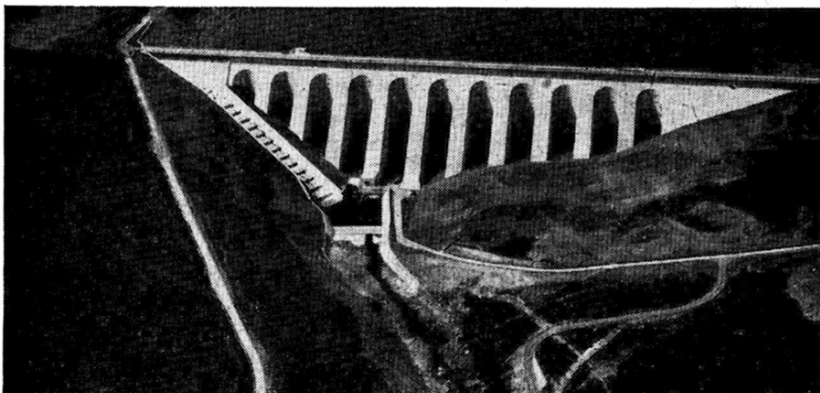


FIG. 12: RHEIDOL: AERIAL VIEW OF NANT-Y-MOCH DAM

in a short gravity section with a channel down the backface of the dam and a stilling pool. The arrangement was based on a model investigation and performed satisfactorily when there was 2 ft of water over the spillway during a recent flood.

114. It might amuse the Meeting to know that in the past there had been at least one dam which did not have a scour pipe. When designing a dam for the North Wales Power Company, Sir Ralph Freeman (father of the present Mr Freeman) was told by the Company that it did not want to spend money letting water out of the dam, but only to keep it in. Many years later when further work had to be done, a scour pipe had to be provided. It was an under-pressure connexion on a large scale and was successfully carried out by the Cementation Company.

115. The Paper contained a good deal of information about substitutes for cement. The cement industry in this country had shown no inclination to provide engineers with the low heat type of cement that they required for dams. This was in marked contrast to experience overseas, where some cement manufacturers had had the type of cement that was required specially ground. It was therefore necessary to look for substitutes and in the Nant-y-Moch dam 25% of the cement had been replaced by fly ash, with excellent results.

116. Although the art of dam design was now highly advanced he doubted whether the materials used today were as good for their purpose as those in such dams as Vyrnwy, Howden, and Derwent—massive structures which seemed to be quite indestructible. Concrete was a material inferior to masonry for both the facing and hearting of dams. He was, perhaps, one of the last people among those present to have constructed what might be called a classical form of dam without construction joints, masonry faced and containing a significant proportion of masonry in the form of 'plums' in the hearting. Unfortunately modern constructional methods and the need to 'keep the big mixer going' precluded this form of construction today.

117. Finally on the matter of drilling and grouting he was a little surprised at the depth limits of the grout curtains quoted by the Authors, but the bee in his own bonnet was drilling. The exploratory drilling could hardly be overdone. Surface rock might seem perfect but one never knew what was underneath. Particularly in the case of granite far below there might be a fatal weakness. The terrible effect that ill chance and a lack of the full facts could have were seen during a visit to Vaiont.

Mr A. D. M. Penman (Soil Mechanics Division, Building Research Station, Watford) said that the first of the two points he wished to make in relation to the Paper

concerned the very accurate measurements which had revealed the movement of the dams when the reservoirs had been filled with water. He suggested that while the North of Scotland Hydro-Electric Board might be able to carry out this type of work, it might not be quite so easy for other people, who were associated with dams in ones and twos, and not in seventies.

119. He had been interested to find that in France the Ordnance Survey department had teams of surveyors with special equipment to undertake the work of measuring the movement of large structures such as dams, setting up all the equipment and taking the measurements from some distance away, to a remarkably high degree of accuracy. He wondered whether there was a lesson to be learned from the French, and whether this country should have a Government organization which was prepared to carry out this type of work.

120. His second point related to the Authors' reference to the Reservoirs Act. Although they had dealt very largely with concrete dams, one of the troubles that might arise related to the behaviour of earth dams through a number of years. It was very difficult and expensive to make borings and take samples of the fill of dams already in position. People did not, in fact, do more than look at a dam from time to time, and if it looked all right, they assumed that it must be all right. It might be worthwhile to consider building instruments into earth dams, not only for measuring their behaviour during construction, as was becoming a normal practice, but also with a view to checking the behaviour of the earth throughout the life of the dam, so that observations might be taken and those responsible might be able to simplify their appraisal of dams in the future.

**Mr E. J. K. Chapman** (Partner, James Williamson and Partners, Glasgow), who added his congratulations to the Authors for a most interesting Paper and a valuable record of what must have been the busiest period of dam building in Scotland, if not in the whole of Britain, said that he wished to refer to two points in the Paper, both relating to massive buttress dams.

122. In § 9 the point was made that overfall crest spillways were not so easily provided as on solid gravity dams since the gaps between the buttresses required decking over. While this was quite true, the additional cost involved had been very small and, in fact, a comparison of the relative cost of the spillway sections of the two types of dam showed an economy of up to 20% in favour of the decked-buttress dam.

123. Apart from the spillway section, a comparison between solid gravity and massive buttress designs for a dam about 120 ft high showed that at least one-third less concrete was required by the buttress dam. However, as the Paper suggested, the maximum overall saving was likely to be realized with those dams which had small flood-producing catchments requiring only short overfall spillways.

124. It might be of interest to note that of the four dams of this type mentioned in Table 1, only Sloy and Lubreoch had spillways formed by decking-over between the buttresses. With the other two, Lawers and Giorra, the spillway had been combined with the intake and scour gate structures in one short length of solid gravity section. This produced a simple and compact design and had merits where relatively large intake arrangements were incorporated in a dam whose spillway crest was relatively short.

125. In § 21 of the Paper, it was stated that some slight leakage had been experienced in vertical joints formed by leaving contraction gaps between adjacent blocks which were concreted later after normal shrinkage had taken place. While this was unfortunately so, the leakage was very minor and in most cases showed only as a dampness with unmeasurable flow. One reason might be that the time interval for shrinkage, before the gaps were finally plugged with concrete, was seldom long enough, as it was a compromise between design and programme requirements.

Cement grouting had been effective where joints had opened sufficiently to allow a small run of water.

126. In many cases, however, damp joints tended to be self-sealing owing to the free lime in the rich face concrete depositing calcium salts in the joints and filling them up. These slight leaks had occurred in vertical joints fitted with preformed plastic water stops in addition to bitumen-coated key checks, and part of the trouble seemed to be the adjacent horizontal joints which offered potential leakage paths around the vertical joints.

127. Although the total leakage water was quite insignificant and the leaks themselves had no structural significance, they were disfiguring and constant efforts had been made to stop them. The elimination of arches (Fig. 3) had helped, as the discontinuity occurring at the arches had been a source of trouble.

128. It might be of interest to mention that during last September an examination was made of Giorra (the latest type of buttress dam without arches), which showed it to be very good, with virtually no leakage or dampness, although dry calcareous deposits indicated where previous dampness had occurred. Although this might be partially due to the temperature of the concrete at the time of the inspection, it seemed encouraging, as Giorra was constructed with 10-ft lifts, the highest so far used for this type of dam.

129. In a further effort to stop leakage, Cruachan dam was being fitted with electrically-heated bitumen plugs in addition to water stops and key checks in the vertical joints, but as impounding had only recently commenced it was too early to say how successful these were.

**Mr J. A. Banks** (Messrs Babbie, Shaw and Morton) referred to Table 5, which gave particulars of curtain grouting. He said it was interesting that the intensity of grout absorbed ranged from 1.5 to 14.3 lb/sq. ft of grout curtain. He had had two instances of dams in which the absorption was 34.8 and 57.3 lb/sq. ft, respectively.

131. The grout absorption was an indication of the degree of fissuring was present in the foundation rock, and the wide range of the records which he had quoted emphasized how difficult it was to make an advance assessment of the character of the rock. To some extent this had been stressed by the recent dam failures in countries abroad, where the rock structure had generally had an important bearing on what had occurred. It emphasized, particularly in the building of higher dams, the importance of rock mechanics and the need for study and research in that direction.

132. He considered that alluvial grouting would come more into practice in this country as favourable sites for other types of dams became less numerous. The Authors stated in § 79 of the Paper that alluvial grouting would enable dams to be built where it was not economic to do so formerly. He was more inclined to say that the new techniques of alluvial grouting enabled dams to be built on sites where, with the previous limited state of knowledge, it would not have been possible to build them at all. In other words, alluvial grouting was providing the possibility of building dams on sites which hitherto had been regarded as unsuitable for dams rather than for any reasons of economic comparison.

133. Additives were referred to in § 52 of the paper. There was great advantage in using air entraining agents particularly with a harsh mix as so often happened in Highland locations where it was necessary to use a proportion of crushed rock sand. In one instance difficulties in the early stages of concreting were quickly overcome by air entrainment. In another—a water supply dam—air entrainment was adopted at a rather advanced stage in construction and it later transpired that segregation had occurred in the earlier placing of concrete. When, subsequently, remedial grouting work was undertaken the demarcation level across the dam before and after air entrainment was quite evident in the quality of the concrete.

**Dr W. MacGregor** (George Wimpey and Co.) said that overtopping of cofferdams

took place at five of the 19 sites listed in Table 2, and that flows in excess of diversion capacities occurred at two other sites after construction had been completed.

135. In the period under review, Pitlochry was one of the early dams to be constructed. On reading § 34 of the Paper, one might get the impression that floods had taken the contractors by surprise. In point of fact, at Pitlochry, flood records covering many years were available to the contractor. These were obtained from a Lea recorder station located about  $\frac{1}{4}$  mile downstream from the dam, and showed that floods up to 40 000 cusec had been recorded.

136. After a very careful study of the problem it had been decided to design the first stage cofferdams to allow overtopping from floods in excess of 25 000 cusec and provision was made for flooding the working area through sluices in the upstream and downstream legs. In addition, in order to avoid an unduly high water level upstream, which could flood an area which had been set aside for workshops and shutter construction, a portion of the upstream leg of sheet piling was designed to collapse when overtopped by 1 ft, and so provide a weir about 120 ft long. He had given details of this work in the discussion of Mr Guthrie Brown's Paper on hydroelectric developments at Pitlochry.<sup>4</sup>

137. For 40 000 cusec, about 30 000 cusec could pass through the diversion channel and about 10 000 cusec over the weir and then through four temporary openings, each 12 ft  $\times$  17 ft, which had been incorporated into the first-stage work. To retain the 40 000 cusec completely would have meant an increase of some 6 ft in the upstream water level.

138. Cofferdamming operations on Scottish rivers were generally hazardous because of the risk of flash floods at any time during the year. In situations such as Pitlochry, where diversion took place through a restricted channel, care had to be taken to avoid scouring of the bed material as velocity increased.

139. The velocity in the rectangular channel at Pitlochry rose to about 20–25 ft/sec. but there was no danger of scouring the channel bed because it was rock. In the approaches, however, the piling had to penetrate a depth of gravel, and the details had to be arranged to avoid loss of material inside the box cofferdam, due to scouring on the outside. Hydraulic models were particularly useful in producing the best solution to problems of cofferdam layouts.

140. The most difficult part of the work at Pitlochry, however, had been the construction of the cut-off wall on the left bank, which had required trench excavation through morainic material to depths in excess of 140 ft. The grouting techniques developed for providing non-rigid cut-offs for dams and cofferdams in permeable foundations might provide cheaper solutions, and it would be interesting to know whether the Authors had any experience with this method in conditions similar to those which existed at Pitlochry.

**Mr John Paton** (Babtie, Shaw and Morton) said that having been associated with the design and supervision of construction of some of the dams referred to in the Paper, he was very glad to participate in the discussion.

142. Under the heading 'criteria for selection of design' the Authors stated that comparatively few embankment dams had been built. His own experience in this field led him to the conclusion that rockfill dams did not compare favourably in price if, as was frequently the case in Britain, there was no suitable material occurring locally or no major contribution by disposal of rock spoil from nearby tunnels or underground works served to reduce the amount which had to be quarried.

143. On the subject of earthfill, one might expect this form to be competitive, since unit costs of earthwork for civil engineering had no more than doubled in the past 25 years, whereas mass concrete unit costs had risen about fourfold, striking evidence of the progress in the development of earth-moving plant. The real trouble with earthfill for dams in the Highlands of Scotland was the weather at the generally high elevations at which many of the hydro dams were to be built.

144. At one such dam, built at an elevation of about 1000 ft, the contractor had had all the necessary plant assembled and successfully raised the massive portion of the embankment 12 ft in height in the month of May 1954. Unfavourable weather set in during June and progress, with the same plant and resources available, averaged less than 2 ft per month for the months of July to December of that year.

145. This could be readily understood from a study of the rainfall figures, which confirmed that the average monthly rainfall for the months September to December of that year was approximately 15 in. Estimating under such conditions was obviously extremely difficult for contractors in tendering.

146. In the same section of the Paper reference was made to the application of prestressing and the suggestion was put forward that a height of about 100 ft was the upper limit for prestressed dams of gravity form. If prestressing was favoured for heights exceeding 100 ft there was probably a case for introducing prestressing into buttress or multiple arch types. Such an arrangement would have the main mass of the concrete centred around the groups of prestressing tendons located in the buttress heads but, as far as he knew, there had as yet been no application of this form to practice.

147. Reference was made in the Paper to the use of precasting techniques and, in the conclusions, to the greater use of precast units and leaner concrete mixes as possible trends towards economy. Precasting had been tried extensively and undoubtedly it had worthwhile applications. Closer collaboration at the very earliest stage between the designer and the shuttering expert might, however, sometimes achieve refinement such as was illustrated in Fig. 3, where the latest form of the massive buttress dam so simplified the shuttering that precasting of large elements was unnecessary.

148. On the subject of concrete mixes, he supported the Authors in saying that there was scope for further investigation and economy as mixing and control techniques in concrete advanced. He wished to refer to examples from accepted practice in two branches of civil engineering which differed widely. In road engineering, it was now common practice to use dry-lean concrete of 16 to 1 or even 20 to 1 mix for the road base, whereas the hearting of massive dams incorporated a mix of, say, 8½ to 1. The secret of the dry-lean concrete base was in the dense compaction during construction and this material, after a short period of maturing, was subjected to the incessant pounding of heavy vehicles, whereas the hearting of concrete of a dam was subject to stresses of relatively low value.

149. While he was not advocating a 20 to 1 mix for the hearting of dams, there was, nevertheless, an apparent inconsistency in the wide difference of standards to which he had referred, and he would welcome the Authors' further comments about this.

**Mr W. E. Blackmore** (Sir William Halcrow and Partners) referred to the Authors' mention of gated spillways (§§ 8 and 9) and said he was interested in their effect on the provisions of the Reservoirs Act.

151. The Act was not clear on this subject. On the one hand it might be said that the responsibility of an engineer signing a certificate under the Act was merely to see that there were gates installed capable, if operated properly, of keeping the level of the water in the reservoir below a level for which the dam was safe. On the other hand it could be held that the engineer must concern himself with the frailty of mechanical devices, such as gates, and take the view that their operational reliability was of a lower order than the reliability of the other factors affecting the safety of a dam; in this case he would have to demand that the dam was made safe even if all the gates failed to operate as intended. Mr Blackmore's firm, which had been responsible for the design of a number of the dams listed by the Authors, now followed the latter criterion. What was the practice, in this respect, of the Authors' other consultants?

**Mr A. C. Allen** (Managing Engineer for Scotland, Sir M. MacDonald and Partners) mentioned the Authors' reference in § 23 of the Paper to contraction-joint seals, and asked whether there was already evidence which led to that comment or whether it contained an element of surmise.

153. The Authors also stated in § 25 that bitumen plugs in conjunction with copper or synthetic joints had been used on many of the Board's dams. Some of the dams with which he had himself been associated had the heated bitumen plug alone, without any strip or keyed joint, and it would be useful to have the Authors' comments on this type of joint also.

154. A point which had not arisen so far was the preparation of lift joints. The Authors referred to the discontinuance on later dams of the practice of applying  $\frac{1}{4}$ -in. thickness of mortar to scabbled joints. On the dams with which he was concerned, up to  $\frac{1}{2}$  in. of mortar was specified for this purpose, and he was still in favour of it. It had an advantage in providing strength at the joint and also in reducing the tendency, which was always present at the bottom of a lift, towards honeycombing and voids. This had already been mentioned as a source of leakage at vertical joints. The leakage appeared to come from the vertical joint but, in fact, it might be travelling through voids in a horizontal joint.

155. The Authors stated that experience now showed that this lime-rich layer was particularly prone to attack by peaty water. It was lime-rich because it was cement-rich, and it was difficult to see the difference between the cement richness in this layer and in the upstream face of the dam, where the cement was provided to give extra protection against peaty water.

**Dr M. F. Kaplan** (Civil Engineering Research Association) asked to what extent the present tendency to build more embankment type dams as opposed to arch dams was influenced by the unfortunate disaster at Malpasset.

157. He was interested to note that although the specified minimum compressive strength at 7 days of the 4:1 Trief concrete was 2400 lb/sq. in. the average attained strength was 2024 lb/sq. in. To what extent did this worry those responsible for the construction of the dams?

158. He supported Mr Penman's suggestion concerning the measurement and observation of dams. How often were observations being made on the dams referred to in the Paper?

The following contributions were received in writing:

**Mr P. B. Lodge** (Deputy Engineer and Manager, North Bedfordshire Water Board), wrote that he was interested in the Authors' remarks on preformed plastic and rubber joint seals (§ 24). Had they definite evidence of loss of effectiveness due to ageing? For service reservoirs the synthetic material appeared to be superior to copper strip.

160. In their reference (§ 76) to the Reservoirs (Safety Provisions) Act 1930, the Authors indicated that they would like to see some amendments to the Act. In view of their Board's wide experience with 70 reservoirs some specific suggestions would be useful.

**Mr M. F. Kennard** (Partner, Edward Sandeman, Kennard & Partners) wrote that the lack of development of fill dams compared with concrete designs was obviously due principally to geological conditions. The large glacial drift deposits of clays and gravels and soft rocks such as shale that had led to the development of large and economical dams for water supply in England and Wales are not found in the north of Scotland. This was illustrated by the figures for fill dams in Fig. 5. The few hydro-electric dams of earth- and rockfill cost about £3-£4/cu. yd all-in, compared with about £1/cu. yd for recent large fill dams in England and Wales, such

as Balderhead, Tryweryn, and Derwent (excluding the deep cut-off). None of these designs included concrete core walls, but had rolled clay cores. Until it was possible to have fill dams in the north of Scotland without expensive concrete cores, it was unlikely that fill dams would be economic in cases where there was a choice.

162. The use of moraine materials abroad seemed to have been on different lines from that in Scotland. For example, at the Mattmark Dam, in Switzerland, selection of the moraine enabled core and shoulder material to be obtained from the same source. The core material had fractions greater than 150 mm removed, and with intensive compaction, a co-efficient of permeability of  $1 \times 10^{-5}$  to  $1 \times 10^{-6}$  cm/sec was obtained. The material at this dam seemed to be similar to the moraine used for the shoulders at one dam referred to in the Paper, where a concrete core wall was incorporated in the design. Had any work been done on the possible use of moraine cores in earth- or rockfill designs for hydro-electric dams? At two fill dams at Shira and Orrin, piezometers were incorporated in the fill to measure pore pressures set up during construction. In these cases, the pore pressures were in fact quite low, but it appeared that if the material was such that pore pressures could be expected, then the material should be sufficiently impermeable for use as a core, either with selection, or with some processing.

**Dr D. E. Wright** (Lecturer in Civil Engineering at Imperial College, lately of Messrs Binnie & Partners) wrote that he wished to comment on the section on grouting in the Authors' comprehensive paper.

164. The control of seepage through dam foundations had been the subject of some discussion and<sup>5,6</sup> it seemed probable that single grout curtains, although important for the consolidation of the foundation and closure of fissures, were unlikely to reduce seepage by more than a third of the ungrouted rock flow. Indeed, they might sometimes be much less effective. Even if some of the Scottish dams had been blanket grouted, it was hardly likely that an 'impenetrable barrier' to the passage of pressure water had been created, as stated in § 64 of the Paper. Had any means been found to check on the effectiveness of the grout penetration?

165. In the design of dams, as much consideration should be given to the provision of effective pressure relief systems for the reduction of uplift pressures as to the provision made for grouting.

166. The writer read the statement in § 67 that grouting pressure was generally 0.5 lb/sq. in. per foot of depth to mean that the grouting pressure at the collar of the hole was 0.5 lb/sq. in. per foot of depth of hole, thus effectively doubling the hydrostatic pressure imposed naturally by water standing to the level of the rock foundation. If this was the case, it would appear that on occasions the grouting pressures at shallow rock depths had been much less than the reservoir head. Were water test and grout pressures ever related to the water pressures to which the foundation would be subject at full reservoir head? Perhaps the Authors would comment on this.

167. The granite foundations of the major water-retaining structures of the Cameron Highlands hydro-electric scheme<sup>7</sup> were fissure and curtain grouted in order to strengthen and consolidate the foundation in areas where the rock was open jointed or badly fissured and to provide a measure of decreased permeability in the zone near the upstream face. The writer hoped that the following brief description of the grouting procedure used on that scheme would be of interest when compared with procedure on the Scottish dams.

168. Grout holes were drilled, tested, and injected in stages of 10 to 15 ft, the first stage never exceeding 10 ft in depth. Each stage was then grouted at either a pressure of 25 lb/sq. in. (due regard being paid to possibilities of rock uplift) or the equivalent of 1.5 times the static head below reservoir T.W.L. at the stage concerned, whichever was the greater. The ungrouted rock was considered satisfactory when the loss of water at the specified pressure was less than 0.5 gallon in 10 minutes per foot of hole tested. The hole was drilled on until two successive stages had passed the water-loss

criterion. Whenever feasible, rock grouting was done through one or two lifts of concrete, in order to reduce the danger of rock uplift and make the grout in the upper rock layers more effective by reducing surface leakage. The grout mixes used were similar to those described by the Authors in § 67.

169. At the Ringlet Falls Dam (130 ft high) a grout curtain was formed in unweathered granite, with primary holes at 25-ft intervals and secondary holes in between. The holes were 60 ft deep into rock on average, with a maximum length of about 105 ft. The average cement take was 1.3 lb/sq. ft of nominal curtain area. At the Habu weir (50 ft high) blanket grouting and multiple pressure relief systems were employed because of the unfavourable joint directions in the unweathered granite foundation. The grout holes in the upstream line were spaced at 8-ft centres, went 56 ft deep into rock on average and had a maximum length of about 70 ft. The average cement take of the upstream row was 0.9 lb/sq. ft of nominal area.

170. The cement take at these structures was from one-third to one-quarter of the figure given for Cluanie dam in Table 5 of the Paper. Good homogeneous granites could differ in character quite widely, perhaps through the presence of joint planes which might be partially open, silted up, or which might have been the avenue for chemical weathering.

**Mr T. H. Douglas** (Senior Assistant, Babbie, Shaw & Morton) wrote that reference had been made in § 25 to poured bitumen plugs. At Shira and again recently at Nant the bitumen was performed lift by lift. A half shutter was erected against a completed lift and the bitumen poured, allowed to set and shutter-stripped shortly in advance of concreting the adjacent block. Although care had to be taken in stripping the shutter the method reduced the difficulty of excluding debris from entering plug holes filled in the more usual manner.

172. §§ 59 and 60 rightly emphasized the importance of rigid and smooth faced shuttering. To achieve a surface which would not deteriorate with time, however, it was essential to take proper precautions in placing and compacting concrete. Mishandling skips could nullify care taken in lining up the formwork and patching could never be a satisfactory substitute for a surface properly compacted initially. Although many contractors achieved excellent results there was a tendency among others to use some of their least skilled labour on the receiving end of the concrete and this attitude was to be deplored.

173. Mention was made in the Paper of grouted moraine techniques for cut-offs. Although this had advantages in special circumstances the cost tended to be high. An alternative method of forming cut-offs which might be even better was the bentonite slurry-supported trench of the 'Icos' type. This had, of course, already been used successfully in the Hyde Park Underpass in London and on dam cut-offs abroad. With more sophisticated means of grouting at the engineer's disposal the normal upstream cut-off trench in rock was becoming less important and might possibly be reduced still further in future.

**Mr D. D. Fraser** (Associate, Babbie, Shaw & Morton) thought the Paper constituted a valuable record of the huge programme of dam construction carried out by the Board since the war.

175. It was noted that contractors generally preferred to build concrete rather than embankment dams, even on sites where conditions favoured the latter form of design. This was surprising, as it might have been thought that dams of rock or morainic fill, involving as they did a technique of construction less susceptible to frost delays and adaptable to high mechanization, would have been more attractive on the exposed and elevated Highland sites. Certainly with some moraines the high rainfall could be a deterrent factor but it would be interesting to know if the Authors could advance other reasons for this attitude on the part of contractors and if they foresaw any change as a result of the experience of major embankment construction now being gained throughout the country on major road and motorway works.

176. It was appreciated that the Paper must inevitably be of a general nature, but a large fund of comparative detail data must be available and Mr Fraser would be grateful for information on the following points. (1) Regarding design allowances for uplift, did observations over the various dams suggest that such allowances were generally satisfactory or was it possible to suggest any modifications to the usual rules which would assist future designs? (2) Was it now possible to state a preference between the alternate block and block-and-gap forms of construction? (§ 21 seemed to suggest that the smaller number of contraction joints in alternate block construction should at least reduce leakage slightly). (3) It was encouraging to learn that cement contents had been steadily reduced over the years. Was this trend likely to continue and lead to still leaner and drier hearing mixes, possibly compacted in thin layers by vibrating rollers? (4) In connexion with the measures taken for protection against the aggressive action of peaty water, while such protection was essential at intakes, penstocks and other thin-walled structures, mass gravity and buttress dams seemed unlikely to be affected to the same extent unless the deterioration extended in depth. It would be helpful to have any information which might be available from the older Scottish dams on the rate and extent of such deterioration with time.

Mr A. K. Biswas (Lecturer, Civil Engineering Dept, University of Strathclyde) wrote that there were three distinguishing aspects of the hydro-electric projects of the Scottish Highlands: extensive tunnelling to increase the catchment area, preservation of natural scenery, and conservation of fish. Scotland had no big river systems and the rivers in general tended to be 'flashy'. The natural catchment area of a number of projects was not large enough to warrant construction of a hydro-electric scheme and extensive tunnelling had been done to increase the catchment area. For example, the catchment area of Loch Sloy had been increased from a mere 6.5 square miles to about 31 square miles by tunnels and aqueducts.

178. The Board had taken infinite care to preserve the Highland scene. The Aigas Dam was built higher up the Beaully river than was first planned solely so that it would not interfere with the picturesque outcrop of rock in midstream at Sugar Loaf. Wherever possible, pipe lines had been laid underground, and surface ones painted to match the surroundings and screened by trees and bushes. Power stations built with Scottish stone not only looked elegant but blended smoothly with the landscape.<sup>9</sup>

179. Fishing played a very important role in the economy of the Scottish highlands both as an industry and a major tourist attraction. Vast amounts of time and money had been spent in developing better and simpler fish passes.

180. The Authors stated that 'in areas where there were ample supplies of materials suitable for use as hard or soft fill, and where the conditions were favourable, preference was given to an embankment dam'. However, the writer thought that the main reason for preferring concrete dams was that the relatively high rainfall in the area, well distributed throughout the year, made construction of earth dams rather difficult.

181. The only complaint Mr Biswas had was that with the possible exception of Pitlochry, recreational facilities had been neglected. Water was the focal point of all outdoor recreations and the demand for it was expected to treble by the year 2000. If the dams and reservoirs could be opened for recreational purposes they would not only be a source of pleasure and relaxation for millions of people but would also provide economic benefits for the people surrounding the project for years to come.<sup>9</sup> Possibly the lack of facilities could be attributed to the fact that in some respects, i.e. access to the dams, the Board had no choice.

182. Would it be possible for the Authors to give some idea about the ice pressures, if these were used in the designs? The problem might be serious, due to climatic conditions so far north. Had the Board made any investigations concerning the problem.

The Authors, in reply to the discussion, expressed their pleasure that so many friends and colleagues had attended and spoken. The value of the Paper had been greatly enhanced by the many useful contributions which had been made.

184. They were particularly gratified that the discussion had been opened by Mr Guthrie Brown, who was not only a distinguished engineer and the creator of the *World Register of Dams*, but a friend of long standing. They shared Mr Guthrie Brown's disappointment that so few embankment dams had been constructed, if for no other reason than it would have meant using material that did not have to be transported into the area. One explanation offered by several speakers was that possibly the required fill could not be found near enough to the spot where it was wanted. Another was that where the material was to be taken out of tunnels, the speed at which it came out might not suit the constructional timetable for the dam. In the end, the last word rested with the contractors who, as stated in the Paper, showed in their tendering no apparent preference for embankment dams.

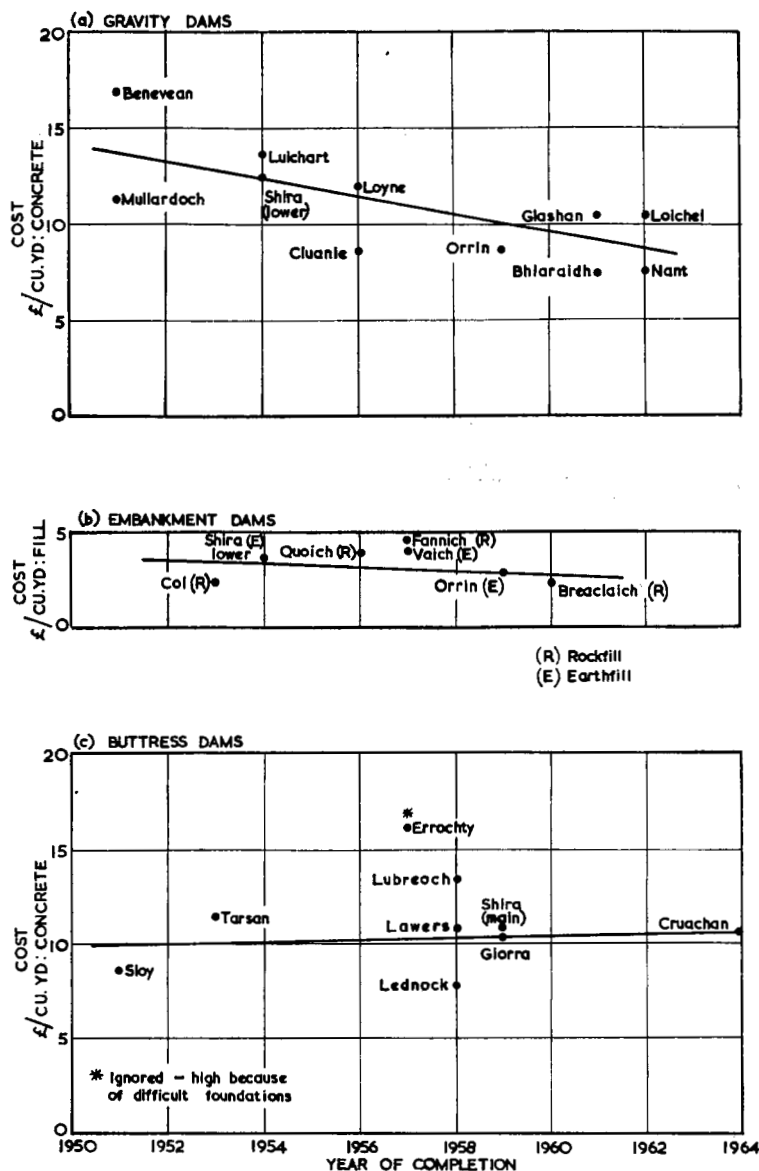
185. It was not unusual for contractors to influence the choice of structures for in the United States and in India there seemed to be little inclination to build thin arch dams. In the former case, one apparent reason for this might have been the lack of opportunity for the deployment of the large constructional plant to which they were accustomed there. In the latter, it might have been for the very opposite reason, namely, insufficient room to deploy all the labour which they wanted to employ on such jobs.

186. The Authors hoped that the Civil Engineering Research Association would not overlook Mr Guthrie Brown's suggestion concerning the need to carry out research into the many problems associated with the design and construction of embankment dams.

187. In answer to Mr Walters' questions about leakage, the Authors did not think that any acceptable degree of leakage had ever been established for hydro-electric structures but, undoubtedly, the aim of every builder of a dam for whatever purpose was that there should be no observable leakage. While it would not be correct to say that this objective had been achieved in the case of the Board's dams, it was the case that most of them were remarkably tight. It was not possible to say what part grouting had played in controlling leakage from the dams in Table 5 because the measurements taken were for flows from all sources and not only from the rock foundations. In no case had the leakage been anywhere near the compensation flow and none were giving cause for concern.

188. In the Paper the Authors had made the point that spillways should be made as long as possible and, consequently, they were pleased that Mr Walters was able to show in Figs 6 and 7 two examples of how the lengths of spillways could be increased. Mr Fulton had had the good fortune of seeing these interesting and attractive spillway structures when, some years ago, he visited Algeria on the same occasion as Mr Walters. He retained, however, the same doubts as he then expressed about using them in a country such as Scotland where surface ice could be expected.

189. When preparing their Paper, the Authors had decided for several reasons not to include any information about dam costs. In any case, it was unlikely that they would have given them on a 'yield' basis as had been asked for by Mr Walters because, in that form, the information could be very misleading. In their opinion, a more suitable basis to use was 'unit content cost'. Even then, the answers for comparison purposes could be affected by inflation over the period of years to which the figures applied and by the difficulty, particularly in the case of hydro-electric dams, of extracting the cost of the dams from the other structures which might have been in the same contract. The position was not made easier when the dams themselves had 'built-in' power stations and included fish lifts and other elaborate provisions for the passage of fish. Subject to these reservations, therefore, Fig. 13 had been prepared to give for (a) gravity, (b) embankment, and (c) buttress dams, separate examples of final costs expressed as cost/cu. yd. As this information was not of



much value without some knowledge of the extent of the inflation over the period concerned, Fig. 14 had been prepared to show how, since 1945, the value of money had changed and the rates of pay and allowances had increased. The extent to which unit costs had risen or fallen over the period indicated whether inflation had been kept at bay or not.

190. In his remarks Mr Dixon expressed some disappointment that a larger selection of dams had not been included in Tables 1 and 2. Since the discussion, the Authors had supplied him with data about several more dams, and these had been included in the discussion.

191. Mr Dixon had made good use of the information provided in Tables 1 and 2 and the addenda (Tables 1A and 2A) by preparing his diagram (Fig. 8). In acknowledging the value of the work, the Authors were pleased to see that in the bulk of the cases the total discharge capacities, after construction, were either close to the normal maximum flood line or well above it.

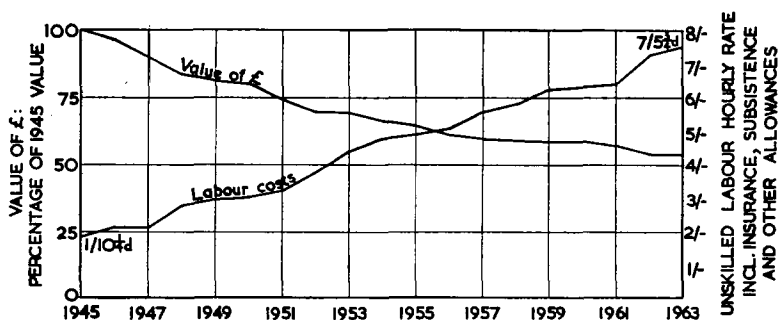


FIG. 14: VALUE OF £ STERLING AND LABOUR COSTS

192. It was also useful to know of Mr Dixon's success in using colloidal concrete and of the conditions for which he considered its use was particularly suitable. Since the Paper had been discussed, the Authors' faith in this material for dams had been somewhat shaken by the receipt of a disappointing report about the condition of some of the concrete on the downstream face of the dam of this type at Loch Dubh at Ullapool referred to in § 51 of the Paper.

193. Mr Gerrard's remarks constituted a strong plea on technical as well as on economic grounds for a greater use of siphon spillways and in Figs 9 and 10 he illustrated two current applications. The Authors had had some experience with dams equipped with siphon spillways but they could not say that these had proved entirely satisfactory in operation. As with most siphons they came on rather quickly and because of the suddenness with which they reached full discharge, they had created complications for other users downstream. Also, apart from trouble from ice getting into the air valves, the control of the making and breaking of the siphons had always been difficult, with, in addition, an associated tendency to vibration. They had had no experience of the siphon hoods shown in Fig. 9 but if the control obtained with air-regulation was as successful as he had indicated and provided that the hoods gave no trouble when there was ice about, there was no reason why a use could not be found on future schemes in Scotland for siphons of the type he advocated.

194. The Authors agreed with almost all the comments by Mr Roseveare but considered that an additional reason for the disappearance of masonry in the construction of dams was the almost complete lack nowadays of the skilled craftsmen needed for such construction.

195. The Authors were grateful for the high opinion which Mr Penman had expressed about the accuracy of the measurements of dam movements given in Fig. 15. The whole question of measurement and the instrumentation of dams was arousing great interest everywhere and it would not be long before the need to make proper provision for observation would become a 'must' for all dams. It was as well, however, that everyone should understand what this might involve. Apart from the provision of reference points, precise bench marks and such special items as inverted plumb bobs of the type shown in Fig. 16, the amount of work involved at site in doing the check readings was quite considerable. To be of any value (a point Dr Kaplan had raised), site checks were required quarterly or half-yearly and on a complicated structure such as an arch dam a full round of measurement might occupy an experienced surveyor and an assistant for anything up to a week. Mr Penman had outlined some of the provisions which he considered should be made on embankment dams. Altogether, the extent of the requirements on such dams could be quite elaborate, involving as they might settlement and deflexion gauges on the core wall or, where the dam had an upstream membrane, on the face slab, and, to facilitate the various observations, possibly inspection shafts in the dam as well.

196. The Authors did not think that there was much prospect of the fulfilment of Mr Penman's suggestion that there might be, as in France, some kind of governmental organization to carry out the measurement of the behaviour of dam structures but were sure that the North of Scotland Hydro-Electric Board would be very willing to make available staff and equipment to undertake measurement for owners of dams who were not as well equipped as they were.

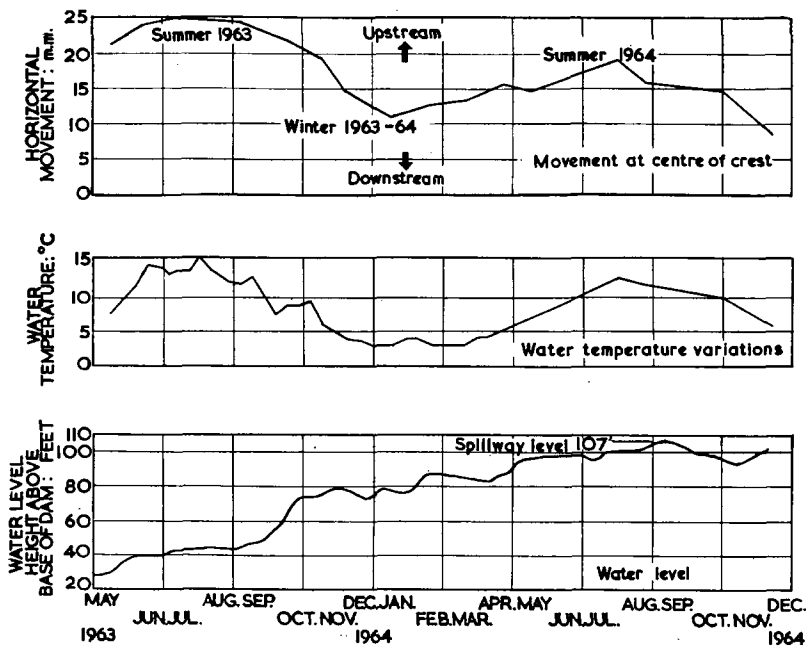


FIG. 15: MONAR ARCH DAM: READINGS

197. Part of Mr Chapman's contribution had been devoted to describing the measures which his firm had taken to eliminate the very slight leakage which had occurred at the closing gaps of the earlier dams. The Authors agreed that while a 'weep' might do no harm, its disfiguring effect was surprisingly great.

198. Mr Chapman had also dealt with the question of the cost of putting a spillway on a buttress dam. He had made the point, and the Authors agreed with him, that, compared with gravity dams, the buttress dams showed the greatest saving in cases where the spillway was short, as usually happened if the natural catchment was considerably smaller than the whole catchment which was being developed.

199. Mr Banks had given some useful additional information about the intensity of grouting at two other dams of which he had knowledge and as the range in the results which were being obtained was so wide this, in his view, demonstrated the need for greater knowledge of rock mechanics from more study and research.

200. He had also expressed the view that alluvial grouting would enable dams to be built on sites where it would not have been possible to build them at all before but obviously this could only be done with due regard to cost.

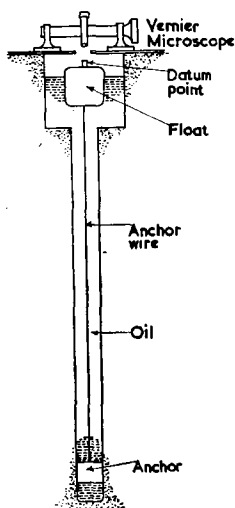


FIG. 16: INVERTED PLUMB WIRE

201. Because of the way in which the Authors had referred to the overtopping of the Pitlochry cofferdam, Dr MacGregor had quite naturally taken the opportunity of explaining that in designing the cofferdam, it had all along been intended that it would allow overtopping when floods exceeded 25 000 cusecs. There had been no question, therefore, of his firm having been taken by surprise when floods exceeded this figure.

202. In reply to his question about the use of grouting to provide a non-rigid cut-off in permeable material, the Authors had had no experience of the use of this technique in morainic conditions similar to those experienced at Pitlochry.

203. Mr Paton had given some very good reasons why so few embankment dams had been built in the Highlands. He blamed the weather for the absence of earthfill dams and while the Authors agreed, they would also like to add the further explana-

tion that an earthfill dam using fine material was not altogether suitable for a hydro-electric project which might require a rapid drawdown. They would certainly not like to see an earth dam with a central core on a pumped-storage project. Mr Paton had opened up some exciting prospects in suggesting (1) the use of prestressing in buttress dams, (2) the greater use of precasting, and (3) the adoption of really lean mixes for hearting concrete. As to the latter, the Authors had had no experience in concrete as lean as 20 to 1 but they do not see why, if properly compacted, such a concrete mix should not be used. If it were economic to do so, they would even be prepared to introduce plums into such concrete. They were certain that very lean concrete could not be a success unless sufficiently dense and impermeable layers of concrete were provided on the upstream and downstream sides of the hearting to protect it from the incursion of the aggressive type of water which was so universal in the Highlands.

204. Mr Blackmore had asked what general practice had been adopted by the Board's Consultants in making allowance for the safety of a dam on the failure to operate of discharge gates provided to pass floods.

205. There was really no doubt about the answer. Anyone designing a dam had to be satisfied that it would be safe in any foreseeable circumstances. Fortunately, it was usually possible to minimize the problem by, for example, not placing reliance for flood discharge wholly on the gates and also, wherever possible, by using self-operating gates rather than those dependent on outside supplies.

206. In reply to questions by Mr Allen and Mr Lodge about contraction-joint seals, the Authors had no evidence that seals of other materials would not last as well as copper. Their views were, as the former had suggested, largely based on surmise supported to some extent by a natural preference for an inorganic rather than an organic material. So far, there was no sign that the leakage on the dam to which Mr Allen referred, which had only heated bitumen plugs was any greater than that occurring at dams which were more elaborately or differently equipped. Mr Allen had expressed himself in favour of continuing to 'butter' lift joints with a  $\frac{1}{4}$ -in. thick layer of rich cement mortar. The Authors' objection to this procedure had been given in the Paper and they still considered that the presence of even a thin band of an extravagantly rich mortar presented aggressive waters with an excellent opportunity of attacking a particularly high concentration of free lime.

207. Dr Kaplan had asked whether the Malpasset disaster had influenced the choice of dams. Actually it had not. For the reasons given in the Paper, there were singularly few sites in the Highland which lent themselves to the adoption of thin arch dams of the Malpasset type. Dr Kaplan had also asked whether the low compressive strengths obtained after seven days for Trief concrete had worried those responsible. They were certainly a little worried at the time but this concern disappeared when the 28 days' tests were carried out, as these gave results very much better than specified. It had to be remembered that when the first tests were made there was no experience to go by and blast-furnace slag was being used about which very little was known.

208. In his written contribution Mr Lodge had asked if the Authors would indicate what amendments they had in mind for the Reservoirs (Safety Provisions) Act 1930. About the time when they had prepared their Paper, the Authors had been given an opportunity to submit their views on the operation of the Act and these and other representations were now being considered by a Committee appointed by the Institution to consider possible changes in the Act. In these circumstances, apart from the difficulty of making a summary, the Authors felt it would serve little purpose if they were to attempt to set out here their views on the matter.

209. Mr Kennard in his submission gave it as his opinion that the lack of development of fill dams in Scotland had been due principally to geological conditions and suggested that until it was possible to have fill dams built in Scotland with cores of clay or suitable morainic material, fill dams would not be economic. Unfortunately, the Highlands of Scotland were very deficient in clays and in the type of moraine suit-

able for core walls and until a cheap way could be found of processing the material available, there was little chance of any change in the relative numbers of concrete and fill dams.

210. In addition, of course, both Mr Paton and Mr D. D. Fraser in their contributions had made the point that the high rainfall in the Highlands constituted a great deterrent against earthfill dams. In their reply to Mr Paton, the Authors had also indicated that wherever there was any question of a rapid rate of drawdown, they would not favour a fill dam with a central core.

211. In his comments Dr Wright had shown particular interest in grouting and had added to the value of the Paper by giving details of the grouting procedure adopted for the water-retaining structures on the Cameron Highlands hydro-electric scheme. His figures of cement absorption were much lower than those given in the Paper and very much below those given by Mr Banks. They helped to reinforce the point made by Mr Banks that a great deal more research was required on this subject.

212. Dr Wright also asked whether water-test and grout pressures were ever related to the water pressures to which the foundation would be subject at full reservoir head. To the best of the Authors' knowledge, this was done but a decision on such a matter was always left to the judgment of the engineer responsible for carrying out the work with his knowledge of the conditions at site.

213. The description which Mr Douglas provided of the methods he used for pouring bitumen plugs was very interesting, although the Authors considered that it carried the risk of damage to the plug during later construction of the adjacent block. Also, they thought his fears concerning adequate compaction when placing concrete in blocks would be largely overcome, in cases where space allowed, by the use of bulldozers and track vehicles for spreading and consolidating the concrete.

214. In answer to the questions put by Mr Fraser, the Authors had the following replies. (1) They did not know of any observations which would justify a change in the usual design allowances for uplift. (2) They had no preference between the alternate block and block-and-gap forms of construction. Very often the decision was controlled by the completion programme. The block-and-gap method, although giving more possible sources of leakage, was usually somewhat quicker. (3) As indicated in the Paper, the Authors were in favour of leaner hearing mixes but had made it clear in replying to Mr Paton that these should not be used unless the hearing was well surrounded by dense concrete. In the case of mass gravity and buttress dams, the Authors were not in favour of any relaxation in the measures taken against the aggressive action of peaty water. The extent to which deterioration could penetrate was surprisingly great and had often reached 3 in. or more. Apart from appearance, a deterioration of this amount could have serious results and should be avoided at all costs.

215. The Authors thanked Mr Biswas for the interesting review he had given of the general circumstances surrounding most of the projects in the Scottish Highlands. In reply to his question about access to dams and reservoirs for recreational purposes, they could only repeat that, so far as the Board were concerned, they had no choice. The decision about access was one for the Estate proprietors alone. The position would be different if Local Authorities could be persuaded to take over and look after the access roads on private land but, so far, none had shown any interest in doing so.

216. Finally, the Authors had no knowledge of any case where the dam design took account of ice pressure.

217. In response to the requests for additional references, the Authors added a further selection.<sup>10-17</sup>

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