Construction of the Monmouth Tunnels in soft rock

R. R. PARRY & G. D. THORNTON

Mr Parry

At Monmouth, our Company, M & H Tunnel & Civil Engineering Ltd, was first called in as mining advisers to the Main Contractor, Cleveland Bridge & Engineering Co. Ltd. It was, for present day contracting of this nature, a unique experience to find oneself advising on how to carry out the project and then being asked to carry out the physical side of the operation.

102. It was also, I believe, unusual to be able to complete such a thorough cost breakdown of the operations and I cannot stress too greatly the usefulness, on a contract of approximately £750 000, of knowing the costs (and hence profitability) weekly. Again the success of using men for multi-purpose operations on this Contract should point out to both management and labour in other walks of life that it is now time to rethink. I was told not to use men for varying trades, but we put the men fully in the picture, paid generous incentive payments dependent solely on their performance, and they rose to the occasion magnificently, although obviously attempts were made to allow them to work solely on one function.

103. I believe this success story was brought about by good initial thinking, good planning and extremely good co-operation at all levels, including Howard Humphreys, Cleveland Bridge & Engineering Co. Ltd, my own Company and also all site personnel. Following the success of this system, I am surprised it has not been adopted for the A40 at Aylesbury and also, for instance, for tunnelling in lieu of open cut on the M62 in the Pennines. I think also, that consideration should be given by the Ministry of Transport to the design of a constant profile for road tunnels. This, in turn, would reduce capital expenditure and perhaps allow applications which, at present, are not considered economic.

Mr J. R. Mottram, Howard Humphreys & Sons

I should first like to pay tribute to Cleveland Bridge who showed great courage in proposing these shields. Their provision was a big capital outlay at the time and I know that that Company was very worried about risk.

105. I find it is very difficult to appreciate the drama of tunnelling unless one actually participates. The sheer size of the tunnels at Monmouth was very impressive when one was standing inside, and the noise at times was quite shattering.

106. Rock shields are not, in my view, a universal panacea. They did very well at Monmouth where, by and large, the ground was dry and also reasonably stable for a day or so.

107. The Authors described a good many of the advantages. I should like to highlight one or two of them. The first pointed out in the Paper is that the shields permitted, and indeed enforced, construction of the permanent lining immediately behind. This, to my mind, is a most important feature for large tunnels. When tunnels are large and when there is plenty of room for plant to work inside, my feeling is that there is no excuse at all for letting the permanent lining lag behind the face. So many troubles have arisen in the past through the temporary supports being up too long and having to carry increasing load.

108. The other advantage is that shields encourage full face working which, in my view, is nearly always the right thing to do. I am very much opposed to the driving

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of large pilot tunnels in advance because they tend to weaken the ground, and when the tunnels have to be enlarged there is trouble because the ground being mined is already disturbed. The technique of attacking an undisturbed face is correct in nearly every case.

109. In the Paper much has been made of the fact that the shields were safe, and I must say that this is becoming more and more important. Methods that were in vogue in the past are not acceptable now. It must be borne in mind that tunnelling cannot be allowed to be a dangerous exercise.

110. There are a few snags which I want to point out. The shields would have made it very difficult to cope with ingress of water, which sometimes occurs even in these shallow subsurface tunnels on road works, and in deep tunnels, of course, one can get constant trouble. The very nature of a shield, with its trailing bars, prevents access to the sides of the tunnel and the roof, and it would have been very difficult to divert streams of water.

111. The other point is that the shields were expensive. I am not complacent about costs. I think that costs in the UK for tunnelling are very high. At Monmouth, had the contractual situation been different (the time factor has been remarked on) I am sure that only one shield would have been used.

112. Again, in the ground at Monmouth 8 ft could have been pulled as easily as 4 ft, and the time factor would have been almost the same. The tunnel was big enough to deploy sufficient plant to get rid of the muck. These various savings, with one shield pulling 8 ft at a time instead of 4 ft would have made a substantial difference to the cost. There is a limit to the length of pull, governed by two factors: (*a*) the longer the pull, the greater the charge, the more vibration, and the greater the chance of loosening rock in the roof; (*b*) rock has not only a transverse strength, but also a longitudinal strength, and the longer the pull the more its longitudinal strength is weakened. In many ways, the 'little and often' technique is a good one, but I think at Monmouth 8 ft pulls would have been quite possible. On the Continent 16 ft or more is reported, but these figures are usually from much deeper tunnels, where the rock is of a different character.

113. It has been mentioned that similar shields were used earlier at Newport, where conditions were very difficult. Shields—skeleton shields at any rate—have also been used before on the Continent. One of the things which impresses me about Continental methods is the increasing use of Shotcrete. I am not too much in favour of the scientists and instruments deciding from day to day how thick the permanent lining should be (this is part of the so-called Austrian method) but I am convinced that Shotcrete is a very good means of giving temporary support, very economically. I wish it could be tried in the UK.

114. All these new methods require courage. They also require some examination of contract procedures. There have been references to the contractual difficulties, and I am sure that, if nothing else, they tended to inhibit discussions at Monmouth. On jobs of this magnitude, where decisions as to method are very weighty and where the risk is very high, I feel that the Engineer should share in the responsibility with the Contractor. This means that the Employer has to be very tolerant and understanding too. There is no reason to suppose that he will not be if he is asked.

115. This leads me to suggest that jobs of this kind are better done by some target contract method. There are two essential features of this procedure: one is that the responsibility is shared, and the other is that an incentive is maintained. If tunnelling is going to continue—and there is much evidence that there will be more road tunnelling in the future—such contract procedures should be examined.

Mr D. A. Howells, Howard Humphreys & Sons

I should like to refer to another paper about these tunnels by Baker and myself.[2] It dealt with the detailed geology of the ground through which the tunnels passed and contained some comments on the considerations governing the design decisions. Members may find it a useful complement to the present Paper.

117. There were two major innovations involved in the tunnels at Monmouth, the fitting of the tunnel shape closer to the specified loading gauge, and the use of a shield. The amount of tunnelling of this size in Britain is so small that opportunities to try out developments are few indeed. One cannot try out a large number of innovations on one job, as they endanger safety; they also cost money which can only be recouped by repetition, and the potential benefits become too difficult to evaluate.

118. The Great Charles Street tunnel in Birmingham is another example where innovations were made which will affect the future development of tunnelling. At a recent OECD Advisory Conference on Tunnelling in Washington in June 1970, it was predicted that the next decade would see great changes in attitudes towards tunnelling and that, in particular with the rapid growth of towns, the problems of maintaining present standards of urban activity would increase so rapidly as to make tunnelling an increasingly economic alternative. In order to meet this challenge, the greatest use needs to be made of every opportunity to improve the whole tunnelling system. One of the Conference recommendations was that each country should designate an agency at national level with responsibility for the co-ordination of assessments of tunnelling activity and, where appropriate, for the stimulation of improvements in tunnelling technology. I hope that when the British organization starts its work, it will find this Paper a useful contribution to the basic literature.

119. I wonder how many years it will be before the huge rock excavations on some of our present motorways begin to look dated. I do not suppose it will be very long.

Mr N. D. Pirrie, Sir Robert McAlpine & Sons, Ltd

I think it is interesting to see the elegant shield that has resulted from the combined thinking of mechanical engineers and civil engineers. Allusion was made to the problems of tunnels at Newport on which McAlpines was engaged some two years earlier. Lessons were learned from that, and I am very happy to see that they were well learned, because it was on the Newport tunnels that the first full shield of this size was put to work.

121. When traditional methods ran into difficulties in ground which was similar to but even worse than that at Monmouth, it was plain that it was quite unsafe to proceed with the traditional methods on such a large full face. A pause was called, and discussions were held with Sir Owen Williams and Partners to decide how to proceed. Arising from a discussion with Bertlin and Partners, it was suggested that the crown shield might be the solution for safety.

122. This was the germ of the idea and the next step obviously was to make a full arch. The shield installed there was similar, in that two pilot tunnels were driven at each side to provide support and guidance to the shield when advancing. The dimensions were 40 ft at invert horizontally, with an invert to crown distance of 30 ft.

123. The differences may be of interest. The concrete lining to the tunnel in this case was 18 in. only at the crown, widening to about 2 ft at the haunches, whereas I believe that in the Authors' it was approximately 0·8 m. The effect on the shield, and the ground was such that, although in the Authors' tunnel it is literally an arch shield with no centre support, at Newport it was necessary to support the face, as it was not possible to get a buttress from the material itself. Three horizontal working platforms were provided and three vertical supports; but at the bottom half of the shield there was a full opening about 14 ft high, so that mucking out equipment, tractors and trucks, could go in.

124. In consequence the arch structure of the shield and its ram supports was only about 2 ft thick and not 5 ft, which is necessary when no supporting beams and columns are provided. With such a thin lining at the top the consulting engineers

could not permit thrusting from the in situ concrete as was done at Monmouth. This resulted in some thrusting problems.

125. In the design of our shield we had nine rams, five of which were situated so that we could thrust from the concrete lining stop end if permitted, and four of which were just within the finished lining profile. These four rams transmitted their thrust axially back along steel box columns, held horizontally in position by the concrete shutter support to a distance of 30 ft back, and then against a transverse steel beam placed across the finished tunnel lining and lodged in pockets cast for the purpose. In this way we were able to thrust off mature concrete. But it was agreed later as progress was made that thrusting could take place on the in situ concrete, and this proved successful.

126. These differences in design are natural progressions. It is pleasing to see how advantage was taken of previous experience in the same situation to develop such an elegant shield as that the Authors have produced.

Mr E. R. Harding, Mott, Hay and Anderson

Having seen a couple of men carried out of a tunnel after two tons of rock had fallen on them, I think that anything which can be done to improve safety is very necessary and desirable. However, many of us have had experience of driving circular shields, designed primarily for soft ground, through rock, where the shield has very often been an embarrassment rather than of assistance, mainly due to the difficulty of controlling it within the tolerances required for erection of the lining. Sometimes the shield has been grouted with flyash or something similar in order to control it.

128. In rock tunnelling there are different problems. The Newport and Monmouth tunnels are of a horseshoe type with pilot headings driven on both occasions in which to lay rails and thereby control the protective hood.

129. The Authors state that when they tried to cut the ground with the shield it buckled, which has happened in the past (sometimes with disastrous consequences) when others have tried to do the same. The rock is therefore a reasonable distance away from the shield at the cutting edge and I should like some additional information on the loading that came onto, or the strength of the trailing bars.

130. Could the Authors give a little more information on the pattern of drilling the face? There were about 100 holes, a wedge cut with peripheral drilling, and the drilling was done largely from the compartments. How close to the periphery was it possible to drill and were any perimeter drilling and blasting techniques attempted?

131. The overbreak was 2%, which may not sound very much, but with such a large cross-sectional area I feel that it is on the large side, bearing in mind that there was a 12 in. pay line.

132. Ventilation is always a problem in rock tunnelling when blasting. How long did the plug of foul air take to disperse?

133. Having been concerned with lining another tunnel with PVC sheeting, I should like to know the approximate size of the sheets and how they are supported.

134. The Authors have said that they doubt whether the shields could have been used for two tunnels. I think this is largely because in this instance they were welded together in situ rather than being bolted, as is more usual and necessary when a shield is built within a confined space.

Sir Harold Harding, Past President

The comments in the Paper on the use of a shield in rock tunnelling are worth pondering. In effect, it is a combination of a moving rib and a drilling 'jumbo' and can be a protection against the unexpected, but only up to a point. Other speakers have mentioned that. I saw the shield in action on two occasions because I was asked by the Consultants to give an opinion on the interpretation of the bores when the discussions first arose as to what the ground was going to be like. As it says in the

Paper, the shield was not included in the tender offer but was decided upon when the loose ground at the portals caused misgivings.

136. That has an interesting psychological and financial implication. But as the question arose, one side saying that the ground might be very bad and the other hoping it would not, I suggested that a coloured photograph should be taken of every length because such photographs show up the different strata and would show finally where the truth lay by scientific proof. I saw these later and it was a very well conducted job, and very interesting. The ground proved to be good.

137. On the question of ribbing versus shields in tunnels, the largest tunnel I have seen was on a trip to Sweden, at Harspranget, where there is a tunnel 15 m wide and 13 m high, with no support whatever. In other cases total immediate support is needed.

138. I wish particularly to emphasize the wisdom of the Consultants in specifying that the lining must be close to the face because of the possible swelling of the marl. In the end, with the shield, the Contractor lined much closer to the face than was actually specified.

139. At the same time as I was involved with Mr Mottram, I was asked to visit a small but long tunnel in Permian marl in the Midlands built to carry a water main. The tunnel had to be completed and the main then laid backwards to the portal. At first the ground was so hard and dry that explosives and dust caused trouble, but the geologist afterwards proved that there were many minor faults and fissures above, and after it began to rain the water percolated through and the ground swelled; the tunnels were on arched ribs which were forced down so that the pipes could not be entered. In the contract the engineer had included items for segmental concrete lining which could be ordered on his word at extra cost. But this had not been deemed necessary until it was too late, so there is an instance of one engineer having foresight and the other one being caught out.

140. Similarly on the Derbendi Khan hydroelectric scheme in Iraq, with an American consultant and an American contractor, there was a large tunnel, almost as big as the Monmouth Tunnel. After its collapse I had to study the papers on behalf of the insurance assessors. Here again was a tunnel in marl, supported on ribs. The tunnel was to be completed in six months and the permanent light steel lining, kept circular by tension wires, acted as concrete shuttering and had to be laid from the end of the drive, working back to the portal. In this out-of-the-way place not only was the number of ribs controlled by the engineer, but also the stockpiling in Iraq. As far as I remember, in correspondence the contractor asked for extra ribs to be issued, and paid for, for use at 0·75 m centres. This was refused, and an insistence on 1·5 m centres was made by the engineer. Due to various reasons, the tunnel was open for ten months in place of six, and water percolated into the marl once more: a rib near the portal was overstressed and collapsed; this brought down the next, and the next, etc., in a sort of domino action.

141. This raises the question of who is to take the risk and who is to pay. For instance, if a shield had been included in the Monmouth tender, would the tender have been accepted? Here it was a sensible precaution, whether or not it might have been possible to complete the tunnel, as specified, on ribs without a shield, and that is a point which the Authors might like to ponder.

142. In these jobs all sides are prisoners of their own contract, and some sort of elasticity is essential. But the trouble is that as more contractors are taken over by big business and accountants, and as more clients are run by such people, the less the engineer has a say in the matter.

The Chairman, Mr J. A. Derrington

There are two or three points on which I should like the Authors to comment. One important matter which has already been mentioned is the question of safety of construction. If engineers and contractors are to work more closely in this field of tunnelling it would seem wise that the specification should state that the work should be carried out with a shield rather than by alternative methods; there would then not be a delay when the ground is opened up and found to be difficult. Long discussions about the financial implications of a change of policy would also be avoided. Would the Authors like to comment on this suggestion?

144. According to my arithmetic (which is highly suspect because it was done in metric units) it would appear that the cost of shields on this job amounted to about 15% of the cost of the tunnel section of the works. If so, a standardization of the section of highway tunnels might well be considered so that shields could be built with a view to dismantling and re-use.

145. May I lastly ask the Authors to comment on one aspect which worried me a little. The thrust of the shield was imposed on concrete with a 4 h strength; even though this was done through the stop end that had been put in, was any step necessary to make certain that the stop end could be moved away from the concrete against which it had been thrust?

Mr A. W. Shilston, Consulting Engineer

I attended the meeting but under the disadvantage of not having previously studied the Paper in detail. I was left at the end with the firm impression of having had the privilege of listening to an outstanding discussion. The Authors have been candid, ready to impart the lessons they have learnt, blending humour with irony in the right proportions. Secondly, one sensed a groundswell of discontent amongst members present with the use of the conventional form of civil engineering contract in tunnelling work of the character embarked upon at Monmouth.

147. The somewhat fluid position contractually arises through uncertainty regarding the responsibility at law for the introduction of safe working methods, a particularly elusive subject with which to grapple, bearing in mind the virtual indivisibility of design and construction in tunnelling work of this character.

148. Under the law as it stands at present in England, the Engineer would seemingly be treading in difficult waters if he unduly concerns himself with the safety aspects of temporary works, yet for social reasons the Employer, as promoter, should be concerned with safety. Economic considerations, of course, dominate the argument and, as in all spheres of endeavour in an increasingly sophisticated world, the definition of a proper demarcation line of responsibility is the most intractable problem of all.

149. If a more enlightened approach towards designing safe working methods into schemes of this character is considered socially desirable, then it is necessary to depart from the present position of allowing the (uncertain) implications of law to control the situation in an area of law still in a state of development. Social advance is usually ahead of the law in the English (common law) system based on judicial precedent.

150. Engineers are, therefore, tied to the contracts controlling the works for which they are responsible. Change calls for education of Employers by their Engineers and express (rather than implied and silent) terms in contractual documents covering safety. Increasingly a strong *prima facie* case for target cost contracts precipitates itself in situations similar to that under discussion, calling for significantly different contract conditions from those in the standard ICE form. This would allow a more rational approach towards safe working methods to be devised by express provision. I hope that this Paper will act as a catalyst to bring about urgent discussion within the Institution on the merits and disadvantages of target contracts.

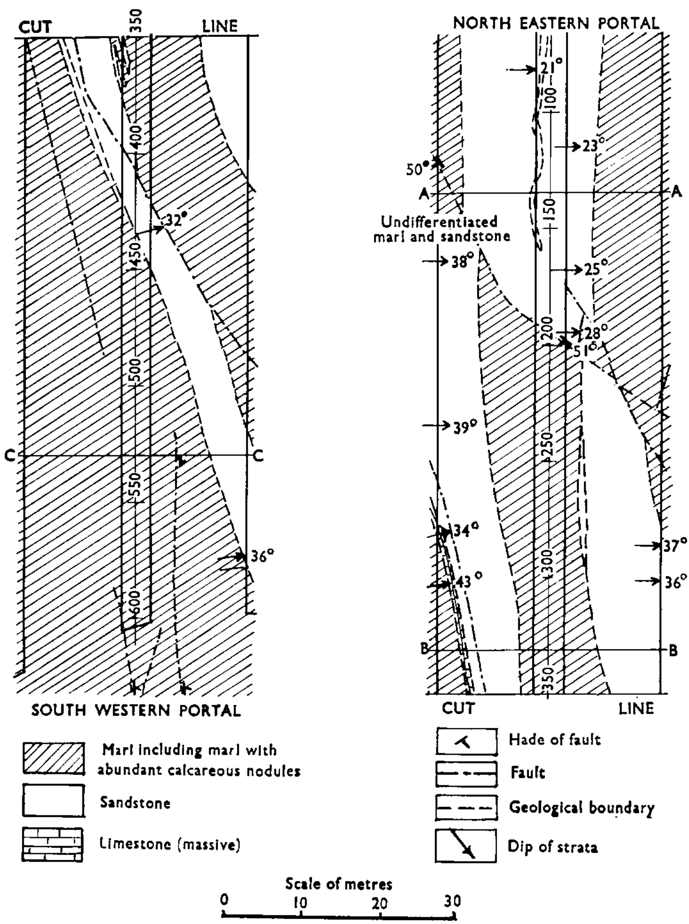
151. Could more be said about the detailed grouting procedures, including the materials and plant used and the method of payment adopted? Was the injection of pea gravel into the larger overbreaks (a technique seemingly quite widely used in the USA) considered?

152. Was the reinforcement in the concrete lining a sufficient deterrent to economic progress in practice to suggest that a design lesson could be registered for the future?

153. Finally could the Authors say, in devising their methods of shield working, to what extent they relied on the anticipated absence of substantial inflows of water through fissures?

Mr C. O. Baker, Howard Humphreys & Sons

The Authors state that the records of boreholes sunk prior to the letting of the Main Contract gave them little or no indication of the possible behaviour of the ground whilst tunnelling. They do, however, state that the geological interpretation included in the tender documents did prove to be substantially correct.



[Courtesy *Engineering Geology*, *Elsevier*]

Fig. 9. Plan at level of road surface showing geological structure in region of tunnels. (Tunnel chainage in feet from NE portal wall)

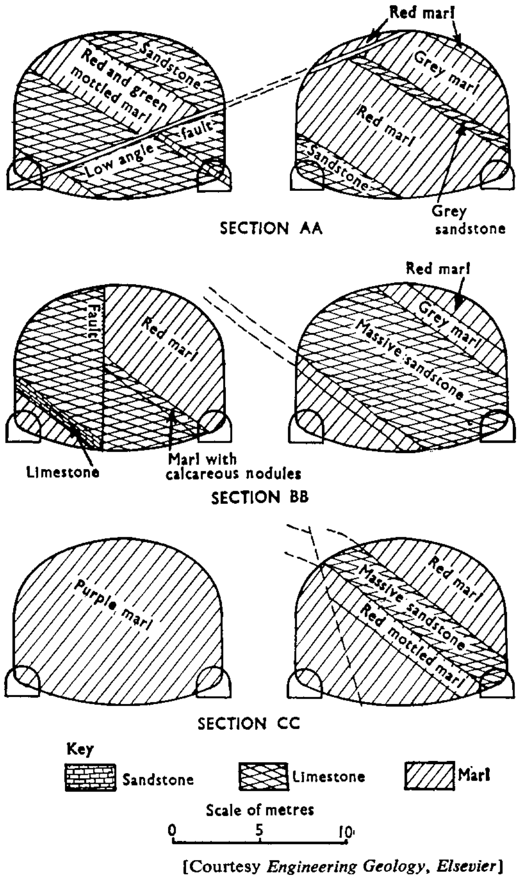


Fig. 10. Cross sections showing geological structure

155. A few comments on the method whereby this interpretation was arrived at, prior to the driving of these large tunnels, may be of interest.

156. The geological structure of Gibraltar Hill was mainly elucidated by a study of outcrops. These indicated that the dip of the strata was southerly and that the tunnel would be driven nearly parallel to the strike. In addition the amount of dip was measured on the rock cores obtained from the exploratory boreholes, and these values were found to agree quite closely with the dips measured at the surface. Slickensiding of a few of the drill cores was also seen, indicating the presence of faulting. Once the general structure was known, it remained to identify the rock and soil types that the twin tunnels would penetrate. This was done by examining the drill cores and outcrops. To help the Contractors, the cores were stored in boxes at a nearby locality on site and were available for inspection both during the tendering period and during construction.

157. Finally the four foot headings were geologically surveyed in detail whilst construction of them was under way. This provided further information which confirmed the earlier findings. The main tunnels were, of course, also geologically

surveyed whilst being driven, and no important differences were discovered between actual results and the predicted ones.

158. The detailed geological structure, as finally mapped, is shown in Figs 9 and 10. As can be seen, the structure was confirmed as being essentially simple. If it had been thought to be more complex, more borings would have been put down at the time of the site investigation.

159. For the Consulting Engineers the main use of the geological data was for the purpose of design and for drafting the specification and contract documents. It was found possible to clarify the documents considerably and important engineering conclusions were drawn from the investigations. In particular, the need for providing immediate temporary support and for speedy construction of the permanent lining was emphasized. Such emphasis must have helped the Contractor in his final selection of method.

Mr W. I. Barbour, formerly Project Manager, Cleveland Bridge & Engineering Co. Ltd

The Paper and the introductory remarks of the Authors do not make clear the basis on which the work was carried out. Cleveland Bridge & Engineering Company Ltd was the Contractor for the Monmouth–Mitchel Troy section of the A48 trunk road, which section included the twin tunnels. As described, an association was formed with M & H Mining Contractors Ltd (referred to here as the Subcontractor), to advise and also to carry out certain work on a subcontract basis.

161. Early in the Contract an order was placed for steel arches with a view to constructing the tunnel in the manner envisaged by the Engineer, and by the Contractor at time of tender. Work proceeded on open cut excavation in front of the North Portal and for the section of tunnel to be constructed on a cut-and-cover basis. In the course of this excavation the Contractor had serious misgivings about the adequacy, from structural and safety considerations, of the steel ribs proposed to support the ground prior to the installation of the permanent concrete lining. At this stage the forepoling was carried out to reinforce the ground in the 'break in' and 'break out' regions.

162. The method of carrying out the tunnels was a major subject of discussion between Engineer and Contractor. At this time the Contractor retained the Subcontractor to advise on various aspects of tunnelling practice. Against the requirements of the specification (set out in the Paper), a number of alternatives were considered, always with the safety of both the labour and the works firmly in mind. It was possible to visit the tunnels at Newport being constructed by Sir Robert MacAlpine & Co. Ltd, in similar materials, and to see the methods used to overcome the difficulties encountered. It was considered that similar conditions could possibly be met at Monmouth and that the method to be used should aim at preventing a single mishap to the works or to the labour. Consequent to these considerations, the Contractor proposed that a shield be used in each tunnel. This proposal was accepted by the Engineer.

163. The Contractor was responsible for the shields, the shutters and the staging, and the Subcontractor for the mechanical and electrical requirements such as hydraulic rams, power pack, ventilation, etc., but all were so interrelated that the eventual design was a joint effort.

164. While the shields were being fabricated, the Subcontractor constructed the four headings to receive the footings and guide channels on which the shields would travel. In addition, and importantly, these headings gave vastly better information of the nature of the ground to be encountered, information which proved of the greatest value on the main drives.

165. The Contractor at this stage reviewed the organization he proposed for the driving of the main tunnels and decided to form an association with the Subcontractor in order to avail himself of the experienced supervision and labour which

the Subcontractor employed. A subcontract was devised on a financial target basis, related to the method that had been evolved. The Subcontractor provided the supervision and labour, and the Contractor the plant and the materials, including the concrete delivered to the pneumatic placers, all within the framework of the Contractor's organization for the whole Contract. The Subcontractor's agent was directly responsible to the Contractor's project manager on site.

166. The arrangements entered into were dependent for success on the goodwill and trust of the various parties, Engineer, Contractor and Subcontractor, both as Companies and as individuals. The measure of success is to be seen in the soundness of the engineering, the quality of the work and the fact that this critical part of the Contract allowed the Contract as a whole to be completed within the two year contract period.

167. Another point of some interest is that a gap-graded mix was used for the concrete for the tunnel lining. This was the choice of the Contractor, following difficulties encountered in obtaining consistent materials for a continuously graded mix. The mix was as follows:

lb/cu. yd	
2230	$\frac{3}{4}$ in. single sized limestone
1042	zone 4 British Channel sand
560	cement (ordinary Portland)
329	water

The average water:cement ratio was 0·63 and the compaction factor 0·95. The 7 day strength was 3700 lb/sq. in. and the 28 day strength 5200 lb/sq. in. against a requirement of 2750 lb/sq. in. The average standard deviation was approximately 600 lbf/sq. in. The concrete was mixed in a Benford batching plant with pan mixer located at the North Portal and transported to the pneumatic placers by Truccrete lorry. No difficulty was experienced in placing this mix through the placers.

Mr Parry and Mr Thornton

We are flattered to have stimulated the expression of some liberal opinions of more experienced tunnellers than ourselves.

169. Dealing with the technical queries first, we would allay **Mr Derrington's** worries over thrusting the shield forward against the green concrete. Ideally we would have preferred to thrust when the concrete was fluid, that is prior to onset of the initial set, and retained within the steel shutter. However, we had not the means of placing the 40+ cubic yards within the 20 min which would have been necessary for that condition. But concrete does possess the phenomenon of autogenous healing of small cracks which occur very early in the hydrating period—this has been demonstrated on major prestressed concrete bridges. The thrusting beam was designed to distribute the load across the concrete to give an average stress of 300 lb/sq. in. We considered that this would not cause any damage, and we were right. Incidentally, the face of the beam was treated with an oil based release agent prior to each section being cast.

170. **Mr Harding** is not impressed with 2% overbreak, but we have expressed this as a proportion of the area bounded by the designed payline in the invert and the extrados of the shield. This actually lay 4 in. inside the contracted payline which in turn lay 12 in. outside the minimum concrete line. If the overbreak is expressed as a proportion within the contracted payline the percentage goes down to $\frac{1}{2}$%, but to be fair and practical, it was 2% of the volume of the hole we were trying to dig. We would still have preferred zero per cent. No delay was experienced for ventilation time. One Olin air mover was used in each tunnel and the atmosphere was reasonable immediately after the short walk back to the face. Exhaust fumes from the heavy mucking plant were more troublesome.

171. The drilling pattern was decided after inspecting each face. Generally, in

marl, if the bottom is heaved out, then the top follows. If massive sandstone overlaid marl, it was necessary to drill and fire this to achieve reasonable fragmentation. In all rounds perimeter holes were used, which were drilled virtually on the line of the extrados.

172. The PVC lining was fixed by a nominated sub-contractor and we have no details of how this was done. Originally it was intended to extend it over the walls and arch, but this proved too expensive. The resulting contrast between the white PVC walls and the concrete arch is quite attractive, and makes a pleasing overall impression.

173. We did not say the shields could not be re-used, we said it would have been a difficult and expensive job to cut them out, and prepare and re-weld them. Mr Harding believes that it is necessary to have bolted joints in shields which are erected in cramped spaces. In view of the heavy and awkward nature of these units we considered a bolted joint necessary to ease assembly and jigging for welding. Even with friction bolts, it is not possible to develop a bolted joint to give the same resistance to bending and shear as the two plates it is connecting. To obtain a full strength joint it is necessary to weld. Why accept a potential weakness in the shield? Welds can be cut out and reformed, if necessary.

174. The trailing bars were of $6 \times 4 \times \frac{3}{8}$ in. rectangular hollow section, designed to withstand a load of 1 ton/sq. ft. A section of faulted ground was found in the early part of the drive which immediately showed up the faults of the system and the trailing arms were the main cause for worry. We lost half of them, had to stop driving for two shifts, and put new ones in—a difficult job—having designed a stronger connexion.

175. **Mr Shilston** mentions the use of pea gravel in overbreak. It was not used at Monmouth. Overbreak up to the springing line was filled during the concreting operation. Large overbreak at the crown was filled with concrete by placing the delivery pipe over the top of the trailing arms. Payment for grout was made against a tendered rate per sq. yd measured on the payline—the contractor cannot win with this one.

176. The question of the economics of thicker mass concrete against thinner reinforced concrete is not easily settled. Although the steel fixing impedes progress, as engineers we consider it an unproven necessity. We feel much happier with a structure that has some steel in it.

177. We were remiss in not mentioning the paper on the geology of the site by **Mr Baker** and **Mr Howells**[2] and apologize for not having done so. Dealing with the geology and design of the concrete lining, the paper contains complementary information to that given in ours. We were relieved to find that we had not trespassed on each other's territory.

178. Both **Mr Mottram** and Mr Shilston query the plans for dealing with water should this have transpired. Notwithstanding our remarks on the use of geological data, boreholes do tend to give a pretty good idea of the water content of the ground. From the information we were given we did not expect much more than we encountered. On one point, however, we were adamant. Water in whatever quantities would not have altered the philosophy behind the design of the shield. The fundamental requisite is to support the ground, water or not. We are confident that we could have handled large amounts of water. Variations in the specification and perhaps design of the reinforced concrete lining would have been necessary.

179. Mr Mottram states that a pull of 8 ft could have been achieved as easily as a pull of 4 ft. This, of course, is said with the benefit of hindsight. We felt that a pull of 4 ft was correct, because of the variation in strength of the rocks. In future applications, however, we are certain it would be pertinent to consider an 8 ft stroke. We should be in favour of achieving this by having the present 4 ft stroke available, thus giving the flexibility of 4 ft or 8 ft, and in the case of 8 ft stroke pushing forward once, erecting a temporary arch to support the trailing fingers and then pushing

forward again off this arch. It would involve the placing of a temporary arch every 8 ft and we feel certain that this could be taken into account in the design of the reinforcing in the permanent lining. Certainly this should have a general effect of reducing the cost of drivage. We would, however, again adopt a policy of caution. It is only necessary to lose the face on one over-ambitious pull and many weeks and pounds would be lost. We cannot help remarking on **Sir Harold's** statement that the ground 'proved to be good'. What is good and bad ground? We suggest such floating comparisons are tempered not by the inherent properties of the rock, but by the way the contractor permits the ground to behave.

180. We considered, prior to starting the drive, that considerable control needed to be put on ground support. But we did not let it fall down just to prove our point. No doubt if we had done, the ground would have been 'bad'. Perhaps one should read the account of the Woodhead Tunnel[3] before considering longer pulls. Regarding the remarks on the expense of the shields, we maintain our opinion that the cost of arches would have been approximately the same. We would also expect the saving to have been minimal through using only one shield. The driving period would have been more than doubled; plant would not have worked to full capacity nor would supervision. The cost of providing one shield would be more than half that of providing two. Considerable time would have been taken in dismantling and re-erecting.

181. Coming to Mr Mottram's comment concerning the contractual situation in Britain, obviously as contractors we would very much welcome any system that took away some of the very heavy risk that is at present placed on the contractor. Although we did not mention it previously, we did have a target contract with Cleveland Bridge. We were fortunate to negotiate a contract that removed some of our risk, but we do not expect the engineers and the clients to go as far as we were able to go with Cleveland Bridge! We think, however, there is certainly a point at which we could meet. Perhaps the Committee currently reviewing the ICE Conditions of Contract will bear these comments in mind. We are delighted that this suggestion should come from Mr Mottram. Perhaps we may see some contracts let on a target basis if consulting engineers will recognize the inequity of placing all risk as the contractor's responsibility.

182. We can also answer Sir Harold's poser 'Would the Contract have been accepted if a shield had been included?' If the tendered sum had been lower than that from any other contractor, then it would have been accepted. Let not the consultants delude themselves. They have congratulated the contractor for his courage in breaking with tradition and developing an unconventional technique. The way lies open to them to institute their ideals based on their contractual experience. Contractors do not exist to build tunnels—they exist to build tunnels and to make a profit. If clients require tunnels, then they must be prepared to accept the risk and pay for dealing with the ground through which their tunnels are driven. We have noticed a most poignant fact in this business. In nearly all cases the client gets his tunnel—it cannot be so said of the contractor and his money.

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