

CORRESPONDENCE

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Allt-na-Lairige prestressed concrete dam †

by

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Mr R. J. T. Casinader (Assistant Engineer at Glenmoriston for Sir William Halcrow and Partners, Consulting Engineers) remarked that despite the use of prestressing the maximum compressive stresses under load were quite low. In drawing attention to that feature the Author had stated in § 26 that "any further reduction in the section of the dam to take advantage of the inherent strength of the concrete would have adversely affected the overall economic position by the increased cost of prestressing and the increased provision necessary by way of anchorage". To what extent was that position affected by the decision to adopt a uniform prestressing force throughout the length of the tendons?

149 Referring to Fig. 5, although the profile above the 955·0 O.D. level was extremely slender the profile below that level broadened out considerably by comparison; that was accompanied by a reduction of the maximum compressive stress under load to extremely low values of the order of 60 lb/sq. in. at the maximum height of 73 ft. In accordance with the decision to adopt a uniform prestressing force throughout the length of the tendons, any improvement in the lower part of the profile could only have been achieved by increasing the tendon force not only in the lower part but also in the upper part, which was obviously uneconomical. If, in view of that, the original decision had been reconsidered and the prestressing force in the lower part only increased (that was, by anchoring the additional bars off at, say, the 955·0 O.D. level), would the overall economic position still have been adversely affected? Intermediate stressing of the tendons might not have been too complicated, since the bars had to be coupled at intermediate levels anyway.

150. The height of the dam was quite moderate, but one might expect future cases where prestressed designs were considered for dams of heights up to 200 ft or more. A rough design theory for such a dam indicated that in order fully to utilize the inherent strength of the concrete in compression at all levels the prestressing force should increase progressively with the height of the dam. Whilst a continuous increase in the prestressing force was not practicable it might be economical in higher dams to adopt a number of stressing levels, say, 30 to 40 ft apart, so that the theoretical condition was approached. With careful programming of construction such a design might prove feasible. Hitherto in the raising or strengthening of old dams it had obviously not been

† Proc. Instn Civ. Engrs, vol. 6, p. 409 (Mar. 1957).

possible to prestress at an intermediate level, but in prestressed dams constructed as such, stressing at intermediate levels was not only possible but was probably essential in the economic design of structures of any considerable height. Would the Author comment on that in the light of his experience with the Allt-na-Lairige dam?

151. Turning to the question of the anchorages and the base of the dam, it might be said that the purpose of prestressing was to induce a favourable stress distribution, in the first instance, at the base of the dam. Had the depth of anchorage been so arranged that the concentrated stresses at the anchorage were sufficiently dispersed to give the required stress distribution at the base of the dam and had any field measurements been made of that stress distribution due to prestressing? That consideration would determine the smallest depth of anchorage allowable with respect to the distance from the tendon to the toe of the dam at the base, irrespective of the magnitude of the tendon force. Was it merely a coincidence that in the section of the dam in Fig. 4 the depth of anchorage was such that with a maximum angle of dispersion of 45° full dispersion of the stress at the base was just achieved? Inasmuch as that dispersion was essential for the proper working of the dam, would the Author comment on it? It would appear to be a problem suitable for investigation by a photoelastic model. Designs for higher dams might require cables at much closer centres than had been used hitherto, with consequent overlapping of anchorage stresses; photoelastic models could give some indication in that case as well.

152. Finally, could the Author give the costs of prestressing the dam, say, in terms of a rate per ton-foot of tendon force, and a rate per ton for the anchorages?

Mr O. C. Anderson (Senior Assistant Engineer, City Engineer's Department, Lincoln) observed that attention had been drawn in both the Paper and the discussion to the substantial keying of the vertical joints to ensure that the dam acted as a continuous unit. What type of horizontal construction joint had been adopted between the 5-ft vertical lifts? It appeared from Fig. 18 that seepage had, in fact, occurred at a number of points along the length of the dam to a depth of about 26 ft below the water level shown (assuming that, at the time of the photograph, that was about 14 ft below overflow level).

154. Presumably, the seepage had been quickly stopped; would the Author comment on the degree of construction-joint seepage encountered as compared with that likely to be encountered in a thicker-section gravity dam of equivalent duty? Was it his opinion that the presence of the very considerable vertical prestress loading had any marked effect on seepage generally?

Mr P. O. Wolf (Lecturer, Department of Civil Engineering, Imperial College, London) observed that, in addition to the details described by the Author, the Allt-na-Lairige Scheme had some other features capable of pointing a lesson to water-power engineers. He recalled that, towards the end of 1945, the late Mr James Williamson, M.I.C.E., had had the duty of advising the North of Scotland Hydro-Electric Board on the details of the development of the Loch Sloy Project. That task included a study of the economics of diverting to Loch Sloy numerous streams over distances up to 6 miles. The Allt-na-Lairige, at a distance of approximately 3 miles from the head of the enlarged Loch Sloy reservoir, was one of the streams considered in that connexion.

156. As Mr Fulton had stated earlier in the discussion, the decision on the kind of development most suitable for any given valley was largely based on an economic comparison, with the yard-stick provided by the unit costs of the energy produced by steam power-stations, varying for different degrees of certainty of supply, different load factors, and also with distance from the nearest load centre on the "Grid".

157. There was a second side to the economic study, which consisted of the broad consideration of the use of the natural resources of the country. It involved the development of each area, possibly beyond the stage where the best commercial return was obtainable, right up to the limits set by the first economic test outlined above.

158. The decision to develop the Allt-na-Lairige Scheme on its own, instead of making it a part of Loch Sloy, would be shown to have been fully justified by a comparison of the figures in Table 2. Allt-na-Lairige was not among the large schemes in the North

of Scotland, but both in its broad conception and in the details described by the Author it proved that the Hydro-Electric Board and its advisers were keenly aware of the national advantage of the widest use of the waters from even the smaller catchments.

TABLE 2.—COMPARISON OF ALTERNATIVE DEVELOPMENTS

	Part of Loch Sloy scheme (approximate figures)	Independent scheme
Level of intake on Allt-na-Lairige: feet above O.D.	1,033	993
Volume of dam: cu. yd	1,000	As described
Catchment area: square miles	4.5	5.3
Length of small diversion aqueducts: miles	4	1.5
Length of diversion tunnel: miles	2.3	—
Length of large aqueduct to be increased in size (Sloy No. 9): miles	1.2	—
Length of 6-ft × 7-ft-3-in. tunnel: miles	—	1.25
Length of 4-ft-6-in. to 3-ft pipeline: ft	—	1,750
Additional plant installed: kilowatts	—	6,000*
Average annual output: millions of kilowatt-hours	15	20
Potential energy equivalent of reservoir storage: millions of kilowatt-hours	—	1.5 originally assumed 2.0 as constructed

* 4.6% of plant installed in Loch Sloy power station.

The Author, in reply, stated that Mr Casinader's final queries had a bearing on the other matters he had raised. The cost of the anchorage worked out at 17s/ton of prestress, and the tendons in the dam above rock level at 3½d/ton-ft. Those rates were comprehensive. The cost given for the anchorages covered rock excavation, bars, wrapping, etc., and the concrete filling in the pits. That of the tendons included forming the temporary shafts and other contingent work in addition to the bars and prestressing.

160. The Author's statement in § 26 was not affected by the decision to adopt a uniform prestressing force throughout the length of the tendons; in fact, curtailment of the bars would have increased the cost of the dam because of the complications involved in prestressing at intermediate levels. Bearing plates, located about 10–12 ft higher than the theoretical point of curtailment, and steel reinforcement similar to that provided at the top of the dam would have been required to distribute the concentrated prestress load applied at intermediate levels. The cost of those provisions would have far outweighed the saving in high-tensile steel bars apart from the effect on progress by interruption of concreting operations and time intervals for maturing. The unit cost of the tendons in the anchorage was about three times that of the tendons above rock level and it would have been uneconomical to increase the anchorage even had there been a case otherwise for curtailment of the bars at the higher levels.

161. With higher dams there might be advantage in prestressing at intermediate levels as Mr Casinader had suggested but the Author remained doubtful; each dam would have to be considered on its merits. A prestressed dam was in effect, a cantilever of varying cross-section and economies were more likely to be achieved by reducing the volume of concrete (as with buttresses) rather than by curtailment of the tendons. The relative cost of shuttering to concrete in forming buttresses was obviously a significant factor.

162. The required depth of anchorage was dependent on the weight and strength of the rock and was not influenced by the base width of the dam. In the event of overturning arising from inadequate anchorage the wedge of rock contained within the lines of shear failure would move with the dam, and whether or not the angle of dispersion from the

bottom of the anchorage intercepted or was out with the base of the dam was of little significance. It was a mere coincidence that in Fig. 4 the 45° angle met the downstream toe of the dam.

163. No field measurements were made to ascertain the stress distribution at the base of the dam. Photoelastic model experiments could give useful results, particularly with regard to overlapping of the anchorage stresses, but since the tests would have been made on a homogeneous material they could not replace full-scale tests on the rock to determine its anchorage value.

164. In reply to Mr Anderson, the procedure in forming the horizontal construction joints in the dam had been thoroughly to remove all laitance and roughen the surface of the set concrete before the next pouring was made. The prepared surface was covered to a minimum depth of 2 in. with a richer concrete ($3\frac{1}{2}$ quality) before the main mass of the concrete was deposited. The seepage referred to by Mr Anderson was little more than a "sweat". There had been no significant run of water at any point on the downstream face of the dam. It could be seen from Fig. 18 that where seepage had occurred it extended over a short length of a horizontal joint where it intercepted a vertical joint and there was little doubt that the main path of seepage was through the latter.

165. It was reasonable to presume that the application of the prestress force had had a beneficial effect on the horizontal joints. More pronounced leakage (which had been sealed) had occurred through the horizontal joints of the control tower gravity block. Apart from that there was no positive evidence that the dam was more free of seepage than would have been the case with a well-constructed gravity dam.

166. The pros and cons of developing the Allt-na-Lairige catchment as an independent scheme compared with diversion of the run-off to Loch Sloy had been, of course, investigated at the outset. The Author was grateful to Mr Wolf for his remarks on that aspect and for the comparative information he had set out in Table 2.

Structural Paper No. 51

The analysis of prestressed concrete structures and the application of recent research †

by

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Mr J. E. Spindel (Senior Engineering Assistant, Bridge Design, London Midland Region, British Railways) stated that making full use of materials of construction was only possible if the behaviour of materials and structures was fully understood. Complete understanding might be unattainable but research such as that described in the Paper, apart from its intrinsic interest, went a long way towards it. The application of the results, however, often uncovered further problems.

222. He was glad to see that one of those, namely, the effect of isolated point loads on slabs, had now received some attention. The "elementary" slab equation (equation (19), § 67) neglected stresses perpendicular to the plane of the slab and led to the absurd answer that bending moments under a point load were infinitely large. The artifice of treating point loads as being distributed over small areas avoided the absurdity, but made the

† Proc. Instn Civ. Engrs, vol. 6, p. 445 (March 1957).