Queenhill Bridge over the River Severn

by

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and

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Mr J. E. Jones (Divisional Road Engineer, Ministry of Transport, Birmingham), after congratulating the Authors on producing an interesting and informative Paper about a structure which was by far the biggest and most important bridge on the M50 Motorway, said it was of interest to note that the line of the Ross Spur had been finally established for the greater part of its length on a line originally conceived in 1945. As a result of the public inquiry held in 1953, three relatively small variations had been made at the Herefordshire end, but they had been very localized and there had been no major departure from the original.

70. In the section of the Paper dealing with basic requirements it was interesting to note the difficulties mentioned in § 4 concerning extreme flood conditions. During the course of construction of the work, flooding in full measure had been the unhappy lot of the contractor throughout the work but particularly in the early stages. In addition to the flooding difficulty, the clear headroom of 44 ft below the summer level of the River Severn would have entailed a very considerable embankment across the flood plain of the river and there had been considerable doubt about the ground being capable of sustaining an embankment of such great height. On that ground also the long viaduct was fully justified.

71. The structure as a whole was a most elegant work and it was therefore all the more unfortunate that very few people would see it in elevation, because it was tucked away in a corner between Worcestershire and Gloucestershire access to which, while possible by public roads, was nevertheless not known to many people. The original proposal for the main river bridge, a very long time ago, had been for a lattice girder type of structure. He was very glad that that had been dropped in favour of the plate girder design finally built.

72. Turning to the construction of the work, the photographs accompanying the Paper showed very well how the work had been done. It was probably true to say that having regard to the size of the job and the site difficulties due to flooding, weather and so on, the work had been carried out with no more than the normal number of headaches to contractors and consulting engineers. Mr Farr, who would speak later, would bear out that statement.

73. Mr Jones directed attention especially to the very excellent pier shutter shown in Figs 10 and 11, which must have proved an excellent investment for the contractor, who with very little trouble had been able to use it to construct every one of the 44 piers of the viaduct, apart from the anchor piers at the ends of the main steel span. The facility of handling the shutter must have proved of the greatest value in

* *Proc. Instn. civ. Engrs.*, vol. 23, December, 1962, pp. 545-564.

the execution of the work. Both the pier and deck shutters had been, of course, properly designed and extremely well constructed, and § 52 indicated the great benefits to be obtained from such care in the design and construction of the shuttering because the concrete finish on the job was virtually that left by the shutters, without the necessity for more than a very small amount of after-treatment of the concrete surface.

74. As was stated in § 55, only the south carriageway of the bridge and viaduct had been ready in time for the opening of the road on 28 November 1960, but, in view of the small volume of traffic which initially used the Ross Spur, little difficulty had been encountered in two-way working over the southern half of the structure.

75. With regard to the organization of the job, the division of the Ross Spur into four separate contracts had been made with two things chiefly in mind. The first had been that the greater part of the structural work should be concentrated into two contracts. Contract No. 4, of which the Queenhill Bridge formed the major part, also contained two separate 400-ft-long reinforced concrete viaducts designed by the Worcestershire County Council. The total length of the contract was limited to about three miles.

76. Similarly, at the Herefordshire end there had been included the all-purpose trunk road by-pass of Ross-on-Wye, which included the Bridstow Bridge over the Wye and the embankment across the flood plain of the Severn. The Bridstow Bridge and the Queenhill Bridge were very comparable in size of main span and approach spans. This Bridstow Bridge and the by-pass road works had been combined with the first three miles or so of motorway to form one contract. An arrangement for supervision very similar to that described in the Paper had been made, with the Herefordshire County Council's resident engineer acting in general over the whole contract, assisted by the consulting engineers' representative for Bridstow Bridge and two other bridges on the motorway itself.

77. In the next section of motorway, Contract No. 2, the same sort of general arrangement existed between the Gloucestershire County Council, as the Minister's agent, and the consulting engineer responsible for the Gloucestershire bridges. There had been this form of dual supervision in three of the four contracts and he was happy to say that in each case the system had worked successfully and without friction. The essential ingredient for such a result was, of course, goodwill between all parties, without which any system was bound to go wrong.

Mr O. A. Kerensky (Partner, Messrs Freeman, Fox & Partners) said that he wished, before becoming critical, to congratulate the Authors on the appearance of the Queenhill Bridge and on the good workmanship achieved in its construction. When he saw it, he had at once been impressed by the quality of the concrete.

79. It was unfortunate that, perhaps because of the limitation placed by the Institution on the number of words, the Paper did not contain some of the information essential for a proper appreciation of the conception and of the detailed design of the bridge. He would like the Authors to augment what was said in the Paper by giving the following additional data:

- (1) Make-up of steel main girders and thicknesses of concrete deck slabs, and, if possible, a dimensioned cross-section of the two bridges.
- (2) Quantities in the foundation work and the superstructure, separated into the viaduct and the bridge.
- (3) The cost of the piers, the foundations, the reinforced concrete superstructure and of the steel bridge.
- (4) Details of the borings would be very helpful on the general arrangement drawing. It was not possible to appreciate some of the points in the foundation design without them.

80. On reading the Paper, many things had puzzled him, and he said he must continue with his twenty questions. Dealing first with the viaducts:

- (5) Why the caissons? Had precast piles or bored cylinder piles been considered? Had compressed air been used in all caissons?
- (6) If caissons were necessary, why were there such short spans? Caisson foundations were expensive.
- (7) Why were steel caissons used? Since kentledge had been required for sinking, he would have thought that reinforced concrete caissons were the right answer.
- (8) What was the expected settlement on the marl? If it was small, why did the Authors use suspended spans and joints in the deck at an average of one per 80 ft?
- (9) Why were the main girders 8 ft deep on an 80-ft span? He would have thought that something more slender would be more attractive and economic.
- (10) Provision had been made for rubbing down the concrete. It did not have to be done, but why had provision been made for it? Concrete ought to come off the shutters in acceptable condition.
- (11) Why had phosphor-bronze sliding knuckle bearings been used when roller bearings gave a better movement at less cost?

81. Coming to the main spans:

- (12) Why were the main spans in steel?
- (13) If in steel, why were they in mild steel and not in high tensile steel, which would be more economic?
- (14) If in mild steel, why were they riveted? Welded plate girders would be appreciably cheaper and more attractive to look at.
- (15) Why no horizontal stiffeners and why were there stiffeners on the outer faces of the web?
- (16) Why were the main girders paired and not evenly spaced? Had they been designed as box girders?
- (17) What were the top laterals for, when the girders were connected by a relatively much stiffer reinforced concrete slab?
- (18) What had shaken him most was to find that the Authors had not used combined action design. In the suspended span at any rate they could have had it almost for nothing; the rivetheads probably would ensure combined action with a few 'whiskers' welded on.
- (19) The links for supporting the suspended span were moving parts with pins in them. What provision was made for maintenance?
- (20) Experience showed that zinc spray must be protected at once by etch primer and some paint. Why had that not been done?

82. Finally, there was the question of cost. This was given in § 62 as £6 10s. 0d. per sq. ft, and he thought that that was on the gross area of the bridge, i.e. including median void, etc. For proper comparison the cost should be on the useful area of the bridge, and on that basis he reckoned it at £9 10s. 0d. per sq. ft. If he was right, it put a different complexion on the cost. However, if all his criticisms were valid, the bridge ought to have cost a great deal more than it did, so that some of his criticisms must be invalid and he apologized for that fact.

Mr P. S. A. Berridge (Assistant Engineer (Bridges), British Railways, Western Region) said he had been thinking along the same lines as Mr Kerensky, but, like previous speakers, he wished first to pay a tribute to the elegance of the Queenhill Bridge, which was very pleasant to look at. He was pleased to see that the Authors

had used the comb type of expansion joint. It was the only joint that gave absolutely smooth riding.

84. Costs were dealt with in § 62, and it appeared that the total cost, including superstructure, piers and foundations, worked out at £6 10s per sq. ft, which at 1962 figures would be £7 6s. That was a most creditable figure and he found it difficult to believe.

85. The cost of a road bridge built recently by British Railways (Figs 21 and 22) had amounted to £7 per sq. ft for the superstructure only. The figure did not account for the demolition of an old superstructure. The precast pretensioned concrete beams had cost 22s. per cu. ft, and it had seemed to him to be a reasonably cheap form of construction. The particular bridge had a span of 85 ft 3 in. centres of bearings, and the beams were 90 ft long overall. The bridge was designed to the same loading requirements as the Queenhill Bridge.

86. Turning to the steel portion of the Queenhill Bridge, like Mr Kerensky he wondered why riveting had been used. He had searched the Paper in vain for the figure of the tonnage of steel, but taking 1 ton per ft run of the bridge it would be 500 tons, and he would expect it to cost at least £75 000 supplied and erected. Perhaps the Authors would say exactly what the tonnage was and how much it cost.

FIG. 21.

FIG. 22.

Had the design been for shop-welded prefabrication with high-strength bolted site connexions, he thought there would have been a saving of at least £11 000 on supply costs alone.

87. Fig. 23 showed the cost of the supply of mild steel plates and sections at the rolling mills, and of fabricated steelwork for plate girder bridges at makers' works, over the past 47 years. Since 1939, the rise in the cost of shopwork had far outstripped the rise in the cost of the steel. This, he considered, was partly the result of firms carrying a duplication of plant and labour for executing both modes of fabrication. Since welded steelwork was cheaper than riveted work, and since the dead weight of steel in the bridge was less when it was welded, the sooner the demand for riveted steelwork ceased the better it would be for British fabricators.

88. Mr Berridge, after showing slides illustrating the different processes used in making riveted and welded work in the shops, said it did not require an exhaustive analysis on the lines of work study to show the advantages to be gained from the relatively small work content in the fashioning of welded girderwork.

FIG. 23: AVERAGE PRICE PER TON OF FABRICATED STEELWORK, EX WORKS, 1915–1962

Mr H. C. Adams (Asst. Chief Engineer (Bridges), Ministry of Transport) said he had had the good fortune to see the Queenhill Bridge on a gloriously sunny day and had looked at it from underneath with the sun shining through the bridge. He could not help feeling that it had the same quality as the great cathedrals of the middle ages, and this had pleased him immensely, because he liked to feel that in these major bridges, which were going to serve many generations to come, it should be possible to carry a message of beauty from this to succeeding ages. He felt that the Queenhill Bridge would convey that message to future generations.

90. The secret of the fine work which had been done was to be found in two early statements in the Paper. First, the site had been recognized from the first to be one of great natural beauty, which presented a wonderful opportunity and secondly, the

engineer and architect had worked together step by step both in the general conception of the structure and in all the details affecting its appearance, right from the beginning. This explained the wonderful achievement that the bridge represented.

91. Having said that, he had one or two minor criticisms and questions. The first had been touched on by Mr Kerensky. Why had not the main span been made of composite construction? It was said that there would have been no economic saving if that had been done, but he wondered whether in the weighing up account had been taken of the bracing placed near the top flanges. The steel bracing between the girders at that level could, he thought, have been eliminated entirely if the concrete deck had been used to provide the lateral stiffness required. Further, if there were no economic saving, it should still be an advantage to make the concrete deck monolithic with the steelwork because the two would act together anyway, whether one wanted them to or not. There would probably come a time when the adhesion between the two would break down and then there might be a risk of moisture penetration with resulting corrosion. He would like to hear a little further discussion by the Authors on the question of composite construction.

92. He had been sorry to find, when inspecting the bridge from underneath, that there was an Achilles' heel to the structure. The piers of the main span, as shown by the photographs, were brought down in fabricated steel which went straight into a concrete base. He had always found that where that was done there was bound to be corrosion. He had looked for it only a few months after the bridge had been opened and had found a ring of rust round that steel just where it entered the concrete. He had called the engineers' attention to this and they had probably done something about it. He would like to know what had been done and also whether in a similar case they would not consider it wise to build the steel with a baseplate anchored down to eliminate any risk of corrosion where the steel joined the concrete. The same criticism would apply to parapets, but the detail at Queenhill had been dealt with admirably and there was nothing to criticize.

93. He agreed with Mr Berridge that the comb formed as near perfect an expansion joint as could be obtained, but, looking at the details, was there a risk of stones and water getting through and being trapped in the bridge seat of the suspended span? The drawings were not quite large enough to show clearly what was happening or to tell the whole story. He did not know whether or not there was access to the sides of the bearings in the suspended span to get rid of any stones or dirt which got through the gap in the deck. He wondered why the bearings themselves had not been placed immediately opposite the webs of the main girders. His instinct told him that that was where they ought to be.

94. He had been impressed by the extent of the temporary works in these major bridge contracts, which seemed nowadays to be a very major engineering operation in themselves.

95. With a wonderful structure such as the Queenhill Bridge, with first-class workmanship, he would hope to find, and perhaps the Authors would tell him, that the men working on the job took a joy and pride in what they were doing. If that were so, he would like to feel that one of the results of it had been happy relations on the work and not much trouble from labour disputes. Perhaps the Authors would say whether or not that was true.

Mr Cyril Parry (Engineer, Lloyds Bank Building, Muswell Hill) said that he was interested in the fact, gathered from Mr Michael Gibb's remarks, that the engineers had, to a certain extent, been given a free hand.

97. That was something new to him and rather unusual, and perhaps explained why the engineers were always so ready to give sympathetic consideration to what might be regarded as perhaps unorthodox proposals, one of which was that the piers should be concreted in one continuous lift for the whole depth, which amounted at a maximum to 40 ft.

98. The accepting of this proposal he felt was partly responsible for the good appearance of the finished piers by the elimination of horizontal joints, which were always an ugly feature of any column.

99. The shape of the column lent itself to the use of a circular mould, so that all stresses could be taken care of by simple tension.

100. The arrangement of the column reinforcement was such as to enable skips to be lowered down the centre of the column and therefore avoided the necessity of dropping the concrete down through shutters.

101. He suggested that not too much notice should be taken of the fact that the engineers had said that it proved more convenient to handle the column shutter by means of a crane rather than the traveller which was provided.

102. It should be remembered that the traveller cost about £1000 whereas a crane would have cost anything from £10 000 to £15 000, and that he had a strong suspicion, judging by the photograph, that there were two cranes employed at the stage of setting this shutter.

103. It would be a difficult business to assemble two large pieces of equipment with only one hook, and if there were two cranes, then there might very well have been £20 000 to £30 000 of capital locked up in a shutter handling operation instead of £1000 in the form of a traveller.

104. A part of the shuttering that was only touched on in the Paper was that of the shuttering of the underside of the concrete on the steel section of the viaduct. This proved to be an unnecessarily complicated operation by virtue of the fact that the cross bracing on the upper portion of the steel girders was placed too near to the underside of the concrete forming the deck of the bridge.

105. Surely an extra inch or two of clearance could have been provided and a slightly different design of the shape of the concrete to have simplified the formwork and made it easier to strike and cope with minor variations in dimensions.

106. Mr Parry could not see what was the structural importance of the ribs on the underside of the overhanging footwalks, but they did prove to be an absolute nuisance when it came to a question of form operating. If it was for some architectural purpose, they were strangely out of view in any of the coloured photographs so that it seemed to him that they could very well have been dispensed with.

107. He was given a free hand by the contractor to make a first class job and to pay particular attention to the concrete finish, and the consultants agreed to accept his firm's proposal that they should make use of ordinary boards which tended to give a less harsh appearance to the finished work than was the case if large areas of material were used for these purposes.

108. They had succeeded in producing a finish which required no touching up, but it should be remembered that the question of whether one had to touch up concrete or not after the removal of the forms was not altogether attributable to the formwork, but it should be attributed to the first class work of the concreting gangs and that everybody in this connexion had been most keen to produce good work.

109. It was a pity to learn, and this only on the day of the meeting at the Institution, that since the contractor had produced such a first class job by the obvious expenditure of more money on formwork than would be the case in a rough job, and in so spending his money eliminated the necessity to carry out rubbing down and unsightly patching, the contractor had had this item struck from his bill and was not being reimbursed for the extra expense involved in producing a job of first class quality directly off the forms. This seemed to him to be a matter to which all concerned should give some thought and attention.

110. He was disappointed that they had not concreted the anchor piers in one lift and therefore the finished job showed two horizontal construction joints, but it would have cost more money to concrete these anchor piers in one lift.

111. However, if the engineers, having seen such work, would specify that these jobs were to be executed in one lift regardless of the formwork costs, then they should all have the pleasure of leaving better looking jobs behind them.

Mr J. R. Whitehead (Highways and Bridges Department, Worcestershire County Council) said that in view of the very happy association which had existed between the County Council and the Authors' firm over the preparation for and the construction of the Queenhill Bridge, his chief, Mr W. R. Thomson, was extremely sorry that he was unable to be present and take part in the discussion. Mr Whitehead wished to add his own congratulations both on the way in which the Paper had been prepared and on its presentation. He had nothing of a technical nature to contribute to the discussion, but he was anxious to corroborate what the Authors had so clearly described with regard to the organization and contracting arrangements.

113. The idea of having, as it were, another engineer within the contract had been quite new to them, and because of this it had seemed at the time that it might present them with a great many unknown problems. He used the word 'unknown' advisedly, because in the event the arrangements had worked perfectly satisfactorily and none of their fears had been realized. Like most simple arrangements, they worked excellently when given the chance and where there was the utmost co-operation, as in this instance. The County Council were now the Minister's agents for the maintenance of the structure and were reaping the benefit of a job well done. That this was so reflected great credit on the Authors' firm, who designed the bridge and supervised the construction, and on the contractors who built it.

Mr E. P. Farr (Managing Director, A. E. Farr Ltd), who expressed his pleasure, as a non-member of the Institution, at being present by invitation, congratulated the Authors on their Paper, which condensed a large amount of information into a very short space. He was pleased about the complimentary things which had been said. Those remarks directed to the engineers were well deserved. Contractors rarely heard so much praise about the quality of their work. His own organization, however, paid great attention to quality and in these days when it was difficult to obtain skilled labour it was very gratifying to hear that the bridge was considered by experts to have low overall cost and a good finish.

115. There had been excellent co-operation, in the first place between the engineers and architect, in which the contractor had played no part, and then between the engineers, the County Surveyor, and the contractor. The engineers had always been ready to meet suggestions which Mr Farr's firm had made. Mr Parry was employed, as he often was, knowing that he was a go-ahead person who would push the work along and produce a good finish and good results generally. Even when Mr Parry produced some astonishing ideas, there had been ready co-operation, though Mr Farr thought that at times Mr Parry had strained the engineers' ideas a little about depth of lift, striking time and so on.

116. From the contractors' point of view, this had been a pleasant job and he was glad to pay tribute to the engineers who had been associated with it. It had ended very happily for them not only because they had made a profit but because the accounts had been settled so promptly.

117. Mr Farr had asked the Council of the Institution to accept a coloured film for the Library, showing the various stages of construction of Queenhill Bridge, including caisson work in the foundations. The film also showed other bridges and the roadwork carried out by his firm on Contract No. 4 of the M50 Ross Spur Motorway.

Mr M. A. May (Principal Engineer (London Division), John Laing & Son Ltd), who congratulated the Authors and all others concerned on a truly elegant structure, said that, as one who in the past had been associated with motorway construction, there was one point about the bridge which concerned him deeply, and that was the absence of a hard shoulder. It seemed to him essential that on a fast motorway there should be provision for vehicles in difficulty to pull off the main carriageway and allow other traffic to continue unobstructed.

119. Looking at the cross-section of the bridge, there was a 24-ft carriageway, a kerb and a 4-ft verge. The bridge was half a mile long and he felt that sooner or later a vehicle would break down and be forced to stay in its lane on the bridge. That seemed to him to be a dangerous situation and he would like to know the reasons and the justification for the hard shoulder being omitted over such an appreciable length of motorway.

Professor Herbert Addison (Consultant) observed that so much had been said about the aesthetic qualities of the bridge, with which he agreed, that it was a great misfortune that in order to look at it one had to be a passenger in a helicopter or a cow grazing in the water-meadows; otherwise there seemed to be very little chance of admiring what was certainly a very beautiful structure.

121. The question of providing facilities for sightseers had already received some attention. Contractors who put up large buildings provided a sightseers' gallery. It would hardly be possible to put up a sightseers' gallery in the case of a bridge, although in certain instances great solicitude had been shown. Near the Wentbridge viaduct on the A1 Road north of Doncaster, there was a lay-by which made it possible to get out and admire the viaduct and go below it and have a most enjoyable sightseeing tour. Was it possible to have similar facilities for the Queenhill Bridge? Could one, for example, get a motor launch on the river from Tewkesbury? People wanted to see these very interesting structures, but as they had to rush along, and were not allowed to stop, it was difficult to find a bye-way which penetrated under the bridge. This was a matter which deserved attention, but with or without additional assistance many people would find their way to the Queenhill Bridge and admire it.

Mr R. W. Higginbotham (Engineer, Rendel, Palmer & Tritton) felt it was unnecessary to add to the congratulations already offered on the appearance of the bridge but thanked the Authors for writing the Paper, because these modern designs which introduced new features were in almost every case extremely interesting to others who were concerned with bridge construction and were a great help to the progress of bridge engineering generally.

123. Some of the questions which he had intended to put to the Authors had been asked by previous speakers, but he would like to know why there was a different radius on the steelwork and whether it would not have been possible to continue the same curve or even to put in a straight there. With the very long radius of the main spans, it seemed a waste to have a curve at all.

124. The Authors' photographs gave a very good idea of the main box girder shuttering itself but no indication of how the diaphragms had been put in. He would like some information on that, on what the diaphragm spacing was and how much shuttering had to be left in those box girders.

125. His last point was perhaps a trivial one, but he wondered whether it would not have been economic to make the column shutters in sections, so that the concrete for the shorter columns did not have to be lowered down quite such a deep shaft unnecessarily.

Mr G. A. Wilson (Chief Engineer, Port of London Authority), referring to the criticisms made of the bridge, said he understood that the answer was to be found in what it had actually cost. He had been fascinated by the question of whether the cost had been £6 10s. or £9 10s. per sq. ft, but was sure that the Authors would be able to resolve that problem satisfactorily. It did not look to him like a cheap job.

127. In § 4 reference was made to floods down the river and the need to have a viaduct across the whole valley. The beauty of the valley and of the bridge would combine to make a bridge engineer believe that it was necessary to have a viaduct right across the valley, and no doubt architectural advice would strongly support that

view, but it was stated in § 4 that the maximum possible discharge was 40 000 cusecs. The width of the river was given as 200 ft and it appeared to be about 40 ft deep, judging by Fig. 1, and a river 200 ft by 40 ft should be able to take a great deal of the flood if the figure of 40 000 cusecs was correct.

128. Had the Authors made a model of the valley? The pictures of the valley showed that it was very wide and flat, with a good many hedges and trees. In the pictures the flood water round the bridge seemed to be quite stationary. The Hydraulics Research Station had carried out two investigations and found that it was unnecessary to create a viaduct to deal with flooding of a river of this sort. Perhaps the Authors, therefore, would make it clear why it had been necessary to build this structure.

Mr E. F. Humphries (Senior Engineer, G. Maunsell & Partners) said that at the time that the work described in the Paper had been going on he had been dealing with the same firm of contractors, Messrs A. E. Farr Ltd in connexion with another road work, and he could support the Authors' statement about the happy relationship which they had stated had existed with that firm, because it had been true in his own case also. He was glad that apparently the Authors had not had difficulty with regard to the completion time, as there had been certain time factors in his own case which had led to difficulties, but the pleasure of working with Messrs A. E. Farr Ltd had been very real.

130. He wished to touch on one or two aspects of the work described by the Authors, not in criticism but to obtain elucidation. A previous speaker had referred to the horizontal curvature of the bridge. It seemed odd, looking at the aerial photograph, which showed an almost straight section in the centre, that there was not a sweeping curve for the whole structure. It was stated in § 7 that the design speed was 70 m.p.h., but experience in the London area showed that traffic travelled at 20 to 30 m.p.h. above the design speed on underpasses and flyovers. It might be thought, therefore, that in this case a simple smooth curve would have been better from the driving point of view. If a radius of 9000 ft were taken throughout the curve, the versine on a 500-ft chord was only about 3 ft 6 in., which was surely not excessive to be dealt with in the design of the steel bridge, or, if the bridge had been in concrete throughout, the torsion induced could have been looked after.

131. The steelwork of the bridge was described in the Paper as a box girder, but in common parlance it was two girders fastened together. The upstream girder for each bridge had been made 7 in. deeper than the other, the object being to give a flush level for the soffit of the main girders, which presumably meant that the level of the girders at any point transversely was the same. It would seem, however, that no one could possibly see this, because wherever one stood to look at the bridge the eye could not line up the girders together, and each of the four girders could have been made the same depth with no difficulty, so lessening the cost of construction of the girders themselves and perhaps simplifying the details of the design.

132. On the question of construction, perhaps someone could say how the hollow sections of the two approach spans had been formed. No clue was given in the photographs. It was difficult to get shutters forming the voids held in the right position, and it would be interesting to hear how it had been done successfully.

133. With regard to organization, when he heard in the discussion that there had been two office fires on the job, he thought it might have been to try to burn the documents covering the arrangement of the contract as set out in §§ 56–60! This sounded most complicated and difficult, and although it had been administered successfully, it seemed a most unwieldy exercise. For example, the consultants' resident engineer was not the engineer's representative on the job. The consultants had been appointed by the Minister, and yet their contact with the Minister for the bridge was through the County Council. They had freedom of judgment and execution of their duties on technical matters direct, but had to go via the County

Council to the contractor for contract matters. All these arrangements were most complicated. He would have thought that a job of the magnitude in question, of well over £1 000 000 for a bridge half a mile in length, could have stood as a separate contract with consulting engineers appointed accordingly and their resident engineer as the engineers' representative, which would have greatly simplified the administration.

Mr A. R. Murray (Sir Alexander Gibb & Partners) said it had been his good fortune to be the resident engineer on the job. Mr Adams had asked about the relations between the various parties on the job. Mr Murray could vouch for the fact that relations had been excellent throughout. The good finish which had been achieved on the concrete had been commented upon, and probably the main reason for it was that the contractor gathered together a body of engineers and men who had a great feeling of pride in the work, and this was reflected in the finished job. Another important factor was that concrete control had been stringent. In the concrete section of the bridge a large proportion of the work consisted of thin webs and diaphragms of about 9-in. thick. This kind of work always called for special care and its success at Queenhill depended to a large extent on the fact that the concrete arriving for placing was just right for the job in hand.

The following contributions were received in writing:

Mr C. R. Neill (Hydraulic Engineer, Research Council of Alberta, Edmonton, Canada) wrote that at first sight it was very difficult to understand why it was necessary to build a bridge 2500 ft long, costing £1 200 000, to cross a river only 200 ft wide. The decision to bridge the entire valley width instead of building approach embankments might have been made for aesthetic, hydraulic, or economic reasons, or a combination of all three. The Authors indicated, in § 4, that hydraulic considerations were paramount. Accepting that, Mr Neill wished to ask the following questions:

- (1) On what basis was the limiting flood velocity of 5 ft/s arrived at? Did this figure refer to channel flow or to spill flow on the flood plain?
- (2) Was the selection of waterway area for the peak flood of 40 000 cusecs governed by backwater considerations, or by a desire to avoid scour around the bridge foundations, or by some other factor?
- (3) Was the river-bed erodible?
- (4) Were any studies made of the probable hydraulic consequences of carrying part of the crossing on embankments, and of the economics of bridge versus embankment?

136. It was not possible to analyse the hydraulics of the situation from the information given, but Mr Neill guessed that the bankfull discharge of the river was of the order of 10 000 cusecs, and that the channel discharge at peak flood level was probably two to three times that figure. He would have thought that the remaining spill discharge could have been provided for by means of relief spans occupying a relatively small proportion of the valley width, without causing serious backwater or scour.

137. He had recently been concerned with a sand-bed river 180 ft wide in a valley 1000 ft wide, crossed by a bridge of about 250 ft total span, with solid approach embankments. The river's bankfull discharge was about 5000 cusecs. In a recent record flood of 20 000 cusecs, considerable temporary river-bed scour occurred below the bridge, but as the foundations had been designed with this possibility in mind, no serious consequences ensued. Backwater effects were negligible.

138. Because of the high costs of bridging relative to embankments, considerable attention had been given in Alberta to keeping bridge spans to a minimum by making hydraulic studies of all proposed crossings and by designing embankments and foundations against scour where necessary. An outline of the methods used, which

were based on the regime theory of alluvial channels, was given in a paper by Sanden.* The Author quoted costs for a 2-lane bridge as from £120 to £300 per lineal foot, against about £30 per lineal foot for a 2-lane embankment 30 ft high. For wider highways the differences were greater.

139. Mr Neill was curious about two other points in the Queenhill design: first, the reason for requiring 44-ft navigation headroom on such a small river, and, secondly, whether piled foundations were considered as an alternative to caissons.

Mr R. W. Bishop (Navy Works Dept, Admiralty) had found the Paper most interesting but he wondered why piles had not been used instead of caisson foundations, to support the piers carrying the approach spans. According to Fig. 10, there was no trouble in getting heavy plant to the site and piles, driven by means of a mechanical excavator with hanging leaders, would surely have been far quicker than sinking caissons with compressed air and kentledge.

141. The site organization described in §§ 57–60 was surprising. The Resident Engineer referred all financial and contractual matters to a Chief Resident Engineer appointed by the County Council, but, on all technical matters, he was directly responsible to a firm of consulting engineers. These three aspects of a civil engineering contract were closely related and it was really impossible to make a decision about one without considering the others. In this instance, the arrangement worked because of the goodwill which obviously existed among all parties, but it seemed hardly a method of site organization to be recommended.

Mr N. A. Hardie and Mr F. G. Wood (Agent and Chief Engineer, A. E. Farr Ltd) wrote that the 54 caisson foundations required some 20 400 cu. yd of excavation of which approximately 8500 cu. yd was carried out in compressed air at pressures ranging between 10 lb and 25 lb/sq. in. The combined total depth of sinking was 2312 ft, the deepest caisson being founded some 59 ft below ground level. Some 700 tons of steel were required for the caisson shells which were erected and welded on site. The 16-ft dia. by 12-ft high shells for the approach span pier caissons were built in erection compounds situated on either bank of the river and transported and pitched into position on levelled ground as required. The taper shells and 10 ft dia. strakes were thereafter erected in place as sinking proceeded. Shells for the river and anchor piers and east abutment caissons were fabricated in place on prepared foundations which were broken out and removed when sinking commenced. The compressed air work was carried out using three 'Gowring' type air locks, incorporating separate compartments for men and materials, with oval type shafting and 1 cu. yd bottom-opening skips, which were handled by 19RB or 22RB excavator cranes. A standard medical lock was also provided. Low pressure air on the east bank of the river was supplied through 6-in. mains with 3-in. branch connexions to each air lock, from two electrically-driven and one diesel-driven 500 cu. ft/min compressors installed in a compressor house adjacent to the east abutment. Similar arrangements were made on the west bank of the river. The average air consumption was approximately $2\frac{1}{2}$ cu. ft/min per square foot of working chamber floor. Sinking of caissons under compressed air was generally effected by 'blowing down' under controlled air pressure at the end of each shift, and the limiting skin friction then recorded was normally about 3 cwt/sq. ft. In the case of the river pier caissons on the east bank where high frictional resistances developed, it became in fact necessary to add approximately 400 tons of kentledge (not 250 tons as stated in the Paper), resulting in sinking efforts of the order of $7\frac{1}{2}$ cwt/sq. ft. The whole of the compressed air work was carried out in accordance with the Special Regulations which

* 'Scour at Bridge Piers and Erosion of River Banks' by E. J. Sanden, Proceedings, 13th Annual Conf., Western Association of Canadian Highway Officials, 1960 (available from Alberta Department of Highways, Edmonton).

FIG. 24: AIRLOCK IN USE ON APPROACH SPAN CAISSON. COMPLETED SOUTH CARRIAGE-WAY SUPERSTRUCTURE BEHIND

FIG. 25: AIRLOCK IN PLACE ON MAIN SPAN CAISSON. NOTE ESCAPING AIR FROM WORKING CHAMBER APPEARING IN RIVER

FIG. 26: WEST BANK. CAISSON SINKING IN PROGRESS FOR THE APPROACH SPANS

FIG. 27: EAST BANK. WELDED STEEL CAISSON SHELLS PITCHED ALONG THE NORTH CARRIAGEWAY AND COMPLETED COLUMNS OF SOUTH CARRIAGEWAY APPROACH SPANS

FIG. 28: APPROACH SPANS. CURVED CORRUGATED SHEETS IN PLACE AS SHUTTER FOR THIRD CELLULAR CONSTRUCTION

FIG. 29: APPROACH SPANS. COMPLETED WALLS OF SECOND STAGE CELLULAR CONSTRUCTION

came into force on 21 April 1958. No serious accidents occurred, but there were a few minor cases of 'bends'; these were, however, adequately dealt with in the medical lock.

143. The temporary timber piles referred to in § 46 of the Paper were, in the main, obtained from selected trees varying between 10 in. and 14 in. in diameter and 15 ft to 30 ft in length. The piles, which were eventually cut down and left in, were driven to a set of 8 to 10 blows to the inch, using 30-cwt drop hammers falling 2 ft 6 in. in the pile frames.

144. The concrete for Queenhill Bridge was mixed at central batching plants situated on either side of the river, deposited into 1 cu. yd 'roll over' skips and conveyed by dumper or lorry to the works where excavator cranes lifted the skips to position for discharging into the shutters. The maximum pour occurred in the deck lift (Stage III) of the portal spans and amounted to approximately 210 cu. yd. The permanent shuttering to the cell roofs of the approach spans consisted of 16 gauge pre-curved, corrugated steel sheets. These were bedded and set on to continuous corbels which were cast into the cell walls. No centre propping was necessary. The turn-round for the portal span shutters was generally 4 to 5 weeks under favourable conditions and not 5 to 6 weeks as stated in the Paper.

145. In the course of the contract, the site became flooded on twelve separate occasions, for an aggregate period of 125 days, during which forward progress had to be very largely confined to whichever parts of the superstructure were available. The highest flood occurred during January and February of 1960 when the water level rose to within 2 ft of the 1947 level—and the flood of longest duration occurred in November and December of the same year over a period of 26 days during which the south carriageway of the bridge was completed and opened to traffic.

146. Figs 24–29 have been included to show various aspects of the construction of the bridge.

The Authors, in reply, said that they appreciated the complimentary remarks made about the bridge and also, judging by the detailed questions put by some of the leading bridge engineers in the country, the interest taken in the Paper; the discussion had usefully filled in some of the omissions in the Paper which the Authors had had to accept through shortage of space. It had been their desire, in conjunction with the architect, to design and build a bridge which would harmonize with the surrounding countryside, and it was gratifying to know that others agreed that this had been done at what might be regarded as an economical cost. The final figure of £1 197 353 could be split up as follows:

A. Construction

	£
Earthworks, including caisson foundations	193 790
Abutments and piers	167 226
Approach span superstructures	329 709
Main spans: steelwork	262 694
Main spans: reinforced concrete deck	28 205
Roadway, parapets, etc.	96 110
TOTAL: Construction	1 077 734
B. General items	119 619
GROSS TOTAL	1 197 353

148. The general items represented the costs of observing the various requirements of the Conditions of Contract and the Specification, and did not include costs

for any plant or temporary works required for the construction. Thus, although the gross unit cost of the bridge amounted to £6 9s. 5d. per sq. ft of gross area, the actual cost of construction worked out at only £5 16s. 0d. per sq. ft.

149. Mr Kerensky and others had asked why certain forms of construction or arrangements were adopted in preference to others which, ostensibly, should have been more economical. This raised the fundamental question of what was meant by economy, for although it would have been possible to have effected economy in material in many ways, this would not necessarily have resulted in a reduction in the total cost, having regard to the conditions under which the bridge had to be built. Apart from the complications in design arising from the horizontal curvature, consideration had to be given to the fact that the site was subject to periodic flooding, and that such access roads as led to the vicinity were ill-suited for heavy traffic. The Authors therefore believed that, if true economy in cost was to be achieved, the bridge should be so designed that, in addition to conforming with the architect's proposals, it could be built without serious interruption to progress by flooding and without incurring the cost of expensive temporary works or heavy transportation charges to or about the site.

150. Most, if not all, of the suggested alternatives had, in fact, been investigated, and some of the conclusions drawn from these considerations were summarized as follows.

- (1) As the trial bores indicated that relatively soft patches of marl might be mingled with what appeared to be hard marlstone, it was considered desirable that foundations should be of a type which would enable the bed to be visually examined before finally determining the foundation level. Comparative estimates showed that bored piles would have been more expensive than caissons, mainly because the cofferdams, required to enable the pile caps to be built below normal ground water level, would have had to be of sufficient height above ground level to give adequate protection under flood conditions.
- (2) Caissons of steel were proposed in preference to reinforced concrete because the shoes could be built clear of floods, and, once placed in position, the steel shell automatically provided protection against flood damage.
- (3) The architectural concept combined with the site conditions were not suited for economical construction in prestressed concrete.
- (4) The approach spans were made of constant length and horizontal curvature to enable the contractor to make the maximum re-use of formwork.
- (5) The architectural concept for the main spans was that the steel piers should, in effect, represent a continuation of the main girders, which were consequently limited in number to two for each half-bridge. Single web girders would have effected a saving in the weight of steel, but, on the other hand, there would have been increased costs in transportation and erection owing to the increased weight of the individual pieces to be handled.
- (6) The horizontal curvature of the deck was determined by the limits in the variation of the overhangs, which were considered desirable from the architectural point of view, combined with the economic advantages of keeping the main girders straight in plan. On account of the curvature of the deck, the upstream girder of each half-bridge was more heavily loaded than the downstream one, and it was found to be advantageous to increase the depth of the web plate by 7 in., thereby maintaining flush soffits, rather than increase the thickness of the flange plates.
- (7) Mild steel was adopted in preference to high-tensile steel because it was desired to limit the deflexion under maximum live load to 1/950 of the span.
- (8) It was found that all-welded girders would have necessitated what was considered to be an excessive amount of site welding if the size and weight

of individual pieces were to be kept within the limits deemed suitable for the site conditions. Only a small saving in weight would have resulted from a compromise of shop-welded girders with riveted or bolted site connexions.

- (9) Linked with the question of whether to adopt composite construction for the main girders was the problem of constructing the curved reinforced concrete deck. This deck had to be laid with great precision as the cross-section, in relation to the straight main girders, varied throughout the length of the bridge. The Authors considered that this work would be facilitated if the top flanges of the main girders were kept in proper alignment by means of lateral bracing and also if the flanges could be kept clear of shear connectors as, being 5 ft wide, they could then serve as working platforms for setting out, access, etc. As the saving in steel from composite construction would have been comparatively small in this instance, it was decided to adopt independent construction, which, incidentally, simplified to a slight extent the placing of reinforcement.

151. In reply to Mr Berridge's enquiry about the tonnage and costs, the total tonnage of structural steelwork in the main spans amounted to 1536 tons, of which the main girders accounted for 1310 tons at an average cost of £140 per ton complete, except for painting. Assuming that it had been possible to save as much as 200 tons by some other form of construction, this would only have meant a saving of about £8000 in material and possibly half that amount in fabrication, or say a total of £12 000. In the opinion of the Authors, the additional costs of erection, in the cases considered, would have exceeded this figure.

152. The Authors were in complete agreement with Mr Adams that, wherever possible, steel columns should be built with a baseplate anchored down to the concrete and should not enter it. In this case, unfortunately, such a detail was not architecturally acceptable, and in consequence the detail shown on Fig. 30 was adopted. Mr Adams had found a ring of rust round the steel just where it entered the concrete, but a detailed examination, shortly after he had reported this, revealed no indication of actual corrosion. The plastic compound protecting the steel was,

FIG. 30: DETAIL AT MAIN PIER BASES

however, visible at this point, and it seems possible that this might have given the appearance of rust. Nevertheless, this remained a detail to which particular attention should be paid in future maintenance.

153. With regard to Mr Adams' further queries about the bearings of the approach spans, these were placed between pairs of ribs in order to reduce the number, and provision was made for access to them from the underside of the bridge.

154. Mr Kerensky and Mr Parry had questioned the introduction of items in the Bill of Quantities for rubbing down concrete. These items were inserted in accordance with the Ministry of Transport's Standard Specification and Notes on the Preparation of Bills of Quantities, although, admittedly, they could have been incorporated with shuttering items in this particular case, as only one type of finish was specified for all exposed surfaces.

155. The Authors agreed with Mr May that it would have been an improvement, from the user's point of view, if hard shoulders had been provided throughout the length of the bridge, but whether the additional cost could be justified is another matter. The same applies to the provision of a view-point to the bridge as suggested by Professor Addison.

156. In reply to Mr Wilson and Mr Neill, it should be explained that the hydraulic requirements for the bridge were specified by the Severn River Board, and, in consequence, do not really come within the scope of the present Paper. Available records of flood damage in this stretch of the River Severn did, however, encourage the Authors to respect the conditions laid down by the River Board.

157. Mr Humphreys and Mr Bishop had expressed understandable surprise about the arrangements for contract administration; they had criticised certain aspects of these arrangements, and the Authors themselves had had misgivings about them before the start. However, as Mr Jones explained, the Ministry had good reasons for desiring these arrangements, and all those entrusted with the administration of the contract had accepted them in a spirit of challenge. It was gratifying to find, in the contributions of Mr Whitehead, Mr Farr and Mr Murray, confirmation of the Authors' view that, in carrying out these arrangements, there had been no loss of efficiency or control. In fact, all those concerned could perhaps take pride in having demonstrated that, with adequate contract experience, goodwill and willingness to merge individual status in the interests of the job, even apparently unattractive arrangements could be made to work—and work well.

158. In conclusion, the Authors would like to thank Messrs Hardie and Wood for their contribution, which, apart from adding valuable information on construction details, served to answer some of the questions raised in this discussion.