Fig. 1. Loch Benevean at the new level, showing part of the road diversion to Glen Affric

The Glen Affric Scheme

The Mullardoch-Fasnakyle-Affric scheme has involved the construction of two dams, two tunnels, a main generating station at Fasnakyle, and a subsidiary underground station at Mullardoch. An unusual operation is being carried out at Mullardoch, where the height of the dam is being raised while the dam is actually under construction

PART ONE

THE North of Scotland Hydro-Electric Board's Mullardoch-Fasnakyle-Affric scheme, which is now in an advanced stage of construction, is expected to produce some 230 million kWh per annum from a catchment area of 124 square miles in Inverness-shire and Ross-shire, having an average annual rainfall of 107 in. One of the many points of interest in this scheme is the way in which it has been planned to preserve the amenities of the district. Glen Affric is one of Scotland's most famous beauty spots, and two earlier private-company's schemes, promulgated in 1928 and 1941 respectively, were successfully opposed. Both of these schemes proposed to convert Loch Affric and Loch Benevean, lying farther down Glen Affric, into one large sheet of water, which, in the opinion of many, would have ruined the beauty of the Glen.

In the scheme now under construction, Loch Benevean has been raised by only 23 ft.—a height that has left Loch Affric untouched—and the main storage is to be derived from Loch Mullardoch in Glen Cannich lying immediately to the north; this loch is being raised by 113 ft. and will carry the bulk of the fluctuations in storage. Thus the main inundation and the fluctuations in water level inseparable from such a scheme have been transferred from Glen Affric to the more remote Glen Cannich, to which, prior to the Board's activities, the only access had been by a rough cart track.

Before the level of Loch Benevean could be raised, the part of the road running alongside the river Affric and Loch Benevean had to be diverted and run at a higher level on the flank of the valley. The new road, which has wide, open verges and several strong bridges, affords a much better prospect than did the road in the valley bed, and we gather that

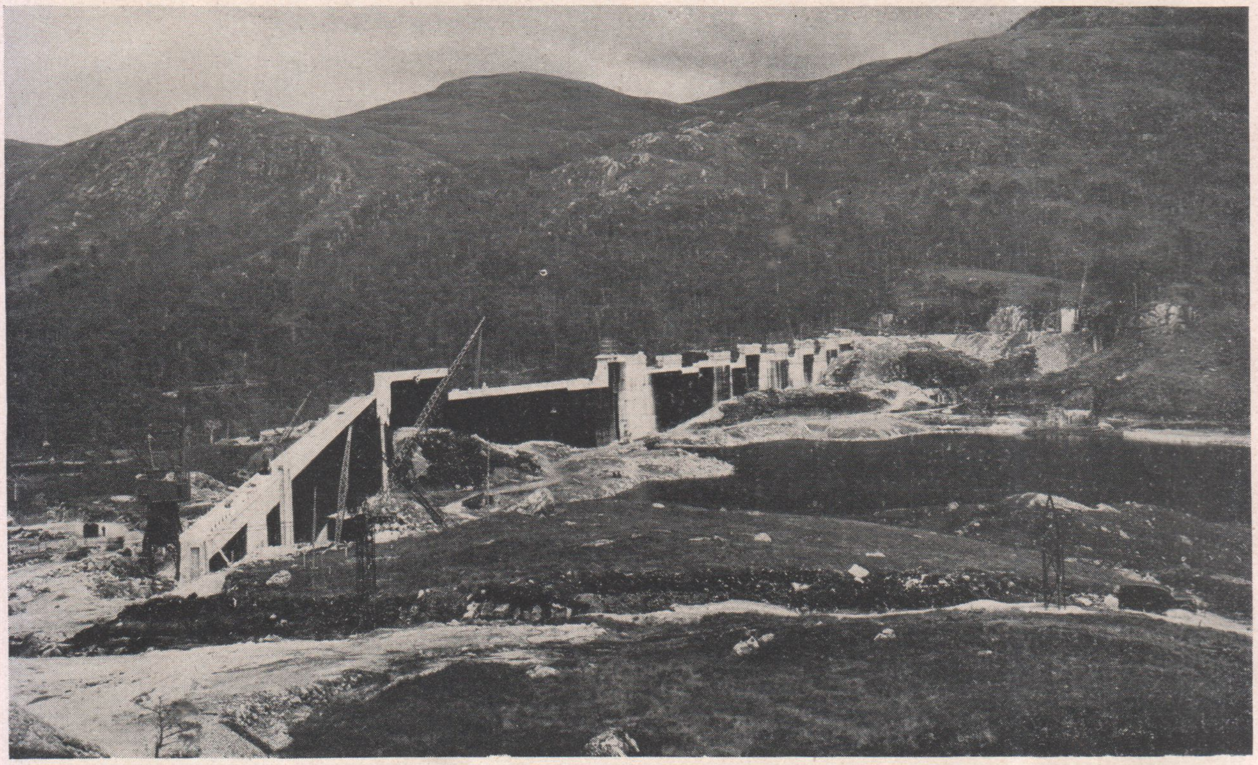

Fig. 3. View looking downstream of the Mullardoch dam before ponding commenced, showing the two wings abutting on the central island

now that the level of the loch has been raised, some who were previously most doubtful of the effect of this scheme on the amenities are now commenting on the improvement in the scenic attractions of Loch Benevean. That this is no idle comment may be gathered from the glimpse of the loch which we reproduce in Fig. 1.

Another development brought about by the scheme has been the improvement of the road from the power station at Fasnakyle to the Benevean dam and the reconstruction of the ten-mile track from Cannich to Loch Mullardoch into a motor road. As reconstructed, these are single track with passing places.

Outline of the Scheme

Mullardoch dam, at the eastern end of the loch, is the biggest dam now under construction in the Board's area, and is 2,385 ft. long by 160 ft. high to deepest foundation. It will raise the loch level from 705 to 817 ft. O.D., and by converting Loch Mullardoch and Loch Lungard into one large sheet of water will provide a storage of 175,500 acre-feet.

From Loch Mullardoch to Loch Benevean a tunnel has been driven 5,738 yards long and of horseshoe section with an equivalent diameter of 15 ft. 9 in. Excavation is also in progress for a 2,400 kW underground station near the Mullardoch intake to make use of the difference in levels between the two lochs.

At Loch Benevean the dam is 582 ft. long and 125 ft. high, and has raised the level from 712 to 735 ft. O.D.

From Loch Benevean a main power tunnel extends a distance of 5,788 yards to a generating station, containing three 22,000 kW sets, at Fasnakyle on the north bank of the river Glass. This tunnel is in three sections—a low-pressure section 4,113 yards long, of horseshoe section and of 14 ft. 6 in. equivalent diameter, a high-pressure circular section 1,408 yards long and 14 ft. 6 in. diameter, which trifurcates near the power-station into three steel-lined tunnels each 8 ft. 4 in. in diameter and 800 ft. long. The low-pressure and high-pressure tunnels are connected by a 341 ft. vertical shaft which continues upwards for a further 150 ft. to form a 45 ft. diameter surge shaft.

Preliminary works for the scheme were on a large scale, and in addition to the road improvement and diversion already mentioned, involved the building of two labour camps and a temporary generating station. The main labour camp was situated at the village of Cannich, in Strathglass, and provided accommodation for 1,400 men. A subsidiary camp at Cosac near the Mullardoch dam houses a further 700 men. The temporary power station was also located at Cannich and consisted of six 600 kW 11,000 V Mirrless/Bruce-Peebles diesel-alternator sets feeding two 11,000 V transmission lines serving the working sites in the two glens. Subsequently these lines were fed from Beauly substation via Kiltarlity, the supply being stepped down from 33,000 V, and the temporary station shut down. The capacity of the Cannich station has been reduced to 1,200 kW and is used as a standby.

Mullardoch Dam

Upstream and downstream views of Mullardoch dam appear in Figs. 3 and 4, and a general arrangement drawing is given in Fig. 2. At this point the watercourse is divided into two branches separated by a central island, and the dam has accordingly been built in two wings inclined to one another and each having an abutment on the island.

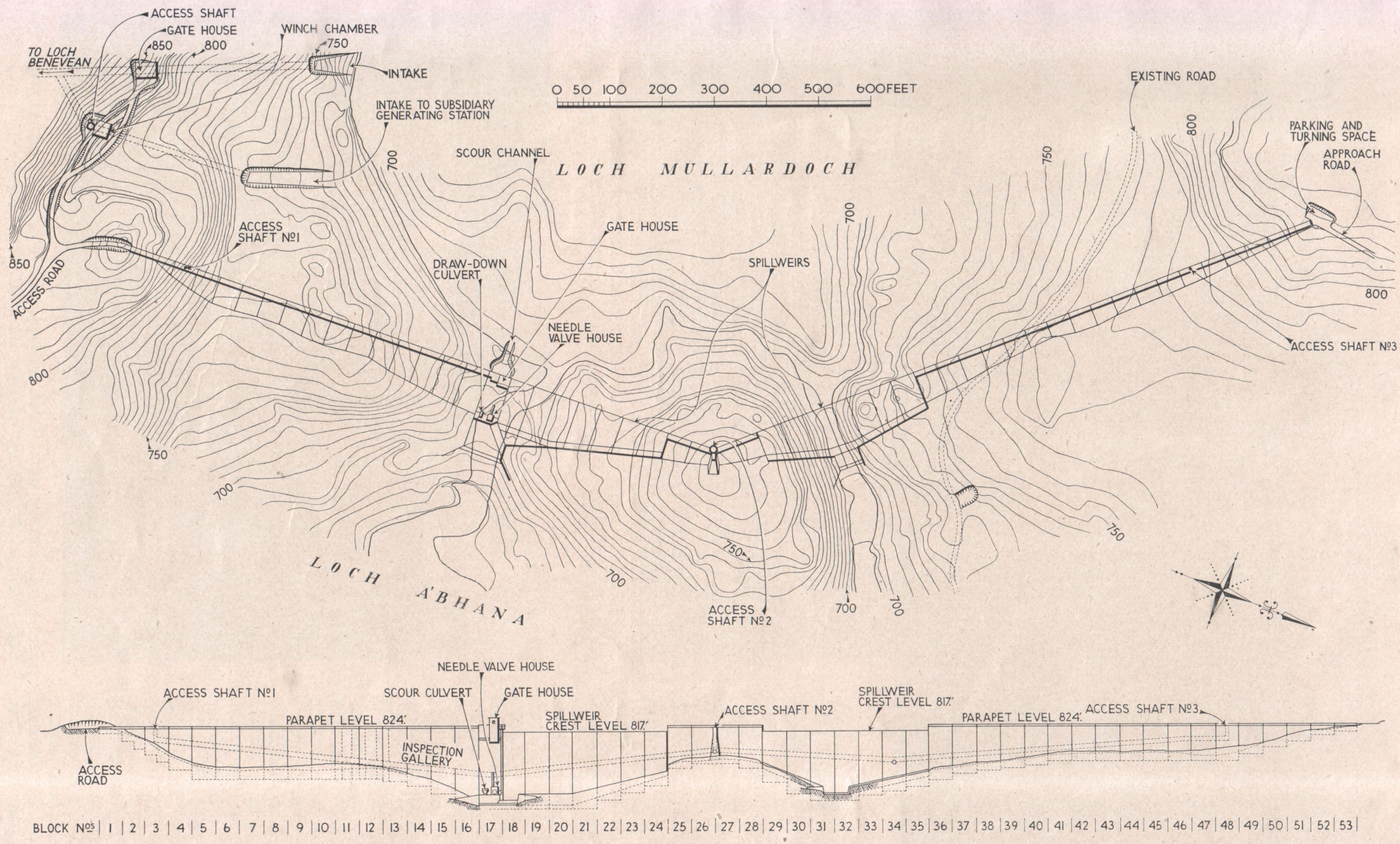

Fig. 2. Plan and elevation of Mullardoch dam, showing the location of the tunnel intake and of the subsidiary generating station

Fig. 4. View of the Mullardoch dam looking upstream, taken after ponding had commenced

Each wing has a spillway 315 ft. wide, and the south wing (on the right-hand flank) is equipped with a needle valve and scour culvert. The dam is of the mass-concrete gravity type and is about 100 ft. thick at the base; it has involved the excavation of some 113,000 cu. yards of rock to payment lines, and will contain 309,900 cu. yards of concrete.

The design of the spillweirs and spillway channels was determined by model tests. Both spillweirs are considerably wider than the watercourses into which they discharge, and the problem was to secure that the water discharged centrally into the watercourse with its excess energy dissipated. This was complicated by the fact that the spillways are not disposed symmetrically about the watercourse. Steps and horizontal sections have been introduced where required into the spillway channels to prevent the downcoming water from leaping over the retaining wall and to regulate the flow into the respective stilling pools. The toe of each spillway is faced with basalt ashlar pitching.

No particular difficulties were encountered in preparing the dam site, which consisted of a rock bed overlain by some moraine and a thin layer of peat. The cut-off trench ranged from 6 to 12 ft. deep except at the outfalls, where the depth was increased as found necessary. The trench was 5 ft. wide at the bottom and was given a batter of 1 in 4. Grouting holes, 3 ft. apart, were sunk from the bottom of the trench to a depth of 20 ft., and grouted at pressures ranging from 40 to 100 lb. per sq. in. In two areas where the rock was of poor quality, a second grouting stage was included, 40 ft. holes being driven between the 20 ft. holes and grouted at pressures up to 100 lb. per sq. in. Two 40 ft. holes in each 45 ft. block were tested for leakage prior to grouting.

Aggregate for the dam is being obtained from a quarry about three-quarters of a mile downstream of the site on the northern flank of the glen. The rock, a psammitic schist, is crushed in a Cedar Rapids

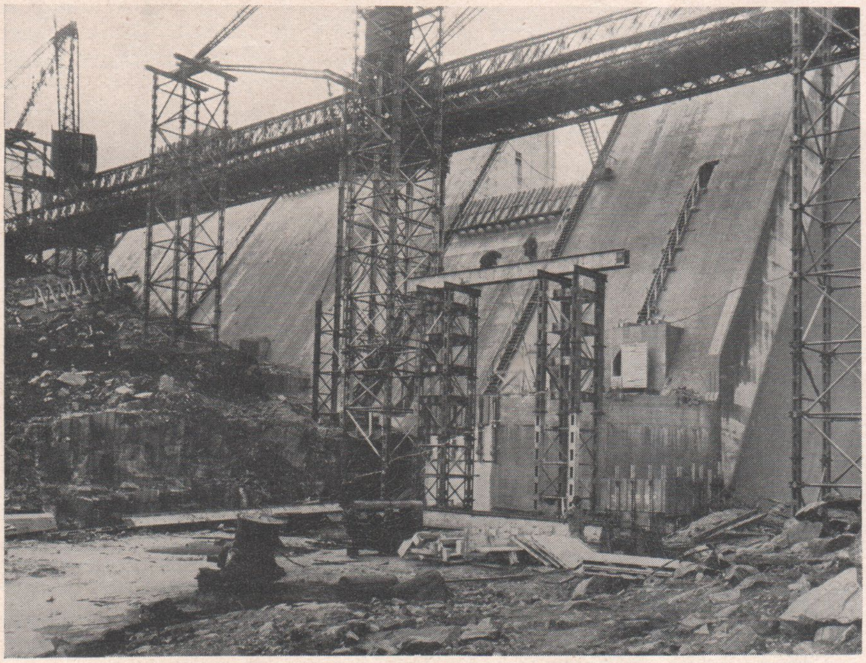

Fig. 5. Mullardoch dam, south spillway stilling-pool section, showing the Bailey bridge carrying the rails for the concrete trolleys

portable crusher and graded to $2\frac{1}{2}$-$1\frac{1}{2}$ in., $1\frac{1}{2}$-$\frac{3}{4}$ in. and $\frac{3}{4}$-$\frac{3}{16}$ in., in which form it is conveyed by an aerial ropeway to the storage silos of the batching and mixing plant, which is located at the northern end of the dam site. Sand procured from a local deposit upstream of the site is carried by the same ropeway, and cement is brought by ship to Inverness and thence by road.

The mixing plant consists of three Stothert & Pitt 1 cu. yard mixers discharging into bottom-opening skips of 2 cu. yard capacity. These skips are carried in pairs on trolleys running on a 2 ft. gauge track, and rakes of one or two trolleys are taken to site by Hudson and Simplex diesel locomotives.

One of the valuable inventions of the last war was the Bailey bridge, and we were particularly interested to find a Bailey bridge in use to carry the concrete trolleys along the dam site. As will be seen from Fig. 5, this bridge spans the site immediately on the downstream side, and carries a double line of rails. Eight electric derricks are disposed at intervals along the site to transfer the concrete skips from the bridge to the dam, and there is also a travelling electric derrick and a steam derrick.

For purposes of construction the dam has been divided into 53 blocks, each 45 ft. wide, with copper sealing joints between blocks. Each block is divided into three 15 ft. panels, and the concrete is laid in 4 ft. lifts and vibrated. Climbing shuttering designed by Cyril Parry is used, as seen in Fig. 6. It consists of wooden shutters in 7 ft. 6 in. widths carried on steel soldiers, the soldiers being secured by two lines of bolts screwed into nuts sunk in the concrete at vertical centre distances corresponding to the lift. At the top of each soldier a placer bolt carries the nut to be sunk in the next lift, and when the shuttering is struck it is moved up a distance corresponding to one line of bolts. Thus each line of bolts is first set in position, then used as the upper fixing for

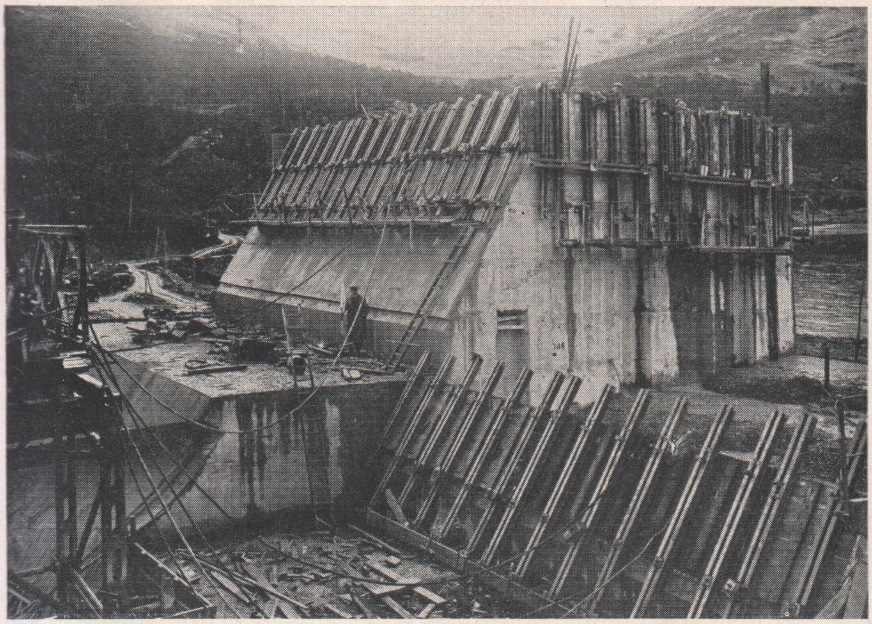

Fig. 6. Two of the blocks in the south wing being carried up at reduced height

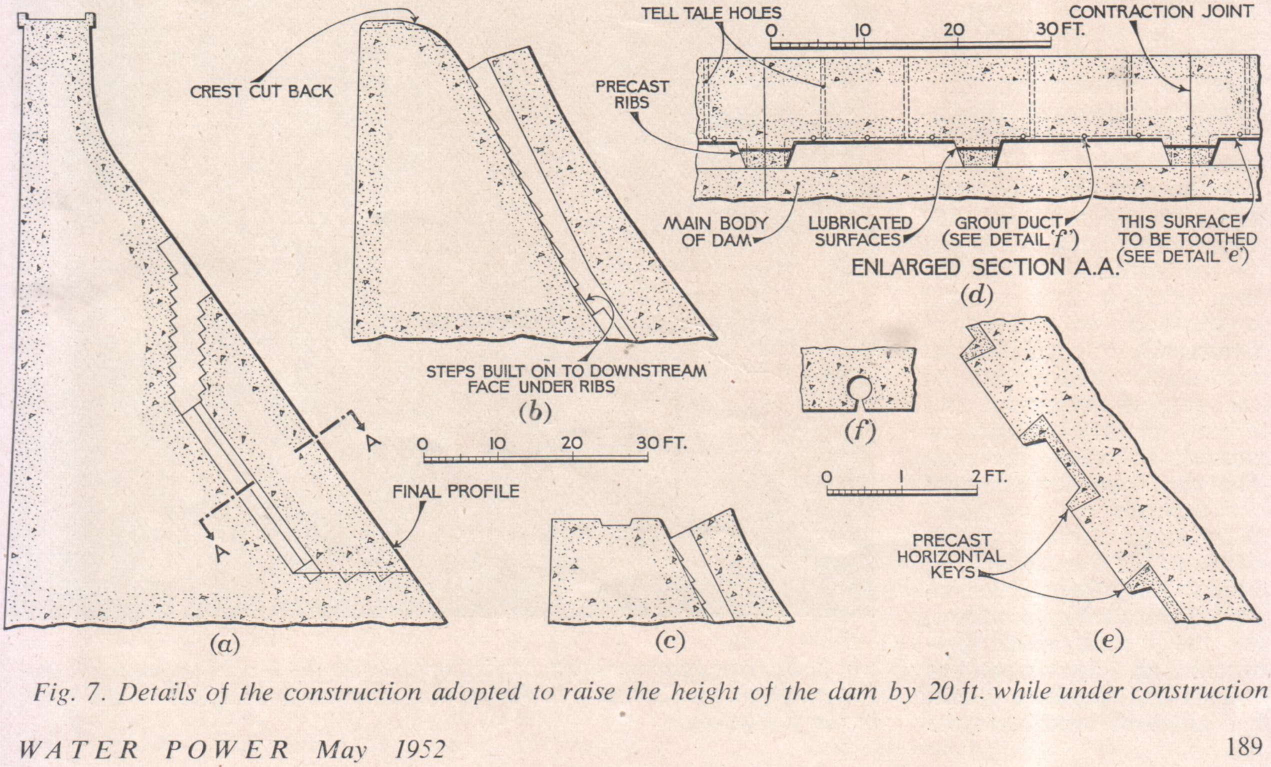

Fig. 7. Details of the construction adopted to raise the height of the dam by 20 ft. while under construction

the shuttering, and finally as the lower fixing.

Seeing that there are two water channels at the dam site it was an easy matter to close the dam. A cofferdam was first placed across the north channel, and all blocks in this region were built up except one, which was left low to pass the river water when the cofferdam was removed. After this had been done a second cofferdam was built across the south channel and all the blocks in that section built up, including that carrying the culverts. This cofferdam was then removed and the water passed through the culverts; the north cofferdam was then replaced and the low block brought up. The dam was finally closed by shutting off the culverts.

One culvert is fitted with a Glenfield & Kennedy 72 in. to 60 in. needle valve with jet disperser at the downstream end and with a 6 ft. span by 7 ft. 3 in. deep free rolling emergency gate at the upstream end, with electric hoisting gear, by the same makers. The other culvert is intended only to maintain a clear waterway when the loch is empty, and has a single-faced sluice on the upstream end and a hinged blank flange on the downstream end. To prevent the opening of this culvert while the loch is full, the sluice control spindle terminates at a point 20 ft. up the face of the dam so that it cannot be reached until the water has been drawn down. Compensation water is tapped off from the first culvert upstream of the needle valve, and is controlled by a 6 in. hand - operated regulating valve.

Changing the Height of the Dam

An engineering operation involving changing the height of part of a dam while it is actually under construction must surely be unique in the annals of dam building. This interesting operation is taking place at Mullardoch, and arose not through engineering considerations but because of a cut imposed in capital expenditure. To effect this it was decided in 1950 to reduce the projected height of the southern half of the dam by 20 ft. This involved a step-back on the downstream side of each block at the height it had reached on the date of the change (see Fig. 6). In 1951 it was found possible to review the position and take advantage of the presence of contractor's plant to go ahead with the whole of the dam to the full height. Nevertheless, this involved some tricky problems, for the blocks, which presented an assortment of heights and step-back levels, had all to be brought to the full thickness in such a manner that the design strength appropriate to the greater height was secured. This was complicated by the fact that the shortage of steel prevented the use of reinforcement.

Although a general procedure was adopted for laying the backing concrete, the exact method of treatment for the various blocks differed according to the heights to which they had been taken. Drawings of the arrangements are given in Fig. 7 and views of the work are reproduced in Figs. 8 and 9. Blocks that were some way off completion (at the reduced height) were carried up with the downstream face vertical until the profile appropriate to the increased height was reached, the top of the block then being completed to profile. On the vertical portion of the downstream face a system of toothing was formed to engage the backing concrete, as shown in Figs. 7 *a* and 9. This treatment would not have been appropriate for blocks that were nearly or fully completed to the reduced height, and in these cases the top was cut back as indicated in Fig. 7 *b* and *c*. Toothing was also cut in the horizontal faces of the step-backs left by the previous reduction in dam height, as shown in Fig. 7 *a*.

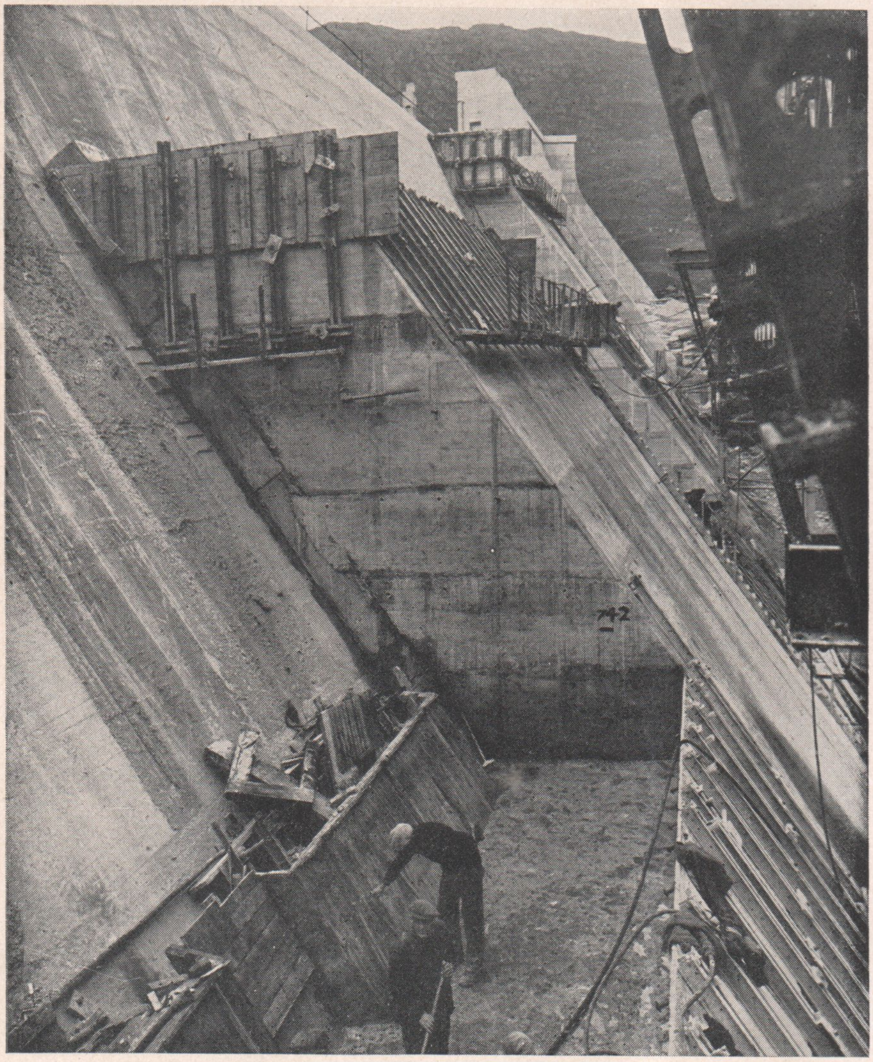

Fig. 8. Backing concrete being carried up to bring the blocks to full thickness. The shuttering for the slots in the backing concrete is being set on the block in the foreground

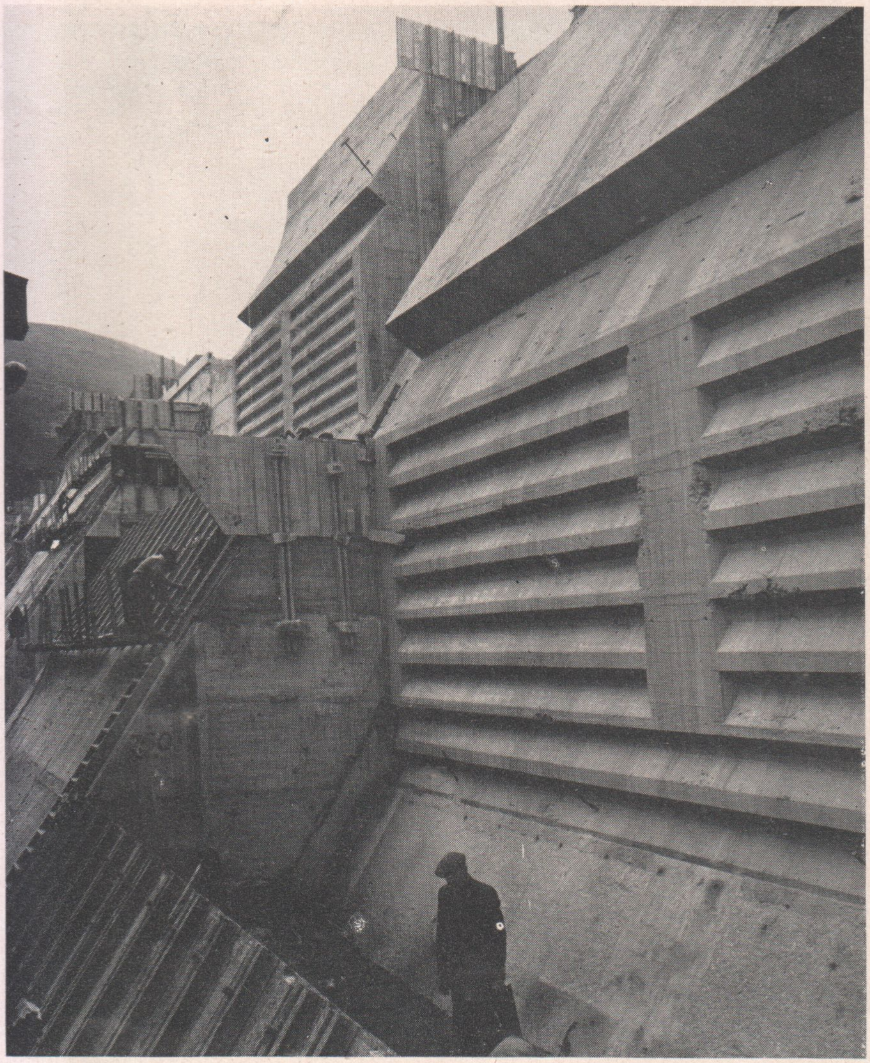

Fig. 9. Blocks 16 and 17 carried up to full height with a vertical downstream face provided with toothing to engage the backing concrete

The problem in designing the backing concrete was, of course, to circumvent the effects of the contraction of the new concrete in relation to the old. It was therefore decided to place the backing concrete in the form of sliding slabs, leaving slots between these slabs and the former face of the dam, which could be filled in when contraction had ceased. Two slots were formed in the backing concrete for each block, 19 ft. wide, 3 ft. deep, and extending from top to bottom of the backing slab. An access gallery at step-back level was left at the bottom of each slab.

To design shuttering for these slots that could have been struck easily in this confined space would have been awkward if the slab were made as a monolith, but the difficulty was surmounted by making a series of precast ribs to form the sides of the slots. The arrangement is shown in the section, Fig. 7 *d*, and in Fig. 8 can be seen the slot shuttering for the block in the foreground and the precast ribs for the adjacent block. Two layers of building paper with an intervening layer of grease were laid between the precast ribs and the backing concrete to enable the latter to slide freely when contracting. Horizontal keys (Fig. 7 *e*) were also laid to form a system of toothing on the inner face of the backing slab. In the case of blocks on which a vertical toothed face had been formed, a corresponding face was formed on the backing slab at a distance of 3 ft. Grouting channels were left in the faces of the backing slabs, and the portions of the dam face included in the slots were thoroughly scabbled.

At the time of our visit the backing slabs were in course of construction, and experiments were in hand on the use of Colcrete as a filling for the slots. This system, which has been developed by Colcrete Limited, Strood, Kent, depends upon the production of a colloidal grout which is stable but highly fluent and can be injected into a prelaid aggregate. In an ordinary grout the wetting of the surfaces of the cement grains by the water is never complete, but in the Colcrete machine the mixture is pumped at high speed through a narrow gap so that a fluid with some colloidal characteristics results. In a second stage this fluid is mixed at high speed with a desired proportion of sand, giving a grout possessing the properties of stability and exceptional fluidity to which we have referred. No chemical constituent is required to produce the grout, high-speed mechanical mixing being the only means employed. This grout is stated to be water repellent, enabling it to be used for underwater work, to fill all voids and fissures completely, and to make a perfect bond with either wet or dry aggregate. When set, it is claimed to be impermeable to water and to provide a certain and thorough key with the surrounding structures.

The aggregate, from which all material below $1\frac{1}{2}$ in. must be excluded, is placed in position independently, and the grout is either poured over it and allowed to penetrate downwards, or introduced near the bottom through grouting pipes or channels and allowed to fill upwards. This method ensures that the aggregate has point contact in all directions. The voidage is therefore less, and proportionately less grout, and therefore less cement, is required to fill it; thermal stresses are reduced, and cumulative contraction is prevented. There are also practical advantages in that the aggregate is not passed through the mixer, which need only be large enough to mix the grout, and the cost of handling the aggregate is less. In frosty weather work need not be stopped because the placing of aggregate can proceed.

(Continued on page 195)

change. On the other hand, most villages are some way down the slopes from the divide and on streams which either are already perennial or could be made so. Also, in spite of his being new to the wheel and still newer to anything approaching gears, the African could understand the simple overshot wheel such as our medieval corn mills had as their early models.

I believe that the change will be gradual and that it will not come through individuals, in spite of the fact that every village will have an odd man or so back from the mines or the railways who can appreciate power and a quicker way to wealth by its use. I would suggest that it will come rather through the village councils, which are now just beginning to appreciate their powers and their financial resources. Sooner or later these councils will learn that bringing water to the village by a furrow and fluming, both for power and water supply, are not white man's magic and that in the end it would enable them and their womenfolk to have more spare time for production of food or cash-crops.

At present the water engineer in Africa is fully occupied with conservation projects, but he will in time be able to educate the African to the concept of water power and it may well be via the simple overshot, geared to a mill of some kind, as we still have it in England.

Yet, even when we allow for the backwardness of the African and the fact that Europeans are thin on the ground, we find a curious lag between the need for hydro power and its development. Now this is almost entirely due to our lack of information about the regime of the rivers over a reasonable period of years. The engineer in Africa is still at the reconnaissance stage, when he is primarily a hydrologist studying the water resources rather than a hydraulics engineer putting them to work. It is an interesting stage but not a productive one; yet we should note that it should employ a whole range of experts, not merely the engineer, since now is the time for what we may call the T.V.A. approach. The Tennessee Valley Authority was given powers to plan every single activity and use every resource in its valley, not merely those directly associated with the rivers. We cannot provide the capital of a T.V.A. nor can we give the wide authority, since international boundaries interfere, but we can try to study the whole needs of a river basin and ensure a harmony between the many activities to which it is suited. I believe that this is being done in a general way for the Kafue in Northern Rhodesia, but there are many other major river valleys where a Commission with wide powers and covering a broad field of experience could avoid the mistakes of piecemeal development and secure a balanced economy.

What are the special difficulties in hydro-power engineering in Africa as compared with those of temperate countries, apart from those common to all the tropics such as the incidence of disease? Perhaps the chief ones are thunderstorms and swamp vegetation. Of the first we need only remark that in a country where 10 in. of rainfall may fall within 24 hours none of the ordinary safety factors for spillways, structures, etc., can apply. The engineer can cope with floods, however, because he can measure them and take his precautions. With vegetation it is different, because ecology has not yet taken a full measure of what aquatic vegetation in the tropics can do. We know that it helps the water engineer in one direction, since it is the vegetation that produces the countless plateau swamps of Africa which delay the run-off. In other ways it is bound to hinder him, as for instance in blocking the outlet of lake Nyasa for a number of years. What it will do when we come to running long canals across country has still to be found out. The moral is that a hydrologist in Africa must either be an ecologist as well or make sure that he takes one.

In summing up, we may say that although there must be a big future for water power in Africa we must never forget that Africa cannot be hurried.

Allis-Chalmers Annual Review

The 1951 Annual Review of the Allis-Chalmers Manufacturing Company, Milwaukee, is the 105th of the series, and records some notable hydro-electric contracts. Two units shipped to Hoover dam, comprising 115,000 h.p. 480 ft. head Francis turbines coupled to 82,500 kVA 180 r.p.m. generators, are claimed to be the largest complete units ever built by one company. Pickwick Landing plant received two more 55,000 h.p. Kaplan units, bringing the total to six. These are stated to be the largest Kaplans in physical size in the United States, the runners being 24 ft. 4 in. in diameter. Other important shipments included the sixth 20,000 h.p. Francis turbine for Grand River Dam Authority, the remaining three of four 105,000 h.p. units for Hungry Horse dam, and the fourth 62,500 h.p. turbine for Bull Shoals.

The first reversible turbine unit for installation in the United States has been ordered by the U.S. Bureau of Reclamation for their Flatiron plant. As a motor-and-pump unit, the set will deliver 370 cusecs against 240 ft. head, and as a turbine-and-generator unit 10,000 kVA at 13,800 V.

Canadian Allis-Chalmers (1951) Ltd. is to build a 150,000 h.p. 2,500 ft. head 377 r.p.m. vertical four-jet impulse turbine for a plant in British Columbia. This plant will establish a capacity record when the 16 units contemplated are ultimately installed. The operating head will be the highest in the two American continents and the impulse wheels are believed to be the most powerful in the world.

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When we visited Mullardoch a weir to retain water for fishing in the river downstream of the dam had already been built by this method, an experimental slot had been filled, and tests were in progress on Colcrete specimens. We understand that the 28 day strength on an unrestrained compression test of a 6 in. test cube made with $2\frac{1}{2}$-$1\frac{1}{2}$ in. local aggregate and a 1 : 2 mix having a 0·58 water : cement ratio was 4,350 lb. per sq. in. A similar cube of plain grout and Logans sand yielded at 4,900 lb. per sq. in. Bond-stress test values were nearly 300 lb. per sq. in.

The method proposed to concrete the slots in the dam is to fill them with 3-$2\frac{1}{2}$ in. aggregate and to grout the two slots in each block in a single pour, the speed of the pour being regulated so that the lower levels begin to set before the pour is completed, ensuring that no part of the structure is subjected to undue hydrostatic head.

(To be continued)