Proc. Instn Civ. Engrs, Part 1, 1986, **80**, June, 769–784

Colliford Dam sand waste embankment and asphaltic concrete membrane

T. A. Johnston and J. D. Evans

Mr Johnston and Mr Evans

The Paper described the behaviour of the dam during impounding to the end of 1984. Reservoir filling has continued steadily and the reservoir is now 70% full in terms of volume and the water level is within 3 m of the spillway crest.

72. The instrumentation has indicated that the dam has continued to behave as expected. The phreatic surface in the foundations is a metre or so below rock-head. The maximum movements noted to date have been 4 mm settlement and a 16 mm horizontal movement, both at dam crest.

73. The membrane still appears to be virtually water-tight with scarcely measurable drips of water into the inspection gallery from the membrane drain. The total flow in the gallery has amounted to a maximum of 1 l/s, most of this being contributed by the low-level drains. The drainage flow at the downstream toe has increased slightly as the reservoir level has risen, the maximum recorded flow to date being 1·3 Ml/day. However, flows have continued to respond to rainfall to a greater extent than to reservoir level.

Mr F. F. Poskitt, *Edmunds Mapplebeam*

The finished embankment has a very good appearance, and the Authors showed some site benefits and some difficulties. They had the benefit of a foundation rock which was granite only 3·8 m below the ground surface, and severe flowlines presumably did not worry them. Slides indicate that across the central section of the valley, there appears to be what amounts to a 10 m high maximum concrete retaining wall. There was a similar situation in the dam that my firm built in Northern Ireland, where the valley was filled downstream with partially grouted lean concrete. Did the Authors consider that or did the residual settlement prove not to be sufficiently severe to result in a differential effect that would cause trouble?

75. The sand is very free-draining. There was a drainage layer of broken stone, put immediately underneath the membrane, no doubt with a higher permeability. The Paper also shows that at 3 m centres drainage pipes were taken from that drainage layer down into the underlying galley. What was the thinking behind that, because many dams in the past have had a sandwich system where a membrane is underlain by a drainage layer and then again by another impermeable layer to create a kind of drainage sandwich?

76. While the latter is a very expensive construction and is not used so much now, it avoids any possible loss of drainage into the embankment. Is it possible for

Paper published: *Proc. Instn Civ. Engrs*, Part 1, 1985, **78**, Aug., 689–709.

any drainage to go down into that permeable sand in addition to what comes into the gallery?

77. The standards set for the asphaltic concrete were very commendable and quite severe. Bitumarin also undertook the testing for the dam with which I was concerned, and at that time the required permeability was 10^{-7} cm/s. There is still no British code of practice or standard specification for asphaltic concrete.

78. Two things which gave us trouble came out very successfully at Colliford namely the effects of weather and slope stability. Wet weather is a problem with dense asphaltic concrete, and a fairly uninterrupted though brief dry period is needed to lay it successfully.

79. Regarding the stability of the slope, the Germans used dense asphaltic concrete frequently and achieved impermeability by overfilling with bitumen and mixing it with chopped asbestos fibre. The Authors have not done that at Colliford and we did not do it in Northern Ireland. When chopped asbestos fibre is used a much closer degree of control is needed to achieve stability with mechanical inter-linking of aggregate particles. Stability was not achieved on the slope with the seal coat that we used, which was bitumen with a mineral aggregate and limestone filler. With such uniform-sized particles stability cannot be obtained.

80. Tests were done at Colliford when the asphalt was fresh and it is known that asphalt hardens over the years. The Authors expressed the hope that there will not be more than 1% deformation in the future—were they looking at the long-term position when the asphalt hardened? The Authors are presumably satisfied that 'Flintkote' will reduce evaporation of the volatile oils in the asphalt that keep it flexible. The hardness of the asphalt is directly related to the amount of evaporation of the volatile oils.

81. Concerning the aggregate, there seemed to be no trouble with adhesion. In Northern Ireland basalt was used but it was extremely difficult to get a quarry to furnish aggregate with sufficiently good adhesion to provide the slope stability that was needed. Although normal tests did not show any great variations, adhesion tests showed considerable differences. There are various criteria that influence seepage through the membrane. Have the Authors any information on these? Bulletin 32 published by ICOLD[12] listed 182 dams with bituminous concrete facings and one of its main conclusions was that monitoring of performance in the future would be very valuable and should continue. Dams of this type have been built in Nigeria and also in Norway, in climates more extreme than in the UK and about the long-term performance of such asphaltic membranes under short and long-term loading. A further ICOLD Bulletin 39 was produced in 1981,[13] and touched on the difficulty of securing satisfactory junctions with rigid structures penetrating the membrane. Mention was made in the latter Bulletin of the use of fibreglass sheeting which had been laid over the junction with a cut-off wall. That seems a useful means of protection against separation.

82. The first recorded use of asphaltic concrete in the UK was at the Shotton Steel Works in 1956, and it will be interesting to see what performance data emerges from all these cases to add to knowledge about asphaltic concrete in general.

Dr A. D. M. Penman, *Fellow*

It was satisfying to learn that the embankment dam was 40% cheaper than the equivalent concrete structure. With the embankment dam, this has always seemed to be the case. It is also good to know that it fits in with the environmental lobby

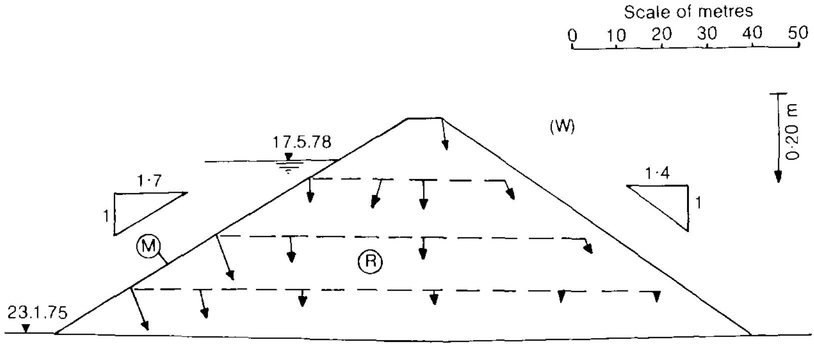

Fig. 13. Deflexion measurements during impounding at Windscar

and that no extra expense was required to make the dam merge into the natural situation. This is only the sixth dam in Britain to use an upstream asphaltic membrane and therefore any knowledge of the behaviour of such dams is important.

84. Windscar was one of the first of these dams. The deformation of the membrane when the reservoir was filled could be measured by horizontal plate gauges which were fitted through the dam at three positions. The deflexion measurements made during impounding are given by the vectors shown on Fig. 13. This instrumentation does not reveal the differential movement that can take place at the plinth. Measurements were made on Marchlyn Dam which was one of the other few British dams to use an upstream asphaltic membrane. For this exercise a trolley was devised which would run on a railway line that was fitted on the face of the asphalt. It ran underwater so that the deflexion that occurred on filling the reservoir could be measured. A description of the measuring trolley has been given by Penman and Hussain.[14]

85. The designers of the dam had made various assumptions and predicted a total deformation of the upstream slope during and subsequent to construction with a maximum of about 250 mm near the middle. The measured movements of the membrane were much less than this, as shown by Fig. 14 the maximum being only about 20 mm in the central part of the membrane. Near the toe, adjacent to the concrete cut-off structure, there was a differential movement of 25 mm, shown by Fig. 15. The beauty of the trolley mechanism was that it shows the movement that can occur between the rigid concrete structure, which is both founded in bedrock and standing on top of the grout curtain, and the asphaltic membrane, which is supported by the fill. As in the case of bridge abutments, the fill is very difficult to compact tight up to a concrete structure with a vertical wall, so in this zone it may be slightly less dense or well compacted than the rest, and this leads to some differential settlement. Special arrangements had been made to allow for more movement at this point, so 25 mm did no harm. However, it shows that there can be larger movements immediately adjacent to the concrete structure. At the bottom of Colliford Dam (Fig. 8 of the Paper) the Authors have wisely made a sloping back to their concrete cut-off to simplify the completion of the sand fill. Could they explain more about that? They have also provided for extra reinforcement of the membrane to allow for differential movement that might occur.

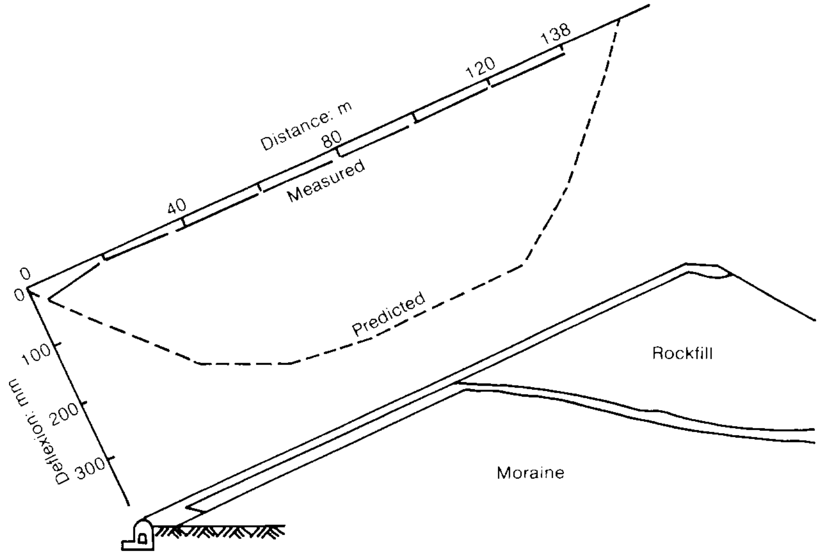

Fig. 14. Membrane deflexion at Marchlyn Dam

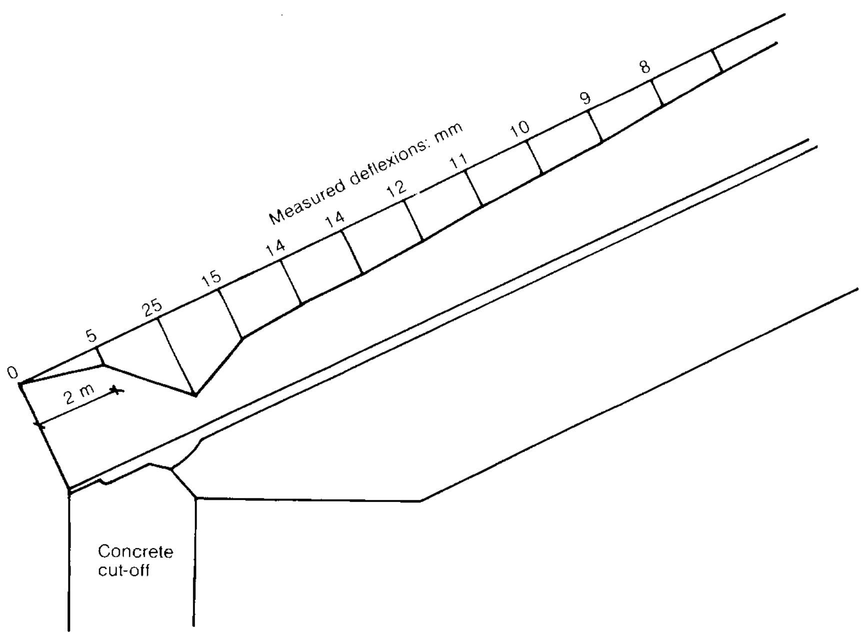

Fig. 15. Differential movement near concrete cut-off at Marchlyn

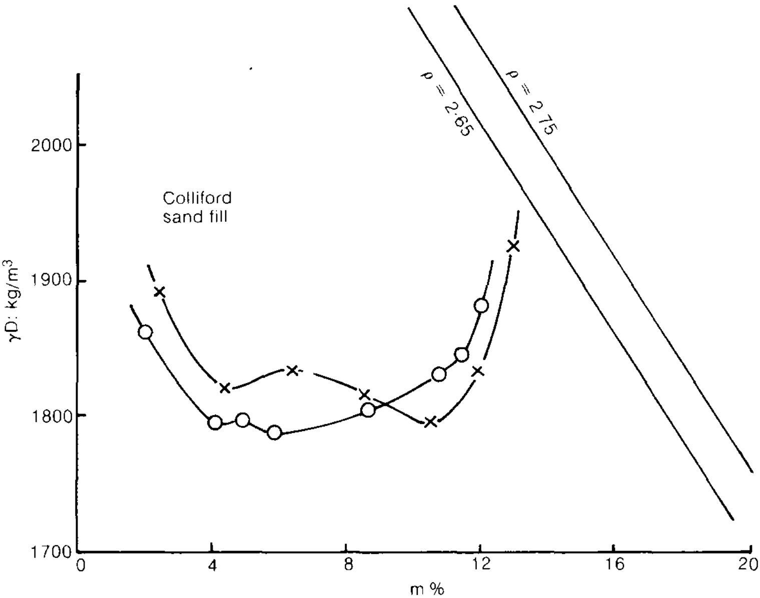

Fig. 16. Colliford—compaction curves and saturation lines

86. It would have been beneficial to have had an impervious layer on the interface between the drainage layer and the sand. The Paper mentions that that sand was free draining. It is possible that, despite the evidence in the rainstorm, some water may be lost into the sand fill. It would have given a more accurate measurement of leakage had the money been available to have some simple method like sprayed bitumen, to make an impervious zone to direct the water into the drains to come out in the inspection gallery where it could be measured.

87. Concerning the problems of compaction of the sand, the Authors showed the upside down sort of compaction curve that develops with sand, but omitted the saturation lines. I have put on saturation lines for specific gravities of the sand of 2·75 and 2·65 in Fig. 16. It is very difficult to imagine such a curve turning over in time to meet the 2·65 line. Perhaps the figures here are wrong. Could the Authors explain this problem?

88. It was originally hoped to move the trolley from Marchlyn to Colliford, but that was prevented by the site delays that occurred at Marchlyn.

Mr J. E. Smith, *Engineering & Power Development (EPD) Ltd*

The fill, as the Authors point out, is rather unusual with an inverted W or U density curve (as in Fig. 17) but it is perhaps not so unusual to people used to working in desert climates. Desert sands and desert fills frequently have this sort of curve which seems typical for the more or less uniform graded material that occurs. The uniformity of that grading probably also leads to the fairly low densities of these sands. The influence of adding a little silt to the material draştically changes that behaviour.

90. The Authors alluded to this in their talk and discussion. They found that other sands elsewhere in Devon showed very different properties. At the dam that my company has built at Balanga in Nigeria the sand used shows a wavy grading curve (Fig. 18). It was produced from a weak sandstone which broke down extensively on placing. It is quite gap graded as shown by the waviness in the curve. The flatter curve in the middle of the grading indicates larger particles mixed with smaller ones with a lack of intermediate sizes. Also plotted in the figure is the Colliford sand which is of a more uniform material. If on the gap grading the coarser material of the Balanga sands is cut out, the resulting grading looks similar to the sand at Colliford (see dotted curve, Fig. 18). However, appearances perhaps can be deceptive because the density curves are very different, as seen in Fig. 17.

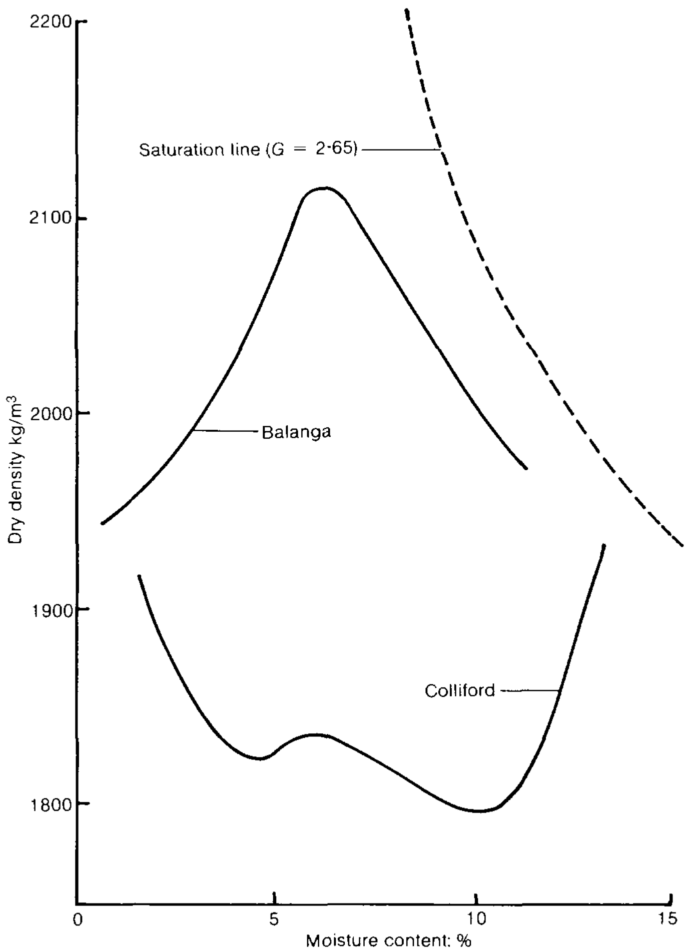

Fig. 17. Compaction curves for embankment sand—Balanga and Colliford

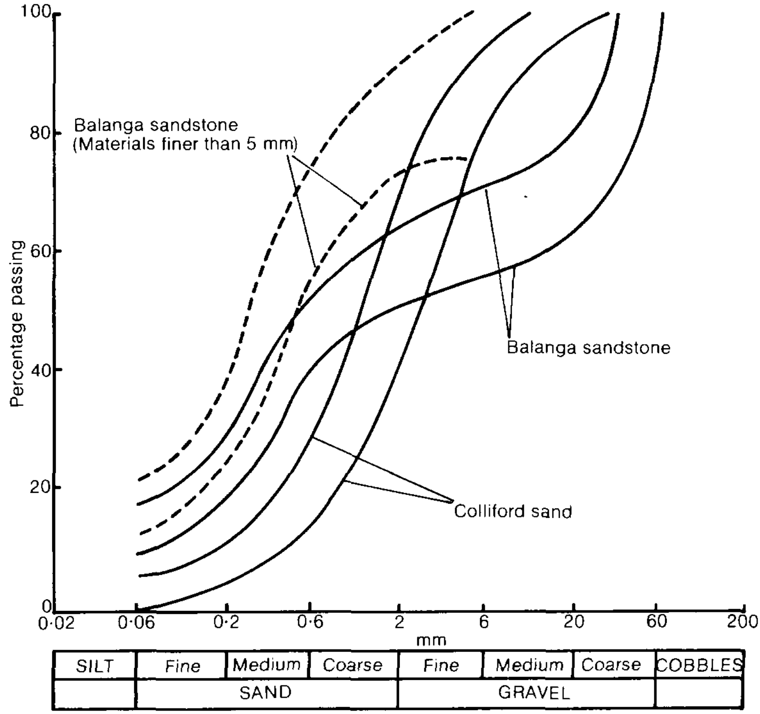

Fig. 18. Sand particle size distribution—Balanga and Colliford

91. There is a great difference in both the density and the shape of the curve. This is probably caused only by the silt content. A further point is that the curve for Colliford sand is close to and tending to cross the 100% saturation line at high moisture content. The 100% saturation line has been plotted assuming a specific gravity of 2·65. Could the Authors comment on these points in the light of any other investigations that they made on other materials? At Balanga the fines made the material very easy to handle. Although very similar compaction plant was used, that is a large smooth-drum vibrating roller of about the same weight as at Colliford, only about four passes were needed to get the maximum density, provided the considerable volume of water needed was added.

92. The Authors found considerable scatter in the density. The cause may be a factor that was found at Balanga. The sand at Colliford is from a granite source and is rather high in feldspars. Balanga had an aeolean sandstone, which was similarly high in feldspars. These caused it to break down very considerably during excavation and placing. Excavation was by ripping, and placing was by dump truck and dozer. The scatter may be something to do with this breakdown. Or is it perhaps not such a big scatter but more the way it has been plotted? The majority of the results lie within a range of only 5% or 6% if extreme results are ignored. That is not extraordinary for variation in compaction of fill on a dam, particularly when test inaccuracies are taken into account.

Fig. 19. Kindaruma Dam

Dr G. P. Sims, *EPD Ltd*

My company has experience of the operation of Kindaruma and Kamburu dams, both with asphaltic concrete faces. These dams are both on the Tana River in Kenya where the climatic conditions are different from southern Britain. Nevertheless data on their performance are of interest.

94. Kindaruma Dam, shown in Fig. 19, was constructed in 1968 of compacted rockfill on a sound rock foundation. It is about 23 m high and 500 m long and is situated at 780 m above sea level. Fig. 20 shows the construction detail of the asphalt face. A drainage layer is sandwiched between two dense asphaltic concrete

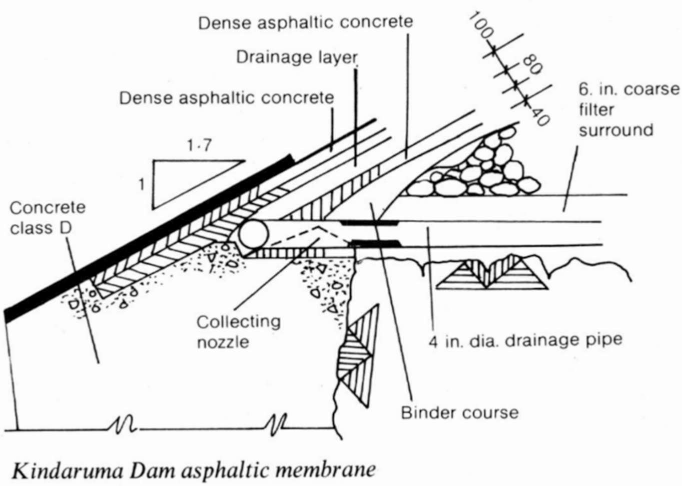

Fig. 20. Kindaruma Dam asphaltic membrane

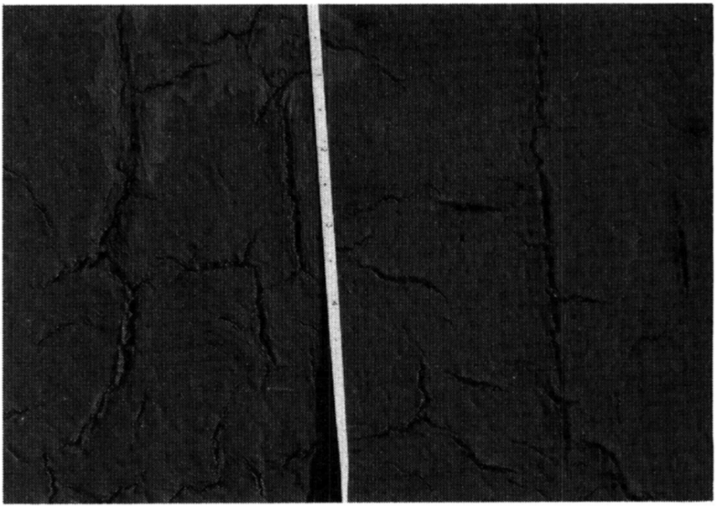

Fig. 21. Kindaruma Dam membrane cracks

layers and over the plinth there is a protective cap of asphaltic material. Drainage water is collected from the central layer and carried away through the dam to a measuring station. Fig. 21 shows cracking within the membrane in the area that is alternatively wetted and dried as the reservoir level varies. Fig. 22 shows essentially vertical cracking both within and above the normal operating range of the reservoir.

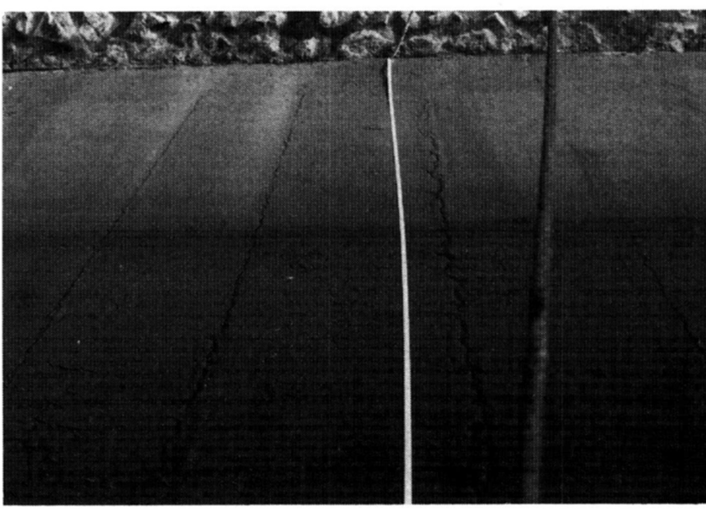

Fig. 22. Kindaruma Dam vertical membrane cracks

Fig. 23. Kamburu Dam

95. Kamburu Dam is shown on Fig. 23. It was completed in 1973 and is 50 m high and 900 m long. It is at 1000 m above sea level. Fig. 24 shows the construction detail of the asphalt face. In this design there is no internal drainage layer. The design of the connection of the membrane to the plinth is similar to that used at Colliford: there is a levelling and binder course and two layers of dense asphaltic concrete covered by a protective layer. Fig. 25 shows surface crazing within the operating range. The crack width here is 2 mm to 3 mm. Fig. 26 shows a more pronounced crack about 5 mm wide.

96. Seepage below both the dams has been constant. That at Kindaruma has been about 200 l/min since 1975 and at Kamburu between 50 l/min and 100 l/min since 1973. As at Colliford the seepage through and under the grout curtain is measured at the same location as that through the membrane.

97. Membrane cracking has been identified at both dams quite early in their lives. Despite the appearance of the cracks, the relatively constant seepage suggests that both dams are working well. Nevertheless we are continuing to measure seepage daily and the need for maintenance is reviewed continuously. Several suggestions have been made during recent inspections as to the causes of the cracks. These include

(*a*) strong ultra violet light
(*b*) loss of volatile components of the asphalt leading to a reduction in ductility
(*c*) downhill creep may be responsible for horizontal cracks
(*d*) relatively poor compaction under the edges of vertical strips may be responsible for vertical cracks
(*e*) the mix may have been locally too rich in bitumen.

The reported seepage rates for Colliford, Kindaruma and Kamburu dams are all between $0{\cdot}1\ l/h/m^2$ and $0{\cdot}7\ l/h/m^2$, based on the area of the membrane.

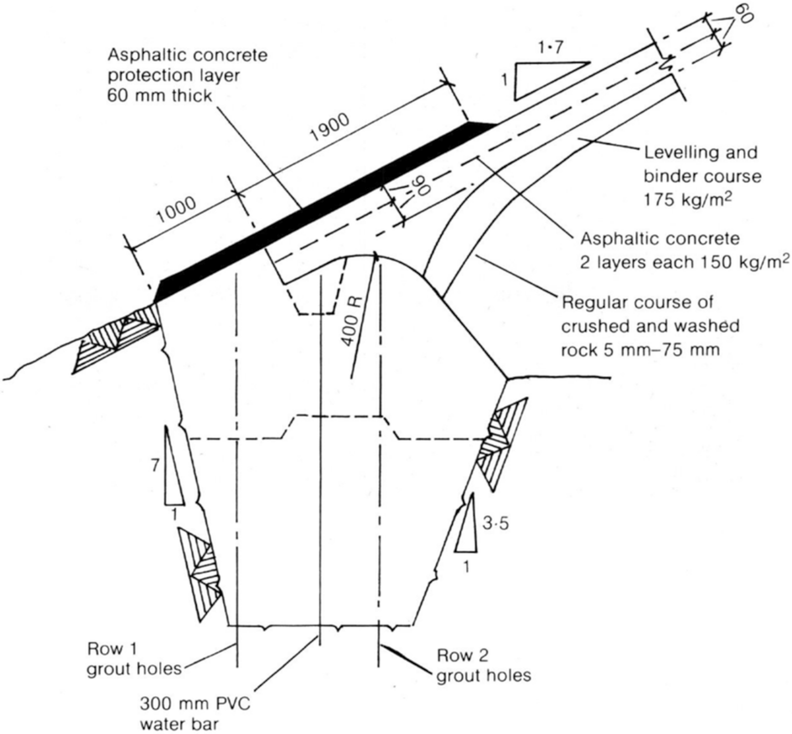

Fig. 24. Kamburu Dam asphaltic membrane

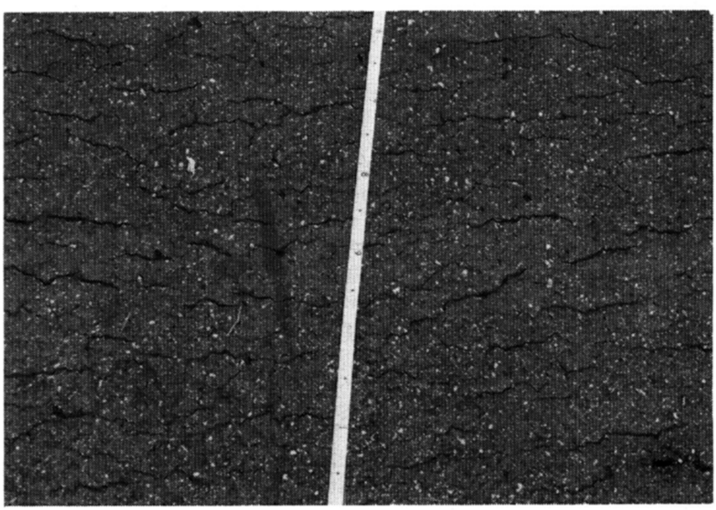

Fig. 25. Kamburu Dam membrane cracks

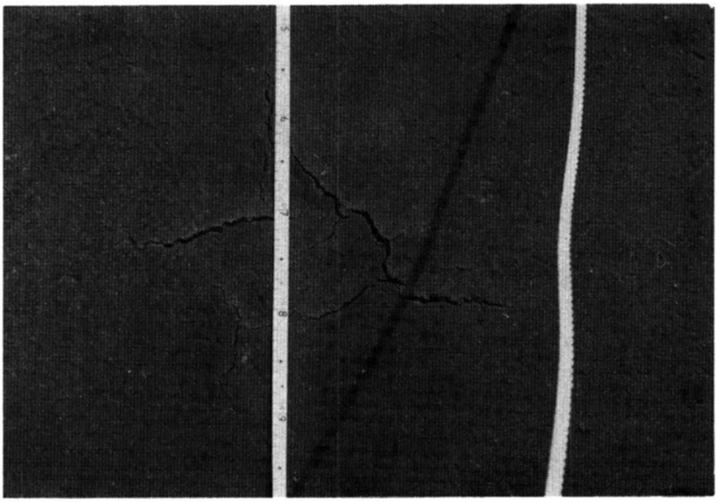

Fig. 26. Kamburu Dam membrane cracks

Mr E. T. Haws, *Rendel, Palmer & Tritton*

Concerning surface protection—I was involved in the 1960s in the investigation and design of Chowilla dam in South Australia. It was a fairly low embankment dam, 17 m high and 5 km long. A bitumen membrane was the only solution because the nearest rip–rap was 100 miles away from the site. The latitude is low 30s south and as ultraviolet light presents problems test panels were constructed facing north. They had maximum exposure over three seasons. They were in very severe conditions in arid desert country.

99. These test panels were treated with a variety of surface protections hot and cold spray with and without added mineral dressing. In that period of time the control panel, the simple straight dense asphaltic concrete, gave the best performance. What is the Authors' opinion on the value of the flintkote that was added at Colliford? The other aspect that was a problem on Chowilla was wave run-up on a smooth bitumen surface. The design had to be for rather severe waves, 5 m high. The economic solution there was to modify the upstream profile of the dam by putting in substantial berms below the highest water level. That adds complication to placing the bitumen membrane, but clearly in that situation it was the economic solution. Have the Authors any comments relating to wave run-up on the smooth bitumen surface?

Mr C. W. Isherwood, *Edgar Morton & Partner*

The suggestion that degradation of the sand waste might take place was received with some scepticism. The sand waste, however, was going to be placed in a completely new environment and subjected to conditions which it had not experienced before. Although laboratory experiments can be devised to illustrate what changes can take place under various sets of conditions, the difficulty lies in extrapolating results to the full-scale structure under field conditions.

101. At Colliford, the potential problems were tackled on the principle of keeping as much water as possible out of the bank and of making sure that what water did get in was removed as quickly as possible. The Authors grasped the nettle of degradation and in effect accepted that eventually the embankment may comprise material somewhat different from that used in its construction.

Mr P. J. Forbes, *WLPU Consultants*

The plot of the results of dry density measurements of placed material and moisture content determinations (Fig. 7) shows, as noted by the Authors, a fair scatter and absence of correlation.

103. My question is whether the moisture content was measured at the time the sand replacement tests were undertaken or whether it was measured at the time of the placing and compaction of the sand.

104. In tailings sands of this type the non-saturated seepage flow of the pore water can be very rapid and the moisture content may consequently have changed between compaction and density measurement. If the moisture content was measured during the density measurement, some time after compaction, this might account for the apparent lack of similarity between the laboratory and site results. The actual compaction achievement could in fact have responded quite well to the amount of water and hence lubrication within the material.

Mr D. J. Pain, *Messrs Sandberg*

Messrs Sandberg were the testing consultants for the contract. The vibrating hammer test (§ 14) was done to BS 1377, test 14, as stated, but the modified vibrating hammer test was to BS 5835, part 1.

106. The day joints between the rips were shown being compacted on a 45 degree face. Apparently these were then heated the next day and it took quite a long time, up to 5 hours, to heat these up to an acceptable temperature before the next layer could be laid. Could the Authors comment on this as to whether they feel this is the only way of doing it, or is there a better way?

Mr R. E. Coxon, *EDP Ltd*

The Authors were fortunate in their availability of materials. Perhaps they were more fortunate that they had no problems with the environmental lobby, since it seemed to be stirring very much the country at large at the moment in connection with dams. Certainly had this dam been under consideration now there would likely have been a campaign against it. Perhaps the lack of action was because the scars on the landscape behind the dam rather distracted the environmentalists from the dam itself.

108. What has come out of the discussion is the apparent lack of available data on operation of asphaltic membranes. That is something which perhaps the Authors will be able to give in ten years' time, after monitoring the long-term behaviour of the dam.

Mr Johnston and Mr Evans

The Authors respond to the discussion under three main subject headings—the inspection gallery structure, the embankment and the upstream membrane. However, *Mr Coxon* does raise an interesting general point—the possibility of environmental objections if the project had been proposed now. Bodmin Moor is not particularly scarred by other development and although there are those who oppose any change, there is a strong body of opinion locally that Colliford Lake is proving to be a valuable landscape feature of the Moor.

Inspection gallery structure

110. *Mr Poskitt and Dr Penman* have raised questions concerning the inspection gallery structure at the toe of the membrane. On the valley sides the top of the structure is just about at ground level but across the centre of the valley it becomes a retaining wall about 5·5 m high. The slope of the downstream face of the structure (Fig. 4) was selected so that the normal sand fill compaction plant could operate immediately adjacent to the concrete and thus avoid the difficulty of compaction against a vertical face. Some settlement behind the wall was regarded as inevitable, and with the sloping face, the settlement should take place gradually over the zone behind the wall.

111. Although the access gallery and the inspection gallery structures have the same top level the junction of the galleries is a potential location of poor compaction. Mr Poskitt mentioned the use of lean concrete at a dam in Northern Ireland. At Colliford, a transition zone of lean concrete was used at the re-entrant angles at the gallery to minimize the effect of differential settlement.

Embankment

112. The Authors were interested in *Dr Penman's* settlement information from Winscar and Marchlyn dams. It appears that the measured settlement at Marchlyn of about 20 mm was about one-tenth of the pre-construction estimate. The Authors' experience at Colliford has been similar. The monitoring equipment is much less extensive but the available results suggest that actual settlement under the membrane has been much less than allowed for. This is a satisfactory situation and may well reflect the higher standards of compaction which contractors can now achieve.

113. Dr Penman and *Mr Smith* have drawn similar graphs, Figs. 16 and 17. The specific gravity of the sand fill is 2·66 and no doubt if the fill had been well graded and included particles of clay and silt size the saturation lines on the graphs would have been useful in assessing compaction. However, the concept of a saturation line is not really helpful with uniform materials such as at Colliford. The size and shape of the particles in the fill dictate the matrix of the fill. Point-to-point contact of the fill material, and hence the same dry density, can be achieved over a reasonable wide range of moisture contents.

114. The method of presentation of the density results in the Paper may have misled Mr Smith and *Mr Forbes* regarding the Authors' view of the material and the densities achieved. The results are all within about 5% of the mean and it is felt that the sand fill was a consistent material and the narrow range of densities confirmed this.

115. The moisture contents were measured at the same time as the sand replacement tests and so Mr Forbes is correct in suggesting that the moisture content at compaction could have been different. The Authors were satisfied with the correlation of the site compaction results and the laboratory tests since it was in line with experience on other projects using sands and gravels where the site compaction exceeded that achieved in the laboratory. The laboratory compaction test procedure used, which *Mr Pain* mentioned, does allow the fill to drain in the test. We would thank him for pointing out the error at § 14.

116. There was no evidence that the surface of the Colliford sand broke down under the action of the rollers as Mr Smith found at Balanga. The breakdown of the surface of sandstone fill is not unusual and the photograph of the Balanga surface was remarkably similar to that observed at Scammonden Dam. China clay sands with low silt contents remain permeable and capable of being worked in all but the most heavy rain. Sands with high silt contents can be compacted to a much higher density and lower air voids and the placing operating is more susceptible to wet weather.

117. *Mr Isherwood's* contribution as the Authors' geological adviser covered many aspects including the possibility of the fill degrading in time. The topic of potential changes in embankment materials should certainly be considered at the design stage.

118. Both Mr Poskitt and Dr Penman mentioned the possibility of introducing a secondary impervious layer between the drainage layer and the embankment fill. This would have directed any membrane leakage more certainly into the inspection gallery but there would have been a cost penalty. However, from experience during construction it appears that a sufficient portion of leakage through the membrane will pass to the gallery. When the embankment and drainage layers were in place but prior to laying the membrane it was noted that, in heavy rainfalls, run-off on the upstream face of the dam flowed through the drainage layer and into the inspection gallery drains though no doubt some part seeped into the embankment. It is important to bear in mind that in considering flows through any part of the drainage system of a dam, it is changes in flow which can be important, rather than the total flow. Accurate total measurement of seepages is often unattainable. Nevertheless, changes in flows can be identified and it is believed that a fairly simple system as at Colliford can give the necessary information to alert the dam owner to any possible future problems.

Upstream membrane

119. The question of the long-term behaviour of asphaltic concrete was raised by *Mr Poskitt* and *Dr Sims*. While the performance specification (§ 42) does mention 'long-term settlements of up to 1% of the depth of the embankment' it is expected that the major part of any settlement will occur during impounding, i.e. at an early stage in the membrane's life. Dr Sims' reports on the behaviour of Kindaruma and Kamburu dams were particularly useful. The problems which can occur at the junctions of the membranes and adjacent concrete structures are generally recognized. It is useful to be reminded that the membrane itself should not be regarded as totally maintenance-free.

120. Mr Poskitt asked for information on the criteria which influence seepage. These topics are well covered in the ICOLD Bulletins and at this stage in the life of the Colliford membrane the Authors are unable to add much which is new. First-class workmanship and conscientious supervision are essential in achieving a uniformly dense material and much time and care need to be taken in preparing the joints at the start of each day and in achieving satisfactory compaction. The nuclear densimeter proved an invaluable tool in ensuring that the required density was achieved.

121. Mr Poskitt and *Mr Haws* requested an opinion on the value of 'Flintkote'. The Authors will be in a better position to answer that question in twenty years time! For the present, it is expected that it will prove useful in protecting the basic membrane from ultra violet light and prevent the asphalt hardening. Before

accepting the material, the Authors devised a weathering test in which samples of asphaltic concrete coated with Flintkote were subjected to cycles of wetting, freezing, and drying with exposure to UV light over a 28-day period without any significant deterioration. Some very small cracks were observed in the surface under microscopic examination but fresh material was visible continuing to provide a seal for the asphalt.

122. The adhesion tests on the aggregate gave some variable results, similar to Mr Poskitt's experience. In the end it was concluded that the aggregate was satisfactory and thought that the addition of limestone filler to the acidic rock would give an additional safeguard.

123. Mr Haws also raised the question of wave run-up and mentioned the problem at Chowilla of designing for 5 m high waves. The design condition at Colliford is very much less severe. Freeboard has been calculated using the methods set out in *Floods and reservoir safety*[15] with a significant wave height of about 0·55 m. The equivalent wave run-up on the 1 : 2 slope is about 1·5 m. However, a wave wall has been constructed at the upper edge of the membrane and it reflects the waves in the design case, i.e. with the reservoir subject to a PMF flood. In this event the design wave run-up is 0·85 m.

124. Dr Sims referred to the similarity of seepage rates at Colliford, Kindaruma and Kamburu Dams but this is unlikely to be more than coincidence. The present seepage through the 88% membrane which is under water (as opposed to the total drainage flow) is only 0·011 $l/h/m^2$.

References

12. International Congress on Large Dams. Bulletin 32, 1977, ICOLD, Paris.
13. International Congress on Large Dams. Bulletin 39, 1981, ICOLD, Paris.
14. Penman A. D. M. and Hussain, A. Deflection measurements of the upstream asphaltic membrane of Marchlyn dam. *Int. Water Power and Dam Construction*, 1984, **36**, No. 9, 33–37.
15. Institution of Civil Engineers. *Floods and reservoir safety: an engineering guide.* ICE, London, 1978.