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The Dokan Project†

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Discussion

Mr F. F. Haigh (Haigh, Zinn & Associates) said that the Authors had credited the Irrigation Development Commission in Iraq, of which he had been President, with putting forward proposals for irrigation and flood control based on storage on the Lesser Zab. That was correct, but he pointed out that the Commission had not been first in the field; the problem had been investigated before the Commission took over and it had been clear that storage there was very desirable and was, indeed, the only way of providing adequate supplies for the irrigation of the Lower Zab areas. Previous to this, three dam sites had been investigated, of which that most favoured had been Torbah, near the head of the Dokan Gorge. The Irrigation Development Commission had brought Dokan into the picture, but he thought it was obvious to any engineer who used the main road up the Lower Zab valley along the edge of the Dokan Gorge that here was an ideal site for a dam. At any rate the engineers of the Irrigation Development Commission had thought so and consequently an investigation had been undertaken although, owing to its position on the river, a higher dam would be required for the same storage as at the older sites. Geological investigation had shown that Torbah and the other sites were inferior to Dokan; consequently Dokan had been included in the Commission's plan. The height and type of dam constructed followed very closely the Commission's proposals.

177. Dam sites existed and had been investigated on all the main tributaries of the Tigris, and it might be of interest to explain why projects had been carried out at some of them and not at others. The sites selected by the Commission on the various rivers had been: on the Greater Zab, Bekhme; on the Lesser Zab, Dokan; on the Adhaim, Damir; on the Diyala, Gibraltar, if geologically sound, or Derband-i-khan. Gibraltar had not passed the geological examination. On the main river there was the Wadi Tharthar depression for flood control, and also for storage, provided that the seepage losses were not excessive or liable to waterlog adjacent lands. These possible disadvantages could be examined while the reservoir was being used for flood control only. The Wadi Tharthar could also control the flow from the two Zabs.

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† Proc. Instn civ. Engrs, vol. 14, pp. 157, 181 (Oct. 1959).

178. There were no extensive irrigation possibilities within the basin of the Greater Zab. It remained a good site for storage for irrigation outside the basin, should the Wadi Tharthar be proved unsuitable. In the case of Dokan, stored water was required for irrigation within the Lower Zab basin and could also be passed by a feeder to the Adhaim catchment; hence the decision to proceed with the Dokan Dam. With regard to the Adhaim, a reservoir was required for flood control and the water could be used within the basin for irrigation. Since this tributary was relatively small and irrigation water could be provided from Dokan this case was not urgent, though it would probably be taken up at some future time. On the Diyala both flood control and irrigation within the basin were required; hence the Derband-i-khan project.

179. Hydro-electric power could be developed at all the dam sites, although, since these were remote from centres of population and industry, it was difficult to compete with the very cheap oil power available in Iraq. In the vicinity of Dokan, however, there were reputed to be extensive mineral deposits and the power for which provision had been made in the dam might ultimately be used for their extraction.

Professor A. J. S. Pippard (Professor Emeritus of Civil Engineering, Imperial College of Science and Technology) referred to Robert Hooke's famous anagram, which stated that the theoretically correct arch for any specified loading was the inversion of a flexible cable similarly loaded. An extension of that theorem indicated that the best theoretical shape for an arch dam was the inversion of a flexible membrane which was sustaining the same water load. This was the justification for the cupola shape referred to by the Authors in § 22. This extension of Hooke's theorem indicated a possible experimental method for determining the best shape for an arch dam in any valley, and in fact some experiments along those lines had been made and he hoped that they would be continued; he thought that they might be helpful.

181. A number of different approaches to the problem of stress analysis of the arch dam had been made, but for a variety of reasons it had not been practicable to use any of them for the Dokan Dam, and so a new analytical and experimental approach had been adopted which had already been described[4, 14].

182. All analytical methods applicable to the uncracked dam were based upon the assumption that the material of which it was built would behave elastically according to Hooke's law. That assumption was only partially true and so the results of such calculations, whether they related to displacements or to stresses, could not be accepted as providing exact information as to the behaviour of the structure. Their value lay primarily in affording a basis of comparison with other structures, the performance of which had proved to be satisfactory. This limitation in the scope of analysis could be remedied to some extent by carrying out tests to destruction on plaster models; a technique which had been very much used in other countries, but had been only recently attempted in Britain. Clearly, however, a really satisfactory correlation of analytical results with the behaviour of the actual structure could be achieved only by subjecting the completed dam to systematic tests, and in § 65 the Authors made a brief reference to the installation of instruments at Dokan for this purpose.

183. When the dam was originally designed it had been intended that an extensive programme of tests should be carried out, and the use of a considerable number of instruments—strain-gauges, thermometers, and instruments to measure pore pressures—had been contemplated. The conduct of such a research was obviously expensive, but appeared at first sight to present no particular difficulty, provided that the gauges could be relied upon to operate successfully when embedded in the mass of concrete. Doubt on that subject had been relieved by experiments made by Mr R. J. Ashby, which showed that these instruments were consistent in their readings when embedded in stressed concrete. Difficulty arose, however, in the interpretation of the readings. It had always to be remembered that any alteration in the gauge length would be registered

[14] References 14–16, are given on p. 97.

by the instrument, irrespective of the cause of such alteration in length. Strain measurements would therefore give the sum of changes due to stress, temperature, creep, moisture content, and so on. To translate the resultant strains into stresses by means of the ordinary elastic relations would give entirely fictitious and misleading results. Such full-scale tests had, it was true, been made and deductions drawn from them by competent and reliable experimenters. A research of this kind must, however, be continued over a long period and readings of the instruments made at regular and frequent intervals during that period. This was essential to ensure that there were sufficient data, correlated with full records of temperatures, water levels, and so on, to enable the movements due to the various causes to be separated.

184. The field-work for such a long-period research was not easy to organize, and even when the results were obtained there was much to be done in reducing and analysing them. Not long ago this might have proved an insuperable difficulty, but today the use of electronic computers would eliminate that particular trouble. It was to be hoped, therefore, that the instruments which had been embedded in the Dokan Dam would be used in such a way as to provide reliable information on the relation between calculated and actual stresses in the structure. It was of particular interest to Professor Pippard to find that the importance of measuring displacements had not been overlooked, and, although the determination of these would need elaborate survey work of a high order of accuracy, the effort should produce results of great value and afford at least an overall check of the reliability of analysis and experimental methods for design purposes.

185. Tests on the indiarubber model[4] of the dam had provided interesting data on its deflected form under water loading. In particular, it was clear that by far the greatest part of the deflexion at the crest had been produced by the top few metres of head. These tests had indicated that the crest deflexion at the centre section of the dam when the water level was 487 m would be little more than one-third of its magnitude when the reservoir was full, i.e. at the top water level of 511 m. The Authors stated that the highest level reached this year had been approximately 487 m, and it would be of great interest to know how much the crest had moved at this stage and still greater, at a later date, to be able to compare it with the maximum deflexion. In that connexion perhaps the Authors could say whether the filling would now proceed naturally until top water level was reached, or whether it would be necessary to restrict the original working level for any reason. It would also be of great interest to know how the concrete in the dam had behaved during the filling of the reservoir. It was to be expected that some surface cracking due to changes of temperature would occur. Any information which could be given about this would be of value.

Mr H. D. Morgan (Partner, Sir William Halcrow & Partners, Consulting Engineers), who had been a member of the International Board of Engineers investigating the dam site in the early stages, briefly outlined their activities and the special circumstances of the site.

187. The Board, he said, had been convened to give assurances of the safety of the Dokan Dam and information on its suitability for irrigation, flood control, and electrical power generation, although the first and most pressing need had been an opinion on the site chosen and its suitability for an arch dam.

188. No mention was made in either of the Papers of the very impressive geological work carried out by Kenneth Early, Chief Geologist of Soil Mechanics Ltd, which had greatly helped to resolve many of the doubts of the Board. It was, in fact, doubtful whether or not the Board could have agreed to support the construction of a highly-stressed arch dam at such an exacting, although topographically attractive, site if it had not been for Early's work and the way in which it had been presented on the spot.

189. The whole site area was riddled with caverns and solution holes, which had meant not only that the dam foundations had to be consolidated, but that a considerable part of the gorge had to be treated to prevent dangerous leakage of water from the reservoir.

190. The dam itself was the biggest arch dam of wholly British design in the world.

At the same time a notable technical tool had been developed for its design, an application of the relaxation method. The alternative to this was the method used by Government agencies in the United States of America for the final designs of important dams, the trial-load method. This had been widely advertised, but Mr Morgan thought that there was very little virtue in it. It resulted only in a fictitious degree of accuracy which was merely an accuracy of figures. It was necessary in all methods of arch-dam design to make certain fundamental assumptions in connexion with the values of the effective modulus of elasticity of the concrete, and of the rock upon which it abutted. These could not possibly be known to a greater degree of accuracy than three significant figures, and sometimes only two, yet he had seen some calculations from American sources where seven figures appeared to have been used. It was grossly unscientific to exceed the accuracy of the data.

191. He had made those remarks before and been rebuked by a young geologist who had said that the coefficient of elasticity of the rock had been measured on the site. If, however, the acoustic resistance of the rock were measured, and from this the dynamic modulus of elasticity determined, it was still necessary to deduce the static modulus. In any event the modulus required was that after grouting, and he believed that much of this preliminary work had in fact been based on figures obtained with the rock in the ungrouted condition.

Mr R. G. T. Lane (Associate, Sir Alexander Gibb & Partners) asked if the flood water had any value and if it would have been worth while providing additional spillage in the gated spillway system, so that the drawdown each year could have been to a higher level?

193. He had been surprised to find that there was only one gallery in the dam. There were about 250 strain-gauges to be read regularly. He would have thought that the provision of additional galleries would have been very worth while, particularly for grouting; their cost would have been negligible.

194. What was the reason for the low level of the various intake openings? There was no mention in the Papers of siltation or bed load; would not higher intake levels possibly have saved some of the rather massive concrete at the base of the dam?

195. On the question of aggregates, had the sand classifier proved to be worth while? How much material had been put aside by the sand classifier and could this rejected material be used elsewhere? Unless such figures were known it was difficult for contractors to estimate.

196. How had the concrete test cubes been made? Had specially big cubes been made or had the big stones been taken out? What were the five visual standards for workability mentioned by the Authors?

197. Would the Authors give more information about the pre-cofferdam which had proved unsatisfactory?

198. Why were the tunnels circular? It was a controversial point, but it seemed that in this case a departure from the circular would have had several advantages. The crown could have been kept narrower and a flatter bottom would have helped access, and both those slight modifications should have helped in the placing of the concrete at the crown and at the invert.

Mr Paul Fouillade (Société Dumez-Ballot) said that in the early stages the contractors had had long discussions on the types of installations to be adopted on the site, the characteristics of the plant to be used, and the methods to be adopted for carrying out the work. He referred particularly to the placing of the concrete; many solutions had been discussed before finally that of using cableways had been adopted. The method had given complete satisfaction and the erection and operation of the cableways had not been at all complicated.

200. He emphasized that the technical difficulties which had been encountered had been successfully overcome. He referred to the high degree of co-operation between, on the one hand the Consulting Engineers and the Resident Engineer and his staff, and

on the other hand the management of the Contractors, their local representatives, their engineers, and their foremen. As an example, it had been possible to work out a method for dealing with the trash racks, which made it possible to speed up the work and to improve their appearance. There had been a constructive exchange of points of view. The drawings which had been made at the time of tendering had had to be modified and adjusted to comply with site requirements, which had appeared only during the progress of the work. In the same way, the contractors had had to face unforeseen practical problems. In such cases individual understanding of the problems had been necessary in order to solve them. For example, initially the filling of the skips had been much too quick, resulting in the segregation of concrete, but it had been possible to provide a braking mechanism on the dumpers.

Mr C. F. Grundy (Managing Director, Cementation Co. Ltd) elaborated on the comparisons made in Table 4, where the various quantities relating to grouting for the Dokan and other projects were compared. He believed that the statement in § 171 that the Dokan grouting programme was one of the largest ever undertaken was correct, and a comparison of the area of curtain and total drilling was probably the fairest means of making the comparison. Drilling usually accounted for the major part of the cost, especially when low-cost clays or sand were used in the grout. It was also probable that Dokan was one of the fastest grouting jobs which had ever been done, owing to the use of percussion drilling to a depth of a little more than 300 ft. The total injection figures, however, could not be neglected, and here Camarasa stood well above the others. At Camarasa the curtain had to stop damage after the dam had already been built and the reservoir filled. The loss had amounted to 220 m.g.d., and one leakage alone accounted for 48 m.g.d. That work had been done about 30 years ago and gave some idea of the difference which it made when a grouting problem had to be dealt with after the reservoir had been filled, as compared with the position today, when the job was tackled along with the construction.

202. Some indication of what might have happened at Dokan if there had not been this thorough treatment before impounding was provided by the two flow paths, which had been treated since the reservoir had been filled. The first of these was described in §§ 17, 18, but he would add one point to illustrate the difficulty of sealing a running flow. Seven holes had had to be drilled close together before the major passage referred to was intercepted. The second instance was described in § 169. In March 1959 water broke through into the left bank grouting tunnel where a narrow fissure crossed the tunnel. This fissure had already been plugged and grouted, as described in the Paper, but the water had by-passed the plug. The first attempt to seal the leakage had failed, with most of the grout travelling back into the tunnel. Further holes were now being drilled and material injected to form a block. Already thirty holes had been drilled (totalling 1,700 m in length) and 1,600 tons of material injected, but there was yet no news of successful sealing.

203. As a further instance of the problems which had arisen by waiting until the reservoir was filled, what had happened at the Hoover Dam would be recalled. Work had had to be done there after impounding because of the leakages which had developed, and the remedial treatment amounted to three times the original grouting. There, of course, the comparison was not quite a true one, because the Hoover Dam had an andesite foundation, whereas the other dams listed in Table 4 were in mainly limestone foundations. The moral, he thought, was that prevention was better than cure!

Mr J. H. Lander (Partner, Sir Alexander Gibb & Partners) observed that the cupola arch design appeared to have been cast aside somewhat lightly as being "an awkward shape on which to hang gates and build intakes to penstocks", but from the drawings it appeared that what seemed to be gate towers were provided on the upstream face of the dam, which would come near to solving the problem of using a cupola design. He did not suggest that a cupola design "would halve the cost and halve the contract period", but he would like to know what other reason had led to its abandonment.

205. Regarding the spillway arrangements, the adoption of the bellmouth spillway was understandable because it utilized the diversion tunnel, but the gated spillway was more difficult to accept. It had entailed the driving of 400 m of 11-m-dia. tunnel—an expensive undertaking. Would it not have been possible to place the spillway gates in the dam structure? The five spillway gates of the Kariba Dam were positioned 100 ft below the top water level, and would throw the discharge water about 250 ft downstream of the dam. The gates measured 31 ft × 30 ft and passed through the cupola arch. Would the Authors explain the reasons for using the tunnel in place of gates through the dam?

206. He questioned the positioning of, and the need for, the grouting tunnels. On the right bank tunnels were probably unavoidable, but had they been really necessary on the left bank? On the left bank of the gorge it seemed from Fig. 15 that it would have been possible to make a benched roadway near the top water contour and to have done all the drilling from a fairly wide roadway in place of the tunnel. The roadway would have had to follow the contours, and so the curtain would have been slightly longer, but the expense of working in tunnels would have been avoided and the use of heavier machines might have improved the verticality of drill holes. What sort of verticality had been obtained with the percussion machines? The normal type were inclined to wander, but the modern type with the percussion tool at the end of the drill-string usually drove quite vertically.

207. The level at which the tunnels were driven was some distance below top water level. This meant that it had been necessary to drill upwards and downwards, and secure at any rate the upstream walls of the tunnel. A tunnel at top water level would appear to have been simpler, as one curtain could have been drilled from the invert of that tunnel.

Mr M. G. Ionides (formerly of the Iraq Government Development Board) referred to the maximum probable flood of 13,300 cumecs (§ 86) and remarked that when building such a large and costly dam it was obviously right to provide for an outsize flood, because the additional cost was not a very big item on the national budget; but he had noticed a tendency, which had shown itself in the discussions in Iraq when reviewing the various dams which were being, or were about to be built, to assume that, since one dam had provided for a maximum flood of 13,000 cumecs and another dam for a similar or larger figure, it was necessary to provide for the flood protection of the entire country and its alluvial plain by adding up all those excessive floods and making provision accordingly. The cost could not fail to be enormous and out of proportion to the country's resources. Could the Authors say something about the frequency which the 13,000-cumec flood represented, and put it into that broader context?

209. The difficulties of engineers were not all technical. Apart from the local difficulties and the difficulties in construction there had also been in this case unusual problems of relations with the customer. Dokan had been one of the most difficult tasks, from this point of view, that an engineer or contractor could ever have to face. The Suez Crisis had led to the rupture of diplomatic relations between Iraq and France, and although the Iraqi Government had not broken off commercial relations and had sent high-level dignitaries to reassure the French contractors all over the country, there were many repercussions. However, confidence was established between the contractors and the Development Board, with the help of Mr Binnie, leading to a mutual determination that the contract must be completed and the dam finished. Mr Ionides suggested that the success of the consulting engineers and the contractors in steering the work to conclusion, although outside the sphere of technicalities, deserved to be recorded.

Mr Terence O'Donnell (Lecturer in Civil Engineering, Imperial College of Science and Technology) referred to the hydraulic-model studies of the Dokan flood-disposal works carried out at Imperial College, London, under the direction of Professor C. M. White. Mr O'Donnell, as an Assistant in Research, had been chiefly concerned for about 18 months with the Dokan models programme.

211. The model results quoted in the second Paper were those taken from models which had finally been accepted as satisfactory in all respects, and on which had been based the structures actually built. As was usually the case, the final satisfactory models had been arrived at only after several unsatisfactory ones had been examined, and objectionable features eliminated.

212. One objectionable feature in the first of the bellmouth spillway models had been the appearance of a hydraulic jump in the flow through the horizontal tunnel. The jump had been unstable and unpredictable, moving up and down the tunnel in a cyclic way, sometimes slowly, sometimes not so slowly and occasionally explosively. This happened with the discharge held at constant values, within a fairly wide range of discharges. Such undesirable behaviour had been eliminated from the model by the steps described in §§ 95 and 98, and there was no danger of its occurrence in the prototype.

213. The main features by which the first model differed from the final acceptable model were:—

(*a*) The vertical bellmouth shaft had been joined to the horizontal tunnel by a simple radiused bend of 40 m radius. (In the final model the join was a straightforward Tee-junction, as shown in Fig. 22a.)

(*b*) The vertical shaft, the 40-m bend and the horizontal tunnel had all been of the same diameter. (In the final model, the shaft of 12·5 m dia. had been joined, via the Tee, to the tunnel of 10·2 m dia.; this reduction in diameter gave an area reduction of about one-third.)

214. Mr O'Donnell showed a film of the flow conditions in the bellmouth of the first model, followed by the unstable jump behaviour in the tunnel of that model.

Mr J. P. Taylor (Messrs Coyne & Bellier, Consulting Engineers, Paris), who had formerly worked at Dokan, referred to some of the problems concerning the artificial cooling.

216. The attitude adopted towards the cooling of dams seemed to vary considerably from country to country. There did not seem to be an internationally-accepted minimum requirement of temperature control, partly, perhaps, because of the different climatic conditions with which designers had to cope, but also, he thought, because of the attitude of designers to the risks of fissuring and cracking in concrete and to the dangers which such fissures might introduce. It was possible to predict with mathematical precision the behaviour of temperature in concrete, but far from easy to interpret the effects of temperature change on the internal stresses and stability of the structure, taking into account the nature of concrete, particularly in its early life, during construction.

217. Dokan was, so far as he knew, the first British-designed dam to be artificially cooled, but the Americans, who introduced the method of cooling, paid tremendous attention to the durability of their dams; and, since the climatic conditions at Dokan and in the Colorado basin were similar, the cooling arrangements at Dokan had been drawn from American experience. The Fontana Dam had been regarded as one of the best cooled of the American dams, and efforts had been made to emulate it at Dokan. No fissures in the concrete had been observed during the period of construction or later.

218. A very tight cooling schedule had been required. First, the dam being an arch dam, cooling to the final steady-state temperature had been necessary before grouting the construction joints, and this had required an embedded-pipe system of cooling. Secondly, the bases of the blocks in the dam were extremely large, measuring 250 ft from upstream to downstream and 65 ft across, without intermediate joints. Pre-cooling of the concrete had therefore been specified to enable emplacement under summer conditions. Thirdly, an annual variation of temperature between hot summer temperatures of 120°F in the shade, and winter temperatures below freezing, had posed the problem of steep temperature gradients between the face and the internal mass of the dam, especially in the autumn, when there was a sudden drop in ambient temperature.

Fourthly, a final steady-state temperature difference of 30°F was expected between the upstream and downstream faces.

219. This last requirement was not usually achieved, but during the late summer and autumn of 1958 conditions were just right for the cooling of the dam before grouting above the level 445 m. The dam had been almost completed and initial cooling for the first 2 weeks after placing had left the concrete at a uniform temperature of 80°F to 85°F. The construction work was confined to the crest and use of all the downstream ladders and supply pipes could be restricted to the cooling staff only. The ambient temperature was still high, enabling the downstream face to be kept at the necessary temperature. The upstream face was sprayed with cold water, and required about 5 gal/min per block to reduce the skin temperature to a maximum of 60°F. The coils were laid parallel to the upstream face and there were usually two on the same lift. They were connected in series and a very small flow of only 1¼ gal/min was led to the upstream coil first and cooled the concrete at a decreasing rate as it passed towards the downstream outlet. Each coil had been regulated individually by inserting a washer with a hole in many cases not more than 2 mm dia. The downstream coil was usually disconnected first since in this zone the required final temperatures, being higher, were easily achieved.

220. Unfortunately, the diffusivity of the concrete was low, making the gradient difficult to achieve. Tests on specimen cylinders of concrete gave a value of 0·027 ft^2/hour.

221. By contrast, the lower part of the dam, being grouted in February and March, had time to lose some of the artificially-cooled temperature gradient by natural cooling from the downstream face. Also, owing to the difficulty of controlling the flows, less favourable results had been achieved.

222. Although considerable success had been obtained in cooling to the temperature gradient in the upper part of the dam, Mr Taylor queried the necessity of doing so. Overcooling in the downstream zone of the dam should not be harmful. Other factors in the construction programme might require that cooling be carried out at a difficult time of year or at a faster rate.

223. Mr Taylor also referred to the cooling of the zones of the concrete restrained by the foundations. A strict specification had been applied, permitting a difference of only 30°F between the maximum temperature and the final steady temperature of the concrete, which required precooling.

224. In practice the precooling of the aggregates was not very effective, since no provision was made to circulate the cooling water in the aggregate baths, nor was the site for the large aggregates of sufficient volume to permit them to soak for more than 15 min. This, combined with the considerable temperature losses in the cooling-water supply mains meant that the summer placing temperature rose to 70°F, and a few lifts of 75-cm height were used in restrained zones to meet the specification. In such a dry climate, spraying of the aggregates in the stock piles with river-water was very efficient, and the aggregate was brought to the batching plant at about 75°F. This meant that if refrigerated baths for the aggregate had been eliminated, the placing temperature would have been about 80°F. The maximum temperatures of the concrete would have been about 105°F for 1·5-m-high lifts, giving a difference of 50°F between the maximum temperature and the final temperature of the concrete.

225. Would this have induced cracking in the restrained zones close to the rock? The possibility of fissures could not be ruled out, though they would probably have been of a minor character. He had seen quoted a value of 45°F between maximum temperature and final steady-state temperature as being the safe upper limit.

226. Finally, the contractors had made an estimate of the cost of cooling which they put at 500 to 600 francs/cu. m. That, at the present rate of exchange and for the whole dam, would amount to about £250,000.

Dr C. S. Hitchen (Consulting Geologist, Balfour, Beatty & Co., Limited) said that he first went to Iraq late in 1945 to report on the Bekhme Dam Site on the River Greater

Zab. During 1946 he had been asked to report on possible dam sites on the River Lesser Zab and had recommended the Dokan site. It was a magnificent site physically, but since it consisted of limestone, he rather feared that much grouting would be required to render the abutments, etc., watertight.

228. It was necessary to emphasize that, in Iraq, limestones were the only hard and competent rocks available and were liable to be leaky owing to solution cavities, enlargement of joints, etc. There were no really competent rocks such as granite, and the founding of dams on limestones or on softer rocks such as marls had to be accepted as a peculiarity of the country. Very thorough and painstaking exploration was, therefore, essential.

229. Geologically, conditions at Dokan were very similar to those at Bekhme. An anticlinal core of massive Judea Limestone was overlain by thin-bedded Shiranish Limestone and this, in turn, by magnesium-rich Shiranish Marl. Percolating water dissolved magnesia from the marl and trickled down through joints and cracks in the Shiranish Limestone to the underlying Judea Limestone, which was converted to dolomite by having part of its constituent calcium carbonate replaced by magnesium carbonate. Owing to its hardness, denseness, and high silica content the Shiranish Limestone escaped dolomitization. When calcite is converted to dolomite there is an increase in specific gravity and this produces porosity in addition to solution effects in the original limestone.

230. Dr Hitchen said that while he had been responsible for the selection of the Dokan site it was, nevertheless, a very obvious choice and he had taken no part in its subsequent detailed exploration which had been so ably carried out by those concerned.

Mr K. R. Early (Chief Engineering Geologist, Soil Mechanics Ltd), who was responsible for the preliminary site investigation, said that his particular interest had naturally been in the foundations and the cut-off. Although the solution caverning above and below river level had been strongly emphasized, it had been said at the same time that an improvement below the river was likely, but that a positive cut-off horizon was unlikely to be found at a reasonable depth. That had now been confirmed, as had also the connexion between Gulneri Gorge and Dokan Gorge.

232. The results of the grouting had established that the Shiranish limestone had a diffuse permeability as opposed to an erratic permeability in the dolomite, which had been expected in a rock with scattered caverning. The overall mechanical soundness of the rock had been proved, and the need to found the left abutment wing below the shale had been confirmed.

233. He wished to correct a possible misunderstanding about the statement in § 125, that the site investigation had led to the belief that the leakage was likely to occur only through the dolomite. Grouting of the limestone at both abutments had in fact been recommended, although limited in extent by the box-curtain system which had been under consideration at the same time.

234. It was strongly implied that solution caverning was mainly confined to the rock immediately adjoining the gorge, and it was said that all important cavern systems occurred on the left bank. He still favoured the possibility of phreatic cavern formation, which had been supported by Davis[15] and Bretz[16], and which accounted for extensive caverning deep within the limestone or dolomite mass. There were many examples in various parts of the world to illustrate this.

235. At Dokan the river might have caused further erosional enlargement and encouraged solutional enlargement, but the existence of not inconsiderable underground streams downstream from the dam on the right bank favoured the idea that solution enlargement of joint systems existed within the rock mass. Another point was that a horizontal boring in the left bank had quite definitely encountered a 20-ft cavern about 80 ft within the rock, coincidental with a minor thrust plane. It was also interesting to note that some trouble had been experienced in leakage from one of the many minor thrust planes 35 m below the dam. This suggested that solution enlargement existed

there. Where unaffected by solution these thrust planes were closed, but where the larger cavern anastomoses were found they were usually on the thrust planes.

236. He was interested in the finding that the worst caverning was in the contact zone. A number of theories suggested themselves to account for this. He noticed that the number of stages tested in the limestone borings was quoted and asked for the equivalent statistics for the dolomite.

Mr W. E. Blackmore (Engineer, Sir William Halcrow & Partners, Consulting Engineers) referred to the statement in § 99 that the bellmouth spillway had been provided with means for the aeration of the underside of the waterstream. Why was this necessary, and would it not reduce the discharge capacity of the shaft?

238. Referring to the electric operation of the spillway gates he said that there had been cases where discharge arrangements relying on the electrically-operated gates had failed because electricity supply usually failed when there was a big storm, such as would also cause a flood; he thought that the supply at Dokan would be particularly vulnerable since, in the absence of generation at the dam, presumably the current had to be brought over many miles of country. Had water- or gravity-operated gates been considered as an alternative?

239. Was there any low-level discharge arrangement from the dam to enable the reservoir to be dewatered? It seemed from the drawings that the lowest discharge was the irrigation tunnel itself; and that would take only 200–300 cumecs. Had consideration been given to retaining intact the upstream cofferdam and diversion tunnel for dewatering purposes?

240. Regarding the intakes for the future turbines and the intakes for the irrigation tunnels themselves, the Authors had adopted a screen with horizontal bars. This type of screen was unrakeable. Did they expect no trouble from trash, or had they made other provisions for clearing it if it should occur?

Mr Ali Al-Hamdani (Civil Engineer, Daniel, Mann, Johnson, Mendenhall) referred to the two floods that had occurred during construction and suggested that sufficient consideration had not been given to the flood which might occur during the 3-year period of construction. There had been an early warning in the first year, when the tunnel had not proved adequate and the upstream cofferdam had been overtopped. There had not been much snow that year, but there were plenty of records available going back to about 1600; apparently they had not been utilized or something had been overlooked.

242. What was the use of the lift on the upper side of the bellmouth? Why did the vertical shaft join the tunnel at a right angle, instead of a bend with a suitable radius?

The following contributions were received in writing.

Mr R. C. S. Walters (Partner, Herbert Lapworth Partners) said that the idea that dams could not be built on limestone should now have its quietus, although it was true that the Dokan grout curtain had cost £2,400,000 and had a length of 2½ kilometres.

244. Other long screens that had been necessary were those recently constructed for the Sarno reservoir in Algeria, in the Pliocene conglomerate, 700 m in length, and for the Barcis reservoir in Italy, in the Upper Cretaceous limestone, 400 m in length.

245. It was obvious that, in order to secure watertightness, more and more reliance must be placed on the grout curtain; hence § 154 describing the usual method of trial-and-error might not be appropriate in the future for an expenditure of £2,400,000, or about 10*s*. per sq. ft of screen. (At Sutton Bingham reservoir it had been about 4*s*. 6*d*.)

246. Hence, with such an expenditure to be envisaged, would it be, for similar work in the future, feasible to explore limestones by a number of 36-in. vertical holes, similar to those under the Fontana Dam, down which visual examinations could be made to explore the cavities in the soft phyllite between the quartzite seams? Could a method be evolved more scientific than thickening the grout by trial-and-error? Would it be possible to have, say, three rows of boreholes, of small diameter, the centre one being

used for grout and the other two for observation? Did the Authors know of any experiments in that direction being done?

Mr D. A. Brown (Senior Engineer, Sir Murdoch MacDonald & Partners) commented on the trouble with the valves at the outlets from the irrigation tunnels.

248. He had been associated with a dam in Scotland where a similar type of valve had been fitted. A question of reducing the angle of dispersion of the conical jet had arisen, and model experiments had been conducted with a short cylindrical sleeve or hood to surround the jet. It had been found that a considerable quantity of the water impinging on the inside of the hood had been projected in an upstream direction and the hood had therefore been abandoned.

249. A point that these model experiments had brought out was the effect of atmospheric pressure on the jet. In the prototype the spread of the jet had been markedly greater than in the model. Purely theoretical considerations indicated that the atmospheric pressure in the model had been too high, thus reducing the spread of the jet. In order to give results truly comparable with the prototype, the atmospheric pressure in the model should have been scaled down.

250. The trouble with the Dokan valves might possibly have been eliminated if a pipe of suitable diameter had been led from the atmosphere to the annular cavity surrounding the valve, but upstream of the conical jet. This pipe would have admitted air which would have reduced any tendency to form a vacuum in the cavity. What were the Authors' views on this point?

251. At several dam sites in Scotland commercial supplies of sand of suitable quality for concrete had not been available locally. He knew of two dams where adequate quantities of good quality sand had been produced at the site by the use of sand classifiers, and he felt that the virtues of these devices were not sufficiently appreciated. He would therefore like some information on the classifier used at Dokan.

Mr R. J. T. Casinader (Assistant Engineer, Sir William Halcrow & Partners) observed that the Paper was not only of interest in its own right but the practical details of construction given enhanced the value of the earlier Paper on the design of the dam by Pippard *et al*[4]. Comparison between the conditions assumed in the design and those obtaining on the site were inevitable.

253. One striking feature of the topography of the dam site was the left abutment, which was more or less a peninsula. Stability analyses had shown this rock mass to be adequate. However, it would be interesting to know if the strain and deflexion measurements indicated any asymmetry in the action of the dam which might result from the left abutment being relatively more flexible than the other, while still being adequate from the point of view of stability. The model experiments carried out had shown a vertical plane of elastic symmetry, but the model did not reproduce the left-bank peninsula. As a result of this finding of the model tests the relaxation analysis also assumed a vertical plane of symmetry. Did the prototype dam exhibit this plane of symmetry?

254. Fig. 4 showed the thrusts on the left abutment caused by water pressure and temperature effects "based on information supplied by the relaxation analysis". Reference 4 gave the results of the "tumbler" analysis only for temperature effects. The accuracy of this analysis could only be judged if the full three-dimensional analysis were also done. In any case the "tumbler" solution had given no indication of the stresses at the abutments. Would the Authors please say how the additional forces on the abutments caused by temperature, as shown in Fig. 4, had been obtained? Had a three-dimensional relaxation analysis been carried out for this condition?

255. Fig. 6 indicated that pressure-relief holes had been drilled in the foundations of the dam. This was also usual practice for gravity dams which were nevertheless often designed against some uplift pressure, since pressure-relief systems had been known to get blocked. Had any uplift pressure been taken into account in the design, considering that the base of the dam proper was about 100 ft wide and the base block even wider? Had a drainage system been installed in the main body of the dam?

256. Table 2 indicated the very high strengths obtained for the relatively lean high water/cement ratio concrete used in the dam—4,670 to 4,800 lb/sq. in. at 90 days with a low-heat cement. How did these figures compare with the specified minimum strength of the concrete and the maximum stress in the dam given by the analysis.

257. Finally, would the Authors care to say a little more about the reasons for choosing a pressure of 2 kg/sq. cm. for grouting the contraction joints? Had the effect of grouting on the stresses in the dam and the stability of the individual blocks been considered?

Mr D. N. W. Earp (formerly Senior Assistant Engineer, Resident Engineer's staff, Dokan) observed that in § 32 reference was made to the fact that low-heat cement conforming to B.S.1370:1947 had been obtained from Sarchinar during the latter part of the construction period. The new factory had been constructed as part of the Iraq Government's Development Programme. It was situated midway between Dokan and Derbendi-Khan, where a dam was at present being constructed across another tributary of the Tigris. The new works had come into production just as the demand for low-heat cement at Dokan had been reaching its peak, and for a period of about 9 months most of the factory's output had been used at Dokan. During this period the works had been able to manufacture a single quality of cement which conformed with B.S.12:1947, as well as with B.S.1370:1947. There would have been no significant reduction in production costs at Sarchinar if the Dokan specification had not called for low-heat cement. The advantage gained by using low-heat cement in the dam, particularly during the critical first week after placing, was illustrated by the following average heat of hydration results which were expressed in calories per gram:—

	at 7 *days*	*at* 28 *days*
O.P.C. from Baghdad factory	69	75
Low-heat cement from Baghdad factory	53	64
Low-heat cement from Sarchinar factory	45	60

Mr P. H. Stern (Civil Engineer, lately Binnie, Deacon, and Gourley (Baghdad)) referred to the potential benefits to flood control and irrigation which the Dokan project was now ready to provide (§§ 2–7). The great difficulties which the contractors had to overcome in successfully guiding this project to its completion likewise handicapped all other civil engineering developments in Iraq at the present time.

260. While the country needed the resources of foreign enterprise to develop the projects which evolved from the regulations and storage now available at Dokan, the field was not attractive to outside contractors.

261. A number of Iraqi engineers were aware of this situation, but it was not well appreciated by the majority of the Government and people. It was to be hoped that these difficulties would be overcome when the several works dependent on Dokan were ready to proceed.

The Authors, in reply, said that Mr Early's geological report in 1952, mentioned in the discussion, had indeed been invaluable.

263. It was hoped to continue over an extended period, as Professor Pippard suggested, measurements of deflexion by the precise survey and by the plumb bobs, together with strain and concrete temperature measurements by the embedded instruments. It was hoped to obtain results for a sufficient number of different conditions of load, temperature, and time to be able to isolate cause and effect.

264. In order to assist in the evaluation of any results obtained, tests had been made during the construction period on samples of concrete as placed in the dam in order to determine values for the creep function, Young's modulus, Poisson's ratio, and the initial drying shrinkage. Reasonably consistent and useful results had been obtained for the first two properties but despite every care the tests for neither Poisson's ratio nor the initial drying shrinkage yielded consistent results.

265. Regarding Professor Pippard's specific questions, from the summer of 1959

water had been released from the reservoir at whatever rate might be determined by the Iraqi authorities from time to time, and owing to a dry winter, the level at the end of March 1960 had been only 475 m, still 36 m below T.W.L. During the hot months of the previous summer the centre of the dam had deflected upstream, reaching, towards the end of the summer, a maximum displacement of about 1 cm in that direction (measured by the plumb bob in Block 7). The water level at that time had reached between 480 and 490 m. During the winter of 1959–60 when the water level had fallen nearly 20 m, the centre of the dam had moved downstream and the net displacement at the time of writing, the end of the winter, was about 2 mm downstream. The movement at the point of suspension of the plumb bob near the right abutment showed a similar pattern. It was evident that the radial strains due to temperature, magnified by the fact that much of the upstream face was still subject to variations in ambient temperature, were prevailing over those due to water load.

266. Tangential movements recorded so far had been small and the evidence was inconclusive, but there was nothing to confirm Mr Casinader's suggestion that the left abutment might be more flexible than the right.

267. Plumb bobs in the lift shaft at the left abutment had not been installed long enough to allow of any deductions being made from them and in fact the Authors stressed that it was really too early to draw any conclusions about dam deflexions from the few records available to date.

268. At the time that the last member of the Resident Engineer's staff left the site no surface cracking of the dam face had been observed nor had anything been reported subsequently. Some slight movement of the contraction joints, which, of course, were open between the copper seal and the downstream face, was suspected.

269. While on the subject of the experimental work, the Authors would like to clear up Mr Casinader's allied question about the arch design. A relaxation analysis had not been carried out to find the temperature effects at the abutments and to that extent the Authors thought that the last sentence of § 14 was misleading. However, in reference 4, p. 223, it was explained that the temperature stresses at the abutments were found by assuming the dam divided into independent horizontal encastré arches, which was considered a better approximation than the tumbler analysis for such conditions. No allowance had been made for the uplift in the analysis and reference 4 also commented on this matter.

270. The Authors agreed with Mr Morgan that the accuracy of any calculation depended upon the accuracy with which the physical constants were measured or capable of being measured. This difficulty could be overcome to some extent by selecting maximum and minimum values within which the physical constants probably lay and repeating the calculations with various assumed values to determine what effect they had on the computed stresses. Time had not permitted this to be done at Dokan because extensive basic research had been necessary in applying for the first time relaxation methods to an arch dam. However, as a result of the pioneering work done by Professor Allen and Dr Severn, comparative studies not only for various assumed physical constants but also for various alternative designs would require less time for any future arch dam, particularly if electronic computers were also used.

271. In suggesting that additional spillage capacity would enable the drawdown each year to be to a higher level, Mr Lane appeared to be under the impression that the reservoir operation rule curve resulted in a loss of flood-water but this was not the case. The whole question of rule curve operation had been discussed by one of the Authors more fully in reference 2, but to summarize, the rule curve did not come into operation unless the water level rose to elevation 505, and if in a wet year it had reached this level by 1 March then it would almost invariably reach top water level by 1 June even if the reservoir operation rule curve were applied. In a dry year or cycle of dry years the reservoir did not reach elevation 505 and so there was no spillage. Additional spillway capacity would therefore not be justified. Also the limitation of spillway capacity was beneficial for flood control which was an important function of the reservoir, and it was

estimated that using the rule curve the following reduction in flood peaks in the lower reaches of the Lesser Zab would be achieved:—

	Uncontrolled flood peak	Controlled flood peak
Probable maximum	18,000 cumecs (§ 86)	3,000 cumecs
75% ,, ,,	13,500 cumecs	2,200 cumecs
50% ,, ,,	9,000 cumecs	2,000 cumecs

272. *The suggestion that the provision of flood protection for Iraq had tended to be* founded on values obtained by the summation of the maximum flood peaks on the various tributaries might be applicable to some of the earlier work on floods. More recently, however, the Hydrological Survey of Iraq (§ 86) included a comprehensive study of the flood potential of the Tigris catchment, which was based on a determination of the most critical combination of flood-producing events which was likely to take place. Meteorological analyses determined the probable maximum storms which could occur over the catchments of the various tributaries and these storms were then used to derive the probable maximum floods for each sub-basin, consideration being given to the contributions from antecedent storm run-off, snow-melt run-off, and base-flow.

273. These probable maximum floods could not be expected to occur concurrently: this would be physically impossible in the Tigris basin. Historical storm patterns were therefore examined in detail and the maximum storm which could occur over the basin as a whole estimated. This resulted in smaller floods at downstream points than would be produced by routing the probable maximum flood of each sub-basin to those points.

274. Referring to the frequency which might be attributed to a 13,000-cumecs flood, the Authors stated that flood frequency analyses were performed but only as a method of comparative classification of flood magnitudes. It was obviously impossible to make a reliable determination of recurrence intervals in terms of thousands of years on the basis of the relatively few years (§ 85) for which data was available. Any such estimate could only be misleading and the Authors were therefore unwilling to assign a frequency to the 13,000-cumecs flood. All that could be said was that the maximum discharge at Dokan over the 27-year period 1932–58 appeared to have been 3,660 cumecs.

275. In reply to Mr Al-Hamdani the Authors stated that the height of the cofferdam had been chosen to make the risk of overtopping a reasonable one: to have designed it to retain even the highest flood of record would have been uneconomical. In the event it had been overtopped only once and the cost to the Contractor had been less than it would have been had the cofferdam been designed to retain the flood of record.

276. The answers to Mr Ali Al-Hamdani's questions about the bellmouth spillway were to be found in §§ 95 and 98 and additional information had been given by Mr O'Donnell.

277. Mr Lane had been surprised that there was only one gallery in the dam but the Authors had no regrets at the omission of additional galleries except for one just beneath the crest to carry various electrical and water services which had necessitated some awkward ducting and manholes. The introduction of galleries and other extraneous features inevitably disturbed the rhythm of concreting, which on a structure of this magnitude was of some importance, and unless they served some definite purpose galleries were best omitted. The cables from all instruments were therefore led in groups to sockets on the downstream face and for taking readings a special cabin suspended from the crest crane was lowered down the face to the appropriate group of sockets—an arrangement considered preferable to carrying the instrument cables up or down several lifts to a gallery. Also the Authors did not recommend the use of additional galleries for contraction-joint grouting. This operation called for a high degree of control, particularly when all joints at a level were grouted simultaneously (§ 61), and since the grout mixers and pumps were best situated downstream of the dam it had been found highly desirable to have all inlets and outlets, gauges and cocks situated on the downstream face in positions visible from the pump operators.

278. Steel penstocks also interfered with the rhythm of concreting and since siltation was not a serious problem it had been decided to keep the intakes at a relatively low

level. If they had been placed higher the placing and welding of the penstocks would have interfered with the concreting for a much longer period. The Contractors had also found the upstream ledge supporting the trashracks a very useful working platform particularly during that time after the closing of the diversion tunnel when the summer flow of the river was passing to the irrigation tunnel.

279. In reply to Mr Lander's question about intakes on cupola dams, while it was conceivable that, with pulleys, gates could be made to operate on curved surfaces, this idea had not found favour with the various gate manufacturers consulted at the time when Dokan was being designed, who all recommended lifting either vertically or on an inclined plane. The unreinforced concrete arches with occasional tie rods let into the face of the dam had been constructed to prevent trash entering the gate openings in the trashracks and to keep it off the gate guides, but they were in no other sense gate towers. Prior to coming to a decision on the type of dam to be adopted several continental arch dams had been inspected. Most cupola dams had no openings through them, the outlets being situated elsewhere, but two cupola arch dams in Portugal, Cabril, and Salamonde with openings through their bases had been visited. At the former a power house had been constructed at the foot of the dam and a 400-ft-high reinforced concrete structure had been constructed in the reservoir for three gates, two for turbines and the third for a low-level outlet. At the latter, an inclined plane with the base extending a considerable distance upstream of the dam had been constructed for a single gate. Both these solutions had been studied for Dokan but with seven outlets to cater for neither had appeared attractive and, since the client had decided to construct a cement factory, the differential cost of extra cement had proved to be small and the saving in concrete for a cupola dam had not been a very important factor. Every case had to be considered on its own merits and these had been the principal considerations that had led to the adoption of an arch dam with a vertical upstream face at Dokan instead of one "with never a straight line". As regards the time factor, after the penstocks had been installed the remaining 80% of the mass concrete in the dam had been placed in 14 months, a relatively short period considering that concreting, during five of these months, had been able to proceed at night only.

280. In reply to Mr Blackmore no special provision had been made for emptying the reservoir since the quantities of water were so large and there seemed to be little point in it. The minimum space between bars in the trashracks was 13 cm and in view of the barren nature of the land in the catchment area no special provision for raking them was considered necessary.

281. Referring to the concrete in the dam, and to Mr Lane's queries, the concrete was wet sieved through a 1½-in. screen before being hand tamped into cast-iron 6-in. moulds.

282. The five standards of workability were as follows:—

Standard A	Very wet. Concrete spread over a large area when the skip was emptied. One vibrator handled concrete easily and vibration was scarcely needed. Men standing on the concrete sank in above the ankle and had difficulty in moving about.
Standard B	Wet. Concrete was easily spread and vibration affected a large area. Men standing on the concrete sank in but did not have difficulty in moving about. This standard of workability might be required around reinforcement.
Standard C	Normal. Concrete flowed well under vibration. Vibrators left no hole when withdrawn slowly. After vibration only shallow footprints left.
Standard D	Dry. Vibration difficult. Especial care needed around shutters, etc. Hole left by vibrator unless withdrawn very slowly but concrete would still flow.

Standard E Very dry. Vibration almost impossible. Vibrator inserted with difficulty and left hole when withdrawn. Fat came to the surface only after heavy work. Edges of concrete cracked and it did not flow.

283. Both Mr Lane and Mr Brown had enquired about the sand classifier which was manufactured by the Dorr Oliver Company in the U.S.A. and utilized the principle of Stokes's law. The reason for its adoption was that difficulties were foreseen in producing from the crushed rock a consistent sand free from excess fines. In the Authors' opinion it made a material contribution to the necessary control of concrete quality. Four ranges of size between 0 and 5 mm could be produced, although the largest range (2·5–5 mm) was separated by screening only. They were stockpiled separately and re-mixed in the proportions required. There had been found to be sufficient undersize in the larger ranges for it to be possible to reject the 0–0·3 mm range entirely, but the Contractor had been able to manufacture a very satisfactory sand from the remaining material.

284. Mr Casinader had enquired about the minimum specified strengths. When drawing up a specification for concrete minimum stresses could be specified provided the responsibility for concrete mixes was placed on the Contractor, but since the Government undertook the responsibility for supplying cement as a prime cost item, and since cooling problems had also to be considered, it was decided to make the Resident Engineer responsible for mix design in the contract and no minimum strengths were specified. Relaxation methods indicated a maximum compressive stress of 515 lb/sq. in. and a maximum tensile stress of 100 lb/sq. in. The Authors doubted whether any significant reduction could have been made in the cement content of the concrete without adversely affecting the workability, but having regard to the computed high tensile stresses, the high strength of the concrete appeared to the Authors to have been desirable.

285. Mr Casinader had also enquired why a pressure of 2 kg/sq. cm had been chosen for grouting the contraction joints. American practice appeared to be to use a pressure of 50 lb/sq. in. (a little less than 4 kg/sq. cm) but experience at Dokan showed that with this pressure leakage past the copper seals was excessive and there were practical difficulties in balancing the pressures at the joints while the grout set. The lower pressure had therefore been successfully adopted.

286. Mr Lane had requested more information upon the pre-cofferdam. The Contractors relied on the tipping of spoil from the diversion tunnel and dam excavations to reduce the river flow sufficiently to allow them to dewater the cofferdam foundations. Although the spoil was to some extent self-binding and what little soil and soft material was available in the vicinity had been tipped down the upstream face, the object had not been achieved.

287. Turning to the spillway tunnels about which Mr Lane, Mr Lander, and Mr Blackmore had all asked questions, the circular shape had been chosen for the bell-mouth tunnel because much of it was under pressure. It was thought that economies in shuttering would follow if the gated spillway tunnel was made similarly. It was doubtful whether in tunnels as large as these, considerations of access favoured the adoption of a flat invert so much as in smaller-diameter tunnels, but there was no doubt that some of the heavy overbreak, which occurred at the sides of the invert where the face shovel had not followed a circular path, could have been avoided. The Authors agreed with Mr Lane that a narrowing of the crown to give more headroom when placing concrete would be advantageous.

288. Mr Lander had suggested that a spillway at Dokan similar to the one at Kariba would have been more economical. However, in comparing the relative merits of different layouts, it was necessary to consider them as a whole with regard to the particular circumstances at each site and not in part. If there had been gate openings through the dam then owing to the narrow width of the valley it would have been necessary to site the conduits and the future power station elsewhere. One of the first alternative layouts studied was an underground power station in the left bank, which

would have enabled the conduits to be sited elsewhere, but since the power station was not to be constructed at the same time as the dam and doubt was felt as to the advisability of carrying out large underground excavations at a later date with the reservoir full, this alternative was discarded. From the point of view of tail water levels for outlet valves and turbines, the configuration of the river-bed was by no means ideal for a spillway either through the dam or on the right bank and the tunnel spillway was unquestionably the best solution hydraulically.

289. In answer to Mr Blackmore, model tests on the bellmouth spillway had shown that at a discharge of 1,250 cumecs there was a vacuum of about 2 m of water around the junction of the bellmouth and shaft, and that the kinetic head was about five times as great as the absolute pressure. While not necessarily excessive it was considered that aeration was advisable to eliminate the risk of cavitation. The aeration did not reduce the discharge capacity.

290. Electricity for permanent operational and domestic needs had to be generated on site and a small Diesel power house had been built pending construction of the hydro-electric station. Consequently, power failure was not such a grave risk as Mr Blackmore had thought but a small standby Diesel set had nevertheless been installed in the spillway gatehouse. While slow and laborious, the gates could also be operated by hand if necessary.

291. Mr Brown had referred to Mr Binnie's oral introduction to the Paper in which he had described some troubles experienced with the regulator valves at the irrigation outlets owing to cavitation and vibration. Pipes had in fact been installed after the trouble was experienced, in order to lead air to the back of the water stream. This had improved conditions at 30% and 40% valve openings but a greater openings vibration still occurred and it was decided that the upper halves of the hoods should be removed entirely. No further trouble with the regulator valves had since been experienced. Fig. 27 showed the modifications carried out.

292. Turning to questions regarding the grouting and geology at Dokan the Authors thanked Mr Grundy for his contribution and agreed that, on a tonnage basis, Camarasa had been a larger grouting job than Dokan. Had treatment at Dokan been deferred until serious leakages were allowed to develop there was no doubt that the cost of grouting would have been greatly increased.

293. In reply to Mr Lander, on the left bank there was, in fact, a benched road at top water level and this was used to drill the portion of the curtain above tunnel level, using wagon drills, but had there been no tunnels it would have been necessary to drill the bottom part of the curtain with the slower and less manoeuvrable rotary drills; this would have taken much longer and on the left bank would have interfered with the main Contractor's operations round the bellmouth spillway—in particular the movement of the prefabricated blocks mentioned in § 123. The additional cost of the tunnels was largely offset by the greater amount of wagon drilling made possible, and the tunnels also allowed visual examination of the rock, which proved invaluable. Tunnels at top water level would only have exposed unimportant rock; while they would have avoided upward drilling (which was only carried out on the right bank) they would have meant increased downward rotary drilling; finally, the tunnels in the middle of the curtain gave more opportunity for individual attention to any isolated patches of bad ground in the lower part of the curtain.

294. Mr Lander was quite correct in stating that the down-the-hole drills which were now available could achieve a higher standard of verticality than the normal wagon-mounted percussion drills which were used at Dokan. However, with the machines then available, holes drilled with down-the-hole equipment would have to have been at least 6 in. in diameter, and under the wet-rock conditions at Dokan, it was extremely problematical whether holes to 300 ft depth could have been achieved with such equipment, whereas the ordinary wagon-drills went to this depth using 2-in.-dia. bits. A certain amount of deviation was unavoidable when small-diameter holes were drilled, whether percussive or rotary machines were employed, but the majority of the few inclination

tests carried out at Dokan had showed a deviation of note more than 2°. These tests were carried out in raking holes.

295. Dr C. S. Hitchen had put forward an interesting theory to account for the formation of dolomite. However, while this might be applicable to other sites, the Authors did not consider that it was true of Dokan; the shale bed would form a protective layer and Mr Early had pointed out elsewhere that secondary dolomitization of the limestone was associated with major fissures in the shale, which would indicate that the solutions came from below rather than above. In the Authors' opinion the primary dolomitization had occurred while the Judea limestone was still unconsolidated.

296. While the Authors welcomed Mr Early's contribution and wished to place on record their indebtedness to him for his share in the preliminary investigation in 1951, they could not agree with his criticism of § 125. The box-curtain solution mentioned by Mr Early had been based on the assumption that a reasonable thickness of Shiranish

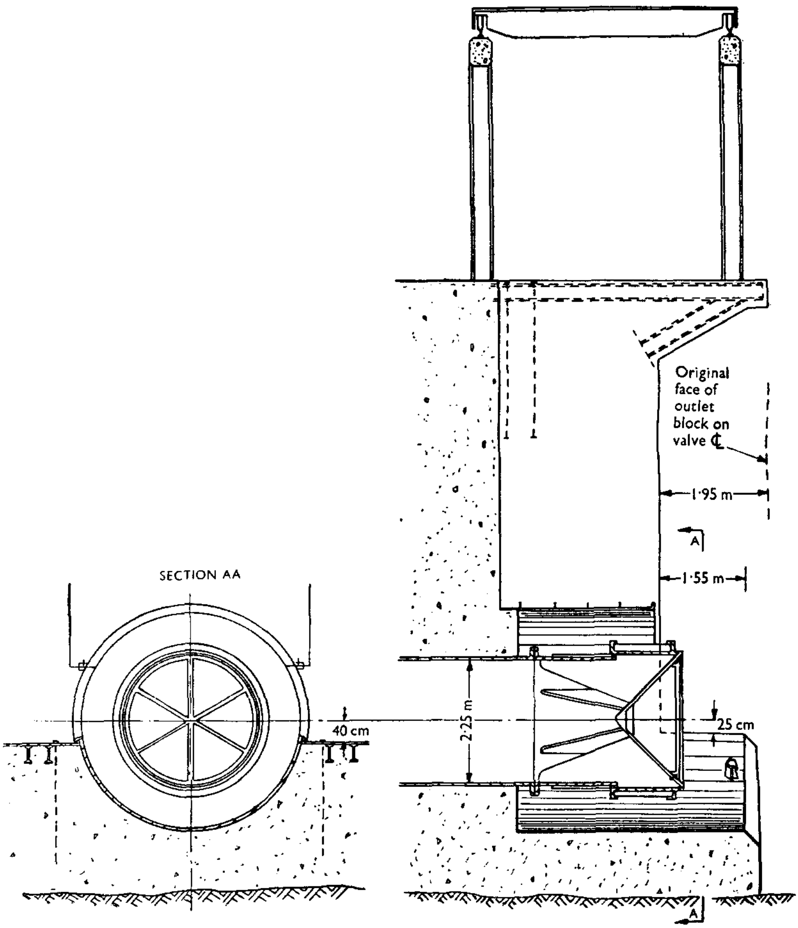

FIG. 27.—MODIFICATION TO HOODS OF IRRIGATION VALVES

limestone would provide an effective seal, and it had been only after further drilling and water testing in 1954 that the alternative design of a classical cut-off curtain had been adopted.

297. The underground streams on the right bank, which Mr Early mentioned, undoubtedly extended for some distance, and on one occasion grout emerged at a stream outlet over 300 m from the point of injection, but the caverning located on the right bank was not comparable with that on the left bank, where one cavern in particular, near the gated spillway, had a volume of 1,000 cu. m.

298. In reply to Mr Early's request, the number of stages tested in the dolomite during reconnaissance was 202; of those, 12 accepted more than the output of the pump, 19 had Lugeon coefficients greater than 10, and 65 had coefficients between 5 and 10.

299. Mr R. C. S. Walters had pointed out that the cost of the screen at Dokan, per square foot, was more than double that at Sutton Bingham. However, at Sutton Bingham the maximum depth of drilling was 120 ft and therefore hand-held drills were used throughout. The rate of consumption of grout at Dokan had been about 2½ cwt per foot drilled, whereas at Sutton Bingham it had been just more than 1 cwt, while the average hole spacing was approximately the same. These factors alone would greatly increase the cost per square foot, without the normal increased overheads due to work overseas in an underdeveloped country.

300. Mr Walters had called the procedure described in § 154 a trial-and-error method, but in fact when working in variable ground, it was always desirable to start with thin mixes, unless drilling water had been lost. Not only was a thin mix necessary if the ground was fairly tight, but it ensured that finer fissures were not prematurely blocked off when the main portion of the grout was passing into wider fissures. The methods mentioned by Mr Walters in § 246 could be applied in limited circumstances below the structures themselves, but in the Authors' opinion for extensive curtains the only economically feasible method of ascertaining the probable expense of grouting was to carry out a test section. Such a test might give a reasonable estimate of the cost of treatment, but there was no method of indicating in advance, in heterogeneous ground, the best mix for each individual injection.

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