Discussion.

Mr. GROVES exhibited a number of lantern-slides illustrating his Paper. Mr. Groves.

Sir GEORGE HUMPHREYS remarked that as far as the construction of Lambeth bridge was concerned, it might almost be said that the work went on with monotonous regularity; that statement was, however, to be interpreted as expressing the view that everyone did his job and that the arrangements of the contractors were all that could be desired. There were difficulties to be overcome in connection with the bridge, but they did not in the main arise from such material factors as the forces of nature. Whenever the position and design of a bridge over the Thames had to be decided, it seemed to be the signal for the letting loose of a great deal of advice, which might be very well-intentioned but was, to say the least of it, embarrassing. However, with sufficient patience even such difficulties could be overcome. Before the War two efforts were made to obtain Parliamentary powers for the reconstruction of Lambeth bridge, and each had failed. After the War, when activities began to be resumed, the financial authorities of the London County Council had said to him, "With regard to the two bridges that were decided on before the War, Lambeth bridge and Putney, we think we can go on with one of them; which will you have?" His advice had been in favour of Lambeth, for two reasons. Firstly, as indicated by Mr. Groves, he had had a very lively apprehension that the old bridge might one day fall down. Secondly, he had always felt that if by chance a disablement of Westminster bridge, however temporary, should occur, serious trouble would be caused if there were no other convenient route across the river; and it should be remembered that that was before Waterloo bridge had given any cause for anxiety. London now had the new Lambeth bridge and the widened bridge at Putney. Sir George Humphreys.

The relation of the new Lambeth bridge to its surroundings had had to be seriously considered. It was felt that a large structure, such as the present one, on the site of the old bridge would have had a bad effect upon the beautiful old buildings at the entrance to Lambeth Palace; the eastern end of the bridge had, therefore, been shifted southward. He would like to record his grateful thanks for the great help which had been obtained from His Grace the late Dr. Randall Davidson, former Archbishop of Canterbury. In 1923

Sir George Humphreys.

a Bill was deposited for the new bridge, and it became an Act in 1924. Just prior to its consideration by Committees in Parliament, the Council invoked the assistance of Sir Reginald Blomfield, who, together with Mr. Topham Forrest, was able to advise the Select Committees that the æsthetic treatment of the structure, occupying as it did a very important position in the London landscape, would receive full consideration. He would not weary the meeting by describing all the discussions which he and Sir Reginald Blomfield had had on the subject. At one time they had thought of putting up elliptical arches, but he had been able to persuade Sir Reginald Blomfield that such a design would entail a wasteful disposition of material. The roadways on each side of the river were right up against the embankment wall, and it was consequently difficult to arrange reasonably easy gradients whilst giving the headway that the Port of London Authority wanted. The exact form for the silhouette of the bridge also occupied their attention, and was investigated by trial and error. At the Becontree housing estate there was a good open tract of country, and with the aid of scaffold-poles and floor-boards they had put up a full-sized silhouette of the bridge, viewed it from a distance, and altered it until it presented a curve which was, he hoped, pleasing to the eye. For the architects' collaboration and assistance he wished to record his indebtedness.

With regard to the construction of the bridge, he was glad to say that a good foundation had been obtained almost exactly where it was expected. Looking back over the operation, he thought there was everything to be said for the method adopted of sinking caissons under compressed air. No doubt estimates might be made which would show that on paper and at first sight open cofferdams might seem more economical; but, as his friend Sir Harley Dalrymple-Hay knew very well, London clay dry and under compressed air was one thing, and London clay with the water getting to it was quite another. The extra expense entailed by the use of compressed air was, in his opinion, amply justified. The Author had alluded to the good distribution of load afforded by the floor-system, the floor being very strong. That was another case in which the expenditure incurred was, he thought, well justified.

The contract time for the completion of the bridge was 3 years. The contractors, when tendering, had offered to do the work in 2 years and 6 months, but he thought that they were unduly optimistic, and 3 years was eventually decided on. The construction actually took a few months longer than that, owing, however, to causes for which the contractors could not be held responsible. Engineers who had worked in London knew the difficulties of dealing with all the various factors concerned—pipes, cables, streetdiversions, and so on. A great deal of trouble was taken at the bridge-yard in assembling the steelwork and in putting together representative ribs. That trouble was taken to good purpose, for the precision with which the steelwork all came together upon the work was remarkable. He would like to congratulate the contractors, and their yard staff in particular, on the high standard which they maintained. In one respect the work was not finished; there still remained the necessity for providing better access between the Westminster end of the bridge and Victoria station. He remembered being twitted with that by counsel when he was trying to get the Bill through; his answer then, as now, was that Rome was not built in a day. He hoped that better provision would soon be made for giving free access for traffic to Victoria. Sir George Humphreys.

Sir REGINALD BLOMFIELD remarked that he hoped compassion would be shown him, because, to his great regret, he knew nothing about the engineering matters which were being discussed. The members therefore would not expect any technical information from him. As an architect, he would like to say that he was full of admiration for engineers, and also that he envied them very much, because he thought they had perhaps the finest job in the world, for two or three reasons. Firstly, their work was often on a tremendous scale. Most architects wanted to do something big, but they did not have the opportunity. When he saw the enormous stresses with which engineers had to deal he felt that theirs was indeed a man's work. A second reason was that they had to fight with the immense forces of nature and make them serve their purpose, which seemed a very fine thing to do. Architects did not have that opportunity, and their problems were comparatively simple, though he would try to indicate that they were not quite so simple as they appeared at first sight. A third reason for which he envied engineers was that they set to work with a single purpose; all they had to do was to produce the most efficient result possible in the most economical manner. He had had a magnificent opportunity of seeing engineering at first hand in the construction of Lambeth bridge, and could not have had a more delightful, considerate, and patient man to work with than his old friend Sir George Humphreys. He found the experience extraordinarily instructive from start to finish. Sir George knew perfectly well what he wanted, and was good enough to assume that his architect colleague did the same. Sir George therefore confined himself to his side, which was the essential one, of the operations, leaving Sir Reginald to do his minor part of the work. From first to last they had never had a single word of difference. Sir George had passed rather lightly over one episode in the design of the bridge. When Sir Reginald received his Sir Reginald Blomfield.

Sir Reginald Blomfield.

first instructions, the bridge was to be of reinforced concrete with a granite facing. He thought that it would be one of the finest bridges ever erected, and set out all the masonry for it, with the elliptical arches which had been mentioned. Sir George finally decided, however, that that would not be a particularly good form of construction, and that it would be very much simpler to have a steel bridge. They therefore began again. Sir Reginald had needed no persuading; directly Sir George suggested the segmental curve he saw that it was the right curve for a steel arch. Sir George did not tell him what he wanted or how it should be done, but left him alone to do the best he could with the elevations, which was all that he had to do in the matter.

There were two points in that connection which he would like to mention. The first was the tremendous trouble that was taken over the silhouette. With the scaffold-pole erection, some 500 or 600 feet long, which Sir George had described, they had managed to get a splendid curve; owing to the foolish insistence of the authorities on certain gradients, it had had to be altered a little over the haunches of the arch, where he had wanted it a little steeper, but he thought the final result was satisfactory. The second was the device of the steel plating in the haunches of the arch, which was doubtless questionable. Sir George had been good enough to let him do that, and he did it for a very definite reason. He had always disliked the contrast between the solid piers and the skeleton framing in some steel bridges, so he thought he would plate the whole arch by panelling, showing definitely, by the panelled appearance, that that plating did not serve any constructional purpose.

The work had been a delightful experience, and he would like to pay a tribute to Mr. Groves, who had been most helpful in every way and most instructive to him personally; Mr. Groves took him all over the work, and he went into all sorts of obscure places and learned something about it.

In conclusion, there was one point to which he would venture to call attention. He had begun by saying that he was entirely unversed in engineering matters; but architects and engineers each had their own very definite functions. It was the fashion nowadays to say that the engineer and the architect should be one. Two centuries ago, when construction was not so specialized, it was very desirable that any one work should be all in one hand; but to-day construction was so intricate that it was quite impossible for one man to fulfil the two functions. Moreover, different qualities were involved. The engineer had to work out all the strains and stresses and constructional necessities; in the case of Lambeth bridge, Sir George Humphreys arranged all the essential data, the gradients, the arches, and so on. But then came the question of its finished appearance, and that was where the architect came in, because he was, or should aim to be, an artist in form on the greatest possible scale. It was very important that the engineer and the architect should work together from the start. The engineer should lay down the essential requirements, and then the engineer and the architect should put their heads together and do their best to embody those requirements in a really beautiful structure. The necessity for engineers and architects to work together increased every day, and he hoped that that point of view would always be maintained between their two callings. Sir Reginald Blomfield.

Sir HARLEY DALRYMPLE-HAY observed that anyone who studied Mr. Groves's Paper would learn something of the way in which the London County Council did their work, which was always good but was also always very expensive; those who were engaged in commercial life could not afford to do work on such a magnificent scale. Sir Harley Dalrymple-Hay.

He had always been a great lover of the old Lambeth bridge, because he had been working underground for a very long time. The connection between those two facts might not be obvious, but he would explain it. When the designer of the bridge, the late Mr. Peter Barlow, was sinking his cylinders, he said to himself, "As this seems to be so easy in the clay, why cannot I drive horizontally and make a tunnel?" Accordingly, he took out a patent, and Sir Harley's old master, the late Mr. J. H. Greathead, M. Inst. C.E., put the idea into practical shape when he built the Tower subway. If Barlow had not built Lambeth bridge when he did, Sir Harley would not have been standing there that evening to talk about it and its connection with tube railways, because the development of tube railways in London arose directly from Barlow's idea.

Sir George Humphreys had stated that there were no constructional difficulties at Lambeth bridge. In considering how a bridge was to be built, one of the most important matters was the question of the foundations. The builder of a bridge naturally wanted to know something about the strata. At Lambeth he believed he was right in saying that there was practically no ballast except at one pier, and there it was only 7 feet thick; the rest of the material was good solid London blue clay. That being so, he would have imagined that the engineer would expect the foundations to be an easy job; but what had actually happened? His old friend Sir George Humphreys had proposed a system of construction which was terribly expensive for work of the kind in question. If Sir George had had to deal with running sand or ballast he could not have done better; but Sir Harley absolutely condemned the construction of Lambeth bridge by a method involving colossal expense, when it

Sir Harley Dalrymple-Hay.

could have been done very much more cheaply. He would not make that statement without giving reasons. It was 43 years since he had worked as a draughtsman on the London and South Western Railway, and had drawn out a reconstruction of the railway-bridge across the river at Barnes. He had compared the caissons which he had then designed with those Sir George had used; Sir George's caisson was of exactly the same type as that which he had designed, although it was longer. His own problem had been much more difficult. The late Mr. Joseph Locke, Past-President Inst. C.E., had built the original bridge of three spans with cast-iron arches, each of 120 feet span and 12 feet rise. When trains came on that bridge the thrust of the arch visibly tilted the piers. He realized that the reconstruction was going to be very awkward, because the bridge had also to be widened for additional lines. He said to himself that there was clay right at the river-bed, and if he drove a cofferdam he would shake the pier down, so he proposed to use a special caisson with two large dredging-wells 6 feet in diameter. It was only of moderate length, being 28 feet by 18 feet with a total depth of 16 feet to the cutting edge in the permanent portion and 23 feet above. That design had been approved by his old chief, the late Mr. W. R. Galbraith, and the work carried out by his late friend Mr. Alfred Szlumper. Compressed air was not used; he had specified that a diver should go down into the caisson, clean up the bottom, and fill the caisson with concrete, so that it might cut into the ground, and allow the water to be pumped out. The pumping was successful, and the whole excavation was carried out in free air. Had any difficulty been caused by leakage, he would have adopted the simple device of driving sheet-piles round the caisson and filling the intervening space with clay. Sir George Humphreys should have adopted that method at Lambeth if any difficulty had arisen in making his caisson tight in the ground. Instead of that, he had employed compressed air, and had had to keep the caisson from floating by filling it with ballast, involving the great expense of putting in ferro-concrete pillars, joists, and a timber deck loaded with about 2,000 tons of material. A simple device of the kind which Sir Harley had described would have sufficed. He was not theorizing; at Barnes the method had been used down to the same depth as at Lambeth, and Sir George could have used it equally well.

He would like to express his great regret that the general alignment of the bridge was not on the line of Horseferry road. Sir George Humphreys had explained that it had to be put sideways, but he did not agree. His opinion was strengthened by the closeness of the Millbank roadway. The circus which had been put on the Westminster side of the bridge was far too small; the cars from the bridge came down a gradient of 1 in 25 or 1 in 30, and at right angles to those coming from Grosvenor road towards Westminster. He had been round the circus in his car a good many times, and on slippery days the cars, he was credibly informed, skidded round it. It was definitely dangerous, and he did not like to think of the probable effect of a hard frost. Sir Harley Dalrymple-Hay.

With regard to Sir Reginald Blomfield's suggestion of a concrete bridge with a granite face, he thought he was right in saying that the late Sir Alexander Binnie had contemplated the construction of a mass-concrete bridge faced with granite at Vauxhall in 1906, and he wondered why it had not been done at Lambeth. He thought that probably Sir George had placed the centre-line of the roadway in its present position rather than on a production of the Horseferry road line so as to enable the piers to be aligned with the run of the water in the river. He did not know whether that was so, but he thought that the bridge would have been very much better if placed on the Horseferry road line, and he would have preferred to see it carried at a high level over each of the main roads, so as to avoid the intersection of lines of traffic.

Mr. DAVID ANDERSON confined his remarks to a discussion of the cost of the bridges that were being put up in London. In the case of Lambeth bridge, for example, on the basis of the figures given in the Paper and upon some figures which Mr. Groves had given him for the approach-roads, the cost per square foot from back to back of abutments for the bridge proper worked out at £8·25 per square foot. He would ask whether the work could not have been carried out less expensively. He had tabulated the cost of arched bridges in London, beginning with the present Westminster bridge, which, though put up in 1862, was carrying modern traffic. Mr. Anderson.

Bridge.	Date.	Spans.	Cost per square foot.
		feet. inches. feet. inches.	
Westminster bridge	1862	95 0 to 120 0	£2 (about)
Blackfriars bridge	1869	155 0 to 186 6	£3·6
Vauxhall bridge	1906	130 6 to 140 6	£4·25
Battersea bridge	1890	113 6 to 163 0	£4·8
Southwark bridge	1912	123 0 to 140 0	£5·4
Blackfriars bridge widening	1909	155 0 to 186 6	£6·5
Lambeth bridge	1929	125 2 to 165 0	£8·0

It would be seen that the cost per square foot of Westminster bridge was only one-quarter of that of Lambeth bridge, and that of Vauxhall bridge only about one-half. So far as Southwark bridge was concerned, he must, he supposed, stand in a white sheet, as he had been

Mr. Anderson. largely responsible for the design. The contract was pre-war, and the figure given was based upon it. It was obvious from those figures that the bridges in London were steadily increasing in cost. He knew, of course, that wages had gone up, and that the loads to be provided for had also increased, but he would like to give costs for three bridges outside London which had been carried out in recent years by his firm. The first was at Newport, Mon.; the arches were small, ranging from 60 feet to 73 feet span, but the work was carried out under very difficult conditions with a tidal range of about 30 feet. That bridge cost £5·1 per square foot. The second was the Trent bridge widening, with three spans of 100 feet, costing £3·1 per square foot; and the third was the Wearmouth bridge reconstruction, a single span of 375 feet, and therefore of much larger dimensions than would arise in London, built in 1929 and costing £5·5 per square foot. In other words, outside London arch-bridges could be put up at from £3 to £5·5 per square foot; why was it necessary to pay £8 per square foot for a modern bridge in London? He could not help feeling that engineers were not fully availing themselves of modern improvements, but were carrying out their work in the same old-fashioned way. Arguments had been put forward that evening both in favour of and against sinking foundations under compressed air. He himself had been guilty of a good deal of foundation-sinking under compressed air, but he would emphasize that, whether it was a right method or a wrong method, it was undoubtedly an expensive method. It ought to be possible for engineers to-day to design better than did their forefathers; they had plant and appliances which their forefathers did not have, and they should be able to get their costs down. He brought that point forward because more bridges were soon to be built over the Thames. He appealed to those who would be responsible for them to make some attempt to bring down the costs; he did not think it was to the credit of engineers that their costs should be going up so steadily.

There were two further points which he wished to mention. Firstly, engineers had quite tamely submitted to the Ministry of Transport's standard loading. He did not know the history of that loading; all he knew was that it had been issued by the Ministry of Transport. The figures given in the Paper showed that there was a very wide distribution of any load over the whole width of the bridge; such effects should be utilized in design, and it ought not simply to be assumed that every 10 feet of width of roadway was to be occupied simultaneously by the Ministry of Transport's loading. He thought that that was absurd, and that engineers had accepted the conditions too readily. As one member had said to him that night, it was another example of the standardization into which engineers in England were being shepherded; he himself thought there was far too much of it. Secondly, he thought that engineers had submitted too much to the domination of the Port of London Authority. He had been consulted by one of the contractors who was tendering for the underpinning of Waterloo bridge, and had found that the conditions laid down by the Port of London Authority in connection with that work were such as to make it practically impossible. The conditions required for the water-traffic were to his mind too onerous, and compelled the use of fairly deep foundations; he thought that engineers ought to protest against such restrictions. In one way and another costs were mounting far too high, and, as he had already stated, he hoped that an endeavour would be made to reduce them in future construction. It might not be possible to get down to £2 per square foot—the cost of the present Westminster bridge—but to his mind there was too big a difference between £2 and £8 per square foot. Mr. Anderson.

Sir LEOPOLD SAVILE, referring to the Paper by Mr. Dean, remarked that he had had a certain amount of experience of bridge-foundations in India; although the bridge in question was of a peculiar type, the design of its foundations presented similar problems to those arising in other cases. The solidity of the foundations of a submergible bridge was of particular importance, especially in view of the strain which it would have to bear when overtopped. It would be seen from the Paper that when it had been found impossible to de-water the cofferdams of piers 4, 5, 6, and 7, it was decided to drive piles and found the piers on a platform on top of them, rather than to attempt to get down to the rock by wells. He thought that in a river of that nature, which apparently had a considerable depth of shingle and sand overlying the rock, there was grave danger of scour; from the description given it seemed that such scour might get underneath those platforms, so that the piers which would then be carried only on piles about 12 feet above the rock might be in a very dangerous position. No doubt the question had been fully considered, but it would be of interest to know the reasons leading to the use of piles instead of wells. Although difficulty would no doubt have been experienced in sinking wells through the very compact sand and gravel in free air, he was of opinion that a good foundation could quite easily have been obtained by sinking two steel cylinders for each pier down to the rock under compressed air. There could then be no question of the safety of such a foundation, even if the river did scour out. Sir Leopold Savile.

Mr. R. P. MEARS remarked that he considered the road-level of the submergible bridge over the Nerbudda near Jubbulpore to have been very well chosen. There was obviously no point in making it Mr. Mears.

Mr. Mears. lower, and there would have been very little advantage in raising it. To put it above high flood-level would have entailed raising it by about 50 feet, which would have involved much greater expense for piers, but an even greater additional cost for the approach-spans or land-embankments required; such land-embankments were very apt to be eroded in Indian floods. The site selected was very good from the point of view of the crossing, but, as would be seen from Fig. 1, Plate 3, it was obtained at the cost of 3 or 4 miles of deviation. The old road crossed the river at Guarighat, which would have been a very difficult site for a bridge. He thought that the authorities did well to make that deviation and to choose the site which they did, because the Nerbudda was particularly difficult to bridge. The criteria governing choice of site were very well tabulated in the Paper. The points of design of a submergible bridge were not so clearly summarized, and he would like to enumerate them. There were eight points:—(1) The spans should not be too small; he would put 35 feet as about the minimum. (2) The head-room should be considerable; not less than, say, 15 feet. (3) Obstruction to the flow of the river should be as small as possible. (4) There should be no perforations or cavities in which any debris could lodge. The handrail should be either removable or collapsible. (5) Any filling used in construction should be of a cohesive type which would stand submersion; earth-filling, for instance, would not do. That was easily dealt with in the parts of India concerned, because lime concrete was obtainable very cheaply, at about 4*d*. per cubic foot. (6) The foundations had to be proof against scour. (7) The bridge had to be heavy and massive. (8) The end abutments, in the case of an arch-bridge, had to be designed to be independent of any counter-thrust from the earth-fill behind, which was always liable to be scoured out. Some existing bridges did not comply with those requirements, for example, the Mandla "causeway" (referred to on p. 179), which also crossed the Nerbudda river, and was built in 1913. It was ½ mile in length, 16 feet wide, and cost just under £10,000, which worked out at the modest figure of 5*s*. per square foot. The causeway consisted of eighty small spans, each of 20 feet, and was built of brick, lime concrete and masonry, lime mortar alone being used. It said a great deal for the extraordinary tenacity of Indian lime that a structure of that kind, forming such a tremendous obstruction to the flow of a river like the Nerbudda, should have stood as it had done for 10 years with comparatively little damage. A new central arch, with abutments below water-level, had been put in because a few spans had been washed away in a heavy flood in 1926. Water in high flood went 20 feet or more over the top. The design was faulty in that the headroom was too low, being only

10 feet, and the spans too small, being only 20 feet. Another bridge, recently built over the Purna river, had been placed at a site that was not really suitable for a submergible bridge. There had been good reason for putting it there, because the old road used to cross there on a temporary bridge every cold weather, so that no diversion had to be made; but the river was on a curve and the bank on the farther side was low, so that during the first season after the bridge was built the river tended to make a short cut across the low bank, scouring out some of the embankment and involving extra works. Other bridges that he would mention were very similar to that described in the Paper. One of them was also over the Purna river, and another over the Tapti river. The latter bridge was submerged by 28 feet during construction, and by 30 feet after its first season. It was stated on p. 183 that the present practice was that such bridges should consist of arch-openings, but he did not agree with that statement. There was a bridge at Narsinghpur of very recent construction which was submerged regularly, and which consisted of reinforced-concrete hollow-slab spans of 35 feet, the piers being of masonry founded on wells sunk about 20 feet into the bed; the road-level was about 15 feet above low-water level. He had always found arch-bridges more expensive than beam-and-slab types, and provided that the latter were properly designed, so that there was no chance of the lodgement of trees or other debris, he thought they were very suitable, particularly where the foundations might be very low down and high abutments would be required, which would involve great difficulty in dealing with the thrust of an arch bridge on its abutments, especially if founded on wells. A bridge over the Waingunga river, which was about $\frac{1}{3}$ mile in length, had a foundation and a site very similar to those of the bridge described in the Paper. The river had a sandy bed, but was not so difficult to cross. The bridge had been submerged during construction, and the erosion that then occurred behind the end abutment gave some idea of the necessity of making it independent of any counter-thrust. As a rule the only way of estimating the depth of scour was to get on the bridge when it was just about to be submerged—because then the river was digging out its bed—and to probe the bottom with a bar. In one case which had come to his notice the bed was 14 or 15 feet below low water-level, and the river had scoured the foundation right down to the bottom; the piles and the concrete pedestals which had been used for the erection of a centering for the arches were exposed and swept away. It was very instructive to realize that the whole of the soft material in the bed had been washed clean away. The foundation in that case consisted of wells sunk by open grabbing through water, and when they had been got down as far as they would

Mr. Mears.

Mr. Mears. go without pumping reinforced-concrete piles were driven inside. It had hardly been expected that scour would actually go below the well-bottoms, but it had done so in some instances. The wells acted as scour-shields and enabled the piles to be braced by under-water concrete near the bottom and again at the top. His remarks with regard to scour led up to a comment on Mr. Dean's Paper, and particularly on the foundation shown in Fig. 7, Plate 3. It was stated on p. 187 that the pier was founded on piles driven to a penetration of 18 inches, and on p. 197 that an average penetration of 15 inches was assumed. Those piles were driven by a 3-ton monkey dropping 10 to 12 feet. It seemed to him that such hard driving into rock would crack either the piles or the rock. In the analogous case to which he had previously referred the rock was less hard and the piles had penetrated 3 or 4 feet. It would be noticed on p. 186 that when driving an experimental pile at the Nerbudda bridge the first 8 inches of the rock was shattered. He did not think a design of the kind in question was stable without a lot of stone pitching. To visualize the conditions, the whole of the sand or boulders lying in the bed should be removed and the pier pictured as standing up on pile points like so many pit-props, with no lateral support of any kind. He thought there would be a distinct danger of the rock being cracked up, and perhaps of pieces being swept away by the violence of the current. It might have been better if two holes of about 2 feet diameter, slightly bell-mouthed at the bottom, had been made down the pier, so that in time of flood stones could be fed straight down the pier into the space below. Even then, however, he did not think that the design was really suitable; he was of opinion that wells would have been better, and he thought that they could have been got down quite successfully by open grabbing with the aid of a diver, and would have made a more lasting type of foundation.

With regard to the cofferdams, the Author stated on p. 186 that they "were excavated and timbered, and were about 50 feet by 30 feet to allow space for the bottom of the pier, which was about 38 feet by 18 feet," and that for pier No. 4 the cofferdam was divided into halves by an additional line of sheet-piles. One cofferdam had collapsed. He considered that the cofferdams were unnecessarily large, which must have added very much to the difficulties of the work. He thought that if the Author had divided his cofferdams up longitudinally and kept the struts short he might perhaps have avoided the collapse. With regard to the concreting, it was stated on p. 190 that the slump was about $\frac{3}{8}$ inch to $\frac{1}{2}$ inch, which seemed rather small. The water—cement ratio was given, but there was no information as to the allowance made for water in the washed materials. It was stated that the concrete-mixing was done in 4-cubic-foot machine mixers. In India, cement was always delivered in 1-cwt. bags, accurately weighed, and the ordinary 10/7 mixer would take the bag, instead of splitting it up and using it in boxes. Mr. Mears.

The temperature-allowances were given as $\pm$ 20° F. As a rule the arches were finished at the end of the season, at the height of the hot weather, so that, although $\pm$ 20° should be a sufficient range, it did not allow a sufficient drop. With a submergible bridge another coefficient was necessary to allow for the expansion and contraction of concrete when alternately wetted and dried.

Mr. Du-Plat-Taylor.

Mr. F. M. G. DU-PLAT-TAYLOR, referring firstly to the Paper on the submergible bridge across the Nerbudda, said that an arch-bridge, or any other presenting so much surface to the current, seemed to be unsuitable for the purpose. He would have thought that a steel girder-bridge, with trestle-type piers, the downstream legs of the trestles being inclined so as to take the thrust of the current and the steelwork being well fendered with timber on the upstream side, would probably have been more satisfactory, being much lighter and presenting less obstruction. The disadvantage of that suggestion was probably its cost, but he did not know very much about that question in India. The speed of the floods was given as 10 to 13 feet per second, which was from 6 *to* $7\frac{1}{2}$ knots. That was a fairly rapid current, but it was one which structures in harbour work often had to resist, and therefore he saw no reason why a steel bridge of the type he suggested should not be feasible and advantageous.

Turning to the Paper on Lambeth bridge, he would like to ask why all the piers had been carried down to the same depth, — 37·50 O.D. It seemed to him that the shore piers could have been founded at a much higher level, particularly as the abutments were founded at — 29 O.D., and a considerable saving could have been effected. With regard to the springing-level, all the Thames bridges had to be designed as a compromise between the requirements of the river user and the requirements of the road user, and it was very difficult to arrange the level so as to suit everybody; at the same time, the springing of the shore arches of Lambeth bridge at 14·50 O.D. seemed to him very low. It was only 3 inches above high water of spring tides. The water-level shown in the Figures was Trinity high water, which was an arbitrary level, and the tide rose 18 to 20 inches above that. At exceptionally high tides part of the arch would be submerged. For instance, the record tide of 7 January, 1928, which flooded part of the neighbouring streets, rose to 18·50 O.D., and overflowed the adjoining embankments. That did not often happen, but in those circumstances the springing would be 4 feet under water, and only the top part of the arch would

Mr. Du-Plat-Taylor. be visible, which would be detrimental from the point of view of appearance.

He had been greatly interested in the description of the demolition of the old wrought-iron bridge. Its defects seemed to have been due mainly to faults in design; the material seemed to have been good, and particularly the cable, which gave test-results equal to any obtained with modern wrought iron. Wrought-iron structures usually had a very long life if they were properly protected from the damp, and he noticed that in the case of the old Lambeth bridge the places where the plating had gone were all, so to speak, between wind and water, or just in the upper part of the surface of the road bed, where the water had got between the road-material and the wrought iron. If the wrought iron had been coated with bitumen, as was the modern practice, probably that material would have been found to be just as good as when it was put up. Some years ago he had had to break up a lot of 40-year-old wrought-iron floating caissons built in 1883. Parts of their plating were alternately submerged and dry, and they had been painted occasionally, but not often. It had been found that the $\frac{3}{8}$-inch-thick vertical plates, which the water ran off, had lost 0·075 inch, or 20 per cent., in 40 years, while the horizontal plates, on which the water lodged, had lost 30 per cent. No mild-steel structure would have lasted nearly so well.

Mr. Firth. Mr. HAROLD FIRTH supplemented the information contained in the Paper by Mr. Groves with some information with regard to the loads and stresses adopted in the design. The live load adopted was the British Standard loading for highway-bridges, as given in the Appendix to British Standard Specification No. 153 for girder bridges, using a multiple of 15 units and placing four trains of that loading on the carriageway. The footway-loading was taken as 84 pounds per square foot. Impact was allowed for in accordance with the provisional formula given in the Specification to which he had referred. The maximum permissible stresses were limited to 5 tons per square inch in compression and 6 tons per square inch in tension. Shear and bearing stresses were taken as 75 per cent. of the corresponding stresses in the same Specification. The range of temperature allowed for was $\pm 30°$ F. The pressure on the clay beneath the foundation of the centre pier worked out at 3·2 tons per square foot for dead load only; that figure was increased to 3·5 tons per square foot with the live load covering the bridge. In the worst case of unbalanced loading, with the centre span under full live load and the adjoining spans unloaded, the maximum pressure on the clay at the extreme edge of the foundation was 4·8 tons per square foot. The maximum earth-pressure beneath the back edge of the abutment (allowing for active earth-pressure only), with live load on the bridge and the river flooded, worked out at 3·6 tons per square foot. Mr. Firth.

The loading-tests had been very carefully made and investigated, and their most interesting feature was the extent of the load-distribution. The maximum deflection of the centre rib of the central span was 0·39 inch, and of the centre rib of the shore-span 0·24 inch. Those were obtained with the test-loading in the "line abreast" position. To give some idea of the distribution, taking the centre span with the test-loading in the "line ahead" position, the percentage of the total load carried by the centre rib according to the measured deflection was 16 per cent. The next two ribs, Nos. 4 and 8, carried 15 per cent.; the next two, Nos. 3 and 7, 12·3 per cent.; Nos. 2 and 8 took 9 per cent.; and the outside ribs, Nos. 1 and 9, 5·7 per cent. It should be borne in mind that if the continuity of the deck over the ribs were neglected, the calculated load on the centre rib with the test-loading in the "line ahead" position would be about half the total load, instead of 16 per cent., as shown by the measured deflection. With the loading in the "line abreast" position the distribution was somewhat similar, and for the shore-spans similar results were obtained, except that the proportion of the load on the outer girders was somewhat less. Another interesting feature of the tests was that after the test-load was run off the shore-span on to the next span there was an upward deflection of all the ribs of the shore-span amounting to 0·05 inch. That indicated that there was some slight deflection or tilt of the intervening pier.

With regard to the live load which was adopted, Mr. Anderson seemed to think that the Ministry of Transport loading was unnecessarily high. He was, however, inclined to differ. The tendency was for the weights of vehicles and loads using the roads to increase. Applications were continually being received for abnormal loads, some of them amounting to 100 tons, to run over bridges. A margin of strength to allow for future increase of loading was therefore desirable. The shore-arches had a ratio of rise to span of about 1 to 3, which was very flat, and to reduce the deflection and vibration it was considered desirable that stresses should be kept low; the low stresses also provided a margin for corrosion. It would have been a "penny wise and pound foolish" policy, in his opinion, to stint the weight of steelwork in such a bridge at the expense of its carrying capacity. The total cost of the steelwork in Lambeth bridge was about £90,000. If the permissible stresses had been increased by, say, 25 per cent., a saving in cost of steel of about £18,000 might have been effected. That represented only about 4 per cent. of the total cost of the bridge, which meant that for a 4 per cent. increase in cost

Mr. Firth. a 25 per cent. increase in carrying capacity had been obtained. That, he thought, was very sound economy.

Mr. Griffiths. Mr. G. J. GRIFFITHS observed that, with regard to the methods adopted in sinking caissons at Lambeth, Sir George Humphreys had remarked that once they got started there were no difficulties, and to his mind that was an answer to criticisms of the method. When dealing with a tidal river he himself would much sooner be under compressed air than in free air, relying on steel piles. From his experience, he felt that the suggested method of sealing the interval between the steel piles and the caisson with clay could not be entirely relied on. Moreover, in a bridge such as Lambeth bridge, which had to last for many years, it was very desirable to make sure of the foundation and get as dry a bottom as possible. He had always found that a drier bottom was obtained with compressed air than with a steel-pile dam. It seemed to him, moreover, that with compressed air there was a greater measure of control, especially when bastard or soft clay might be encountered. He had experienced trouble from that cause more than once; in one case in the Oxford clay a weir travelled downstream 4 feet 6 inches in the night, and in another a small dam across a lock travelled upstream 2 feet 6 inches in a night. It was as well, therefore, to make sure of good foundations, and although the initial cost might appear somewhat heavier the gain in safety and the absence of any delays meant a saving of money in the long run. It had been suggested that the platform for unloading was a very costly measure. Looking at the drawings, he did not see that it could have cost more than some hundreds of pounds, but he was open to correction.

Mr. Anderson had complained that river-engineers demanded that foundations should be taken to a lower level than he thought was necessary. Mr. Griffiths had to deal with some 500 miles of tributaries to the Upper Thames, and possibly before long would have 1,000 miles, in addition to 136 miles of the Thames itself. He would not like to say how many bridges that involved, but very few of them had their foundations deep enough. The river authorities were precluded, under the Act of 1894, from dredging within 60 feet of any bridge over the Thames itself. That crippled the poor river-engineer seriously, and, after all, the river had been there before the bridges. He had no less than seven good bridges which were "all up in the air," and he dared not do anything to the river until those bridges were put right. He thought that Mr. Anderson should reconsider his suggestion, because the position was a nightmare to the river-engineer. He might be speaking egotistically, but there were very many bridges which were causing trouble in that way, and he felt very strongly about it. It was his experience, moreover, that many bridge-engineers, once they had built a bridge, forgot all about the foundations, and it was left to the unfortunate river-engineer, who saw that a flood was coming and knew what was happening because he saw scour going on in the vicinity of his weirs, to say to the bridge-engineer, " I wish you would have a look at your bridge and see what is happening." He hoped that Mr. Anderson would withdraw his suggestion, because he did not want the younger generation, who would be building the bridges of the future, to keep their foundations too high. He asked all river authorities to say to county and local authorities, " Your plans are passed subject to the foundations being taken down to such a level as will allow dredging of the river to be carried out to the required depth." **Mr. Griffiths.**

Mr. Ernest Batchelor remarked that the road-bridges of the Central Provinces could be divided very roughly into four categories. There was the modest paved causeway, passing the flow in the cold and also in the hot weather. Then there was the raised causeway, passing the flow towards the end of the monsoon period, which was a good deal less than the average of the monsoon flow. Then there were the submergible bridges, such as that described in the Paper, and finally there were the high-level bridges. There were very few high-level bridges in the Central Provinces, although the area of the Central Provinces was larger than that of Great Britain. From 1905 to 1908 he was Deputy Commissioner of the Damoh district, to the north-west of Jubbulpore. When he took charge of that district it had no high-level bridges or submergible bridges, although it was nearly as large as Yorkshire. The best road at that time was that between Jubbulpore, Damoh, and Saugor, but there was no proportion in the causeways along that road ; one stream might have a fairly good causeway, but the next stream, only a few miles farther on, perhaps had the same catchment and no causeway at all. In 1907 it was proposed to improve a road taking off to the south from the Jubbulpore road and to provide it with paved causeways, which were the most humble variety. The estimates made by the P.W.D. had been submitted through him for his comments, and he had proposed that instead of the paved causeways submergible bridges should be provided throughout. In his remarks he pointed out that a ferry, which was always used with a paved causeway, was a very weak link in a military road, and that a submergible bridge would ensure the maintenance of traffic during the monsoon period, which was of great importance in a time of famine and scarcity. To secure some measure of proportion in the various bridges constructed he suggested the use of a formula which should define the flood-discharging capacity of the various bridges on the road, and based that formula on an examination of the rainfall-statistics made at several stations **Mr. Batchelor.**

Mr. Batchelor. in or quite close to the catchment-area of the largest river which would be crossed by the road, one with a catchment-area of 1,000 square miles. His formula was $Q = CA^{\frac{1}{2}}$, where Q was the discharging capacity of the bridge in cubic feet per second when the flood just filled the lowest arch in the bridge, C was a constant and A the area of the catchment in square miles; C would vary somewhat throughout the Provinces, and would increase with the mean annual rainfall. There was a severe failure of the rains in 1907 and a great scarcity in the following year, and relief measures, for which he was responsible, were opened on a very large scale. In that year the road which he had just mentioned was provided throughout with submergible bridges, and was continued on to Patan. It immediately attracted the traffic from Jubbulpore. In the following few years various other large submergible bridges were constructed in the Damoh district. From 1914 to 1916 he had been Deputy Commissioner of the Wardha district in the cotton area some way to the south, and gave considerable attention to the roads, which were even worse than those in the Damoh district. On looking through the estimates for the provision of a causeway over a fairly large stream near headquarters he entered into an examination of the rainfall-statistics for the previous 6 years, and concluded that if a submergible bridge were constructed according to the formula he suggested, with a coefficient of 800, it would have been submerged on a few occasions only during a year, and then only for a few hours. In 1916 he had submitted a note to the Indian Industries Commission on the improvement of road communications in India by the use of motor-cars, and in that note he dealt, among other matters, with the question of submergible bridges. In the next few years several submergible bridges of considerable size were constructed in the Wardha district.

So far as he was aware, the first records of flood-levels in a river in the Central Provinces were those of the Nerbudda river referred to in the Paper. Those records were much to be preferred to an empirical formula such as he had suggested, but he had had to be content with rainfall-statistics. He would like to suggest that the value of Mr. Dean's Paper would be increased if he would supply a graph showing the flood levels in the Nerbudda river over as long a period as possible. An Indian river such as the Nerbudda in flood was a very formidable obstacle indeed. Moreover, India was not a country with large sums of money to spend. At the same time, it was easy to realize how valuable bridges such as that described by Mr. Dean were to the people of the country, and he hoped that in the near future the Central Provinces would have the good fortune to have many more added to their road system.

Mr. H. W. S. Husbands, referring to Lambeth bridge, said that Sir Harley Dalrymple-Hay had called attention to the small size of the circus on the Westminster side of the bridge; it was in effect a one-line circus, which would only take one line of traffic crossing another line, so that it could not give more than half the capacity of the bridge or of Millbank. He did not imagine the bridge was ever used to its full capacity, but it seemed a pity that a bridge which had cost so much should not have approaches enabling it to take the full four lines of traffic for which it was built. That capacity would probably not be used in the immediate future, but if, as Sir George Humphreys had said, anything went wrong with Westminster bridge it would be required. He therefore thought it would have been better, as Sir Harley Dalrymple-Hay suggested, to carry the bridge over both embankments, but would prefer to do so at a slightly lower level by lowering the embankments at each side instead of raising them; the crown of the bridge was about 20 feet above the original embankment-levels. In that way the bridge could be used to its full capacity if necessary. On the Lambeth side the Albert Embankment was crossed on the level, and the full capacity of either road could not be utilized. Mr. Husbands.

The grading of the approaches was not mentioned in the Paper, but he had looked at the Lambeth approach when it was nearly completed, and considered that it might have been very much better. The average grade on the bridge itself was given as 1 in 30·7, with a vertical curve, but that did not convey much. As a matter of fact, the gradient had to start at about 1 in 22 to get the vertical curves in, and, although that gradient was for a short length only, it appeared unnecessarily steep. The bridge was fairly long, and it was of course impossible to get any very pronounced bow for the top chord; it seemed to him a mistake to steepen the grading merely in order to give a more pronounced bow to the bridge, for the sake of architectural effect. There was another point which seemed to show a lack of appreciation of the fundamentals of the treatment of curves and grades. Between two curves which were both of the same sign there was a short length—about 7 feet—of straight. With reverse curves such a length of straight between the tangents was usual and indeed necessary, because the change of curvature was the sum of the degrees of curvature of the two curves, but where the two curves were of the same sign the change of curvature was the difference of the degrees of curvature, and if a length of straight was put in it simply made matters worse. There was no doubt that in the case in point one of the curves could have been lengthened and the length of straight taken out. If the sharper curve were continued the other tangent offset would be only about

Mr. Husbands. 0·01 foot, and if the flatter curve were continued the offset would be about 0·002 foot; that small piece of straight was therefore quite unnecessary.

The caissons had apparently been sunk by what might be called a staggering motion. He would be interested to know what was the reason for adopting that method, as he could not see that there was any advantage in sinking one side before the other. If one end were let down lower than the other, obviously more weight was put on the two lower jacks, and in any case if one of the jacks ran away too fast it would leave the weight on three of them, as would be the case if the whole four were lowered together.

The panelling was apparently designed for architectural effect. His "singular namesake" (if he might so describe him), Professor Joseph Husband, M. Inst. C.E., had stated [1] that architectural effect was best obtained by employing correct proportions for the bridge, and anything which disguised the function of any part of the bridge, such as making a cantilever bridge look like a suspension bridge, was strongly deprecated. He himself thought that in the case of Lambeth bridge it would have been very much better if the vertical and diagonal spandrel bracing had been clearly indicated in the panelling, instead of the squares which had been adopted.

Mr. Frank. Mr. T. PEIRSON FRANK remarked that he participated in the discussion only because he felt that some remarks made by previous speakers called for comment. He would like to make it clear that he had had no connection with the design or construction of the bridge, which had been nearly completed before he became Chief Engineer of the London County Council. Sir Harley Dalrymple-Hay had advocated what might be described as the open-cofferdam type of construction, as used in the case of a railway-bridge at Barnes,[2] where Sir Harley had employed some caissons which were quite small compared with those used at Lambeth. A similar type of construction had been employed for the foundation of the piers of the Tower bridge,[3] but there, although the area was fairly large, being 193 feet by 93 feet, the size of the individual caissons was only 28 feet by 28 feet. In the case of Lambeth bridge, on the other hand, the caissons were approximately 108 feet by 37 feet. The type of construction used at Lambeth had been used for Southwark bridge, where the dimensions were about 102 feet by 28 feet, and also in the

[1] "The Æsthetic Treatment of Bridge Structures," Minutes of Proceedings Inst. C.E., vol. cxlv (1901), p. 139.

[2] A. W. Szlumper, "The Reconstruction and Widening of Barnes Bridge, L. & S. W. Ry.," Minutes of Proceedings Inst. C.E., vol. cxxiv (1896), p. 309.

[3] G. E. W. Cruttwell, "The Foundations of the River-Piers of the Tower Bridge," Minutes of Proceedings Inst. C.E., vol. cxiii (1893), p. 117.

case of piers in the Blackfriars bridge widening. Others, therefore, had adopted the compressed-air type of construction in similar circumstances. No one knew better than Sir Harley Dalrymple-Hay that in the London clay there were found deep furrows filled with gravel. Sir Harley would no doubt recollect encountering such a furrow on the up-river side of Charing Cross bridge when driving the Bakerloo tube; Mr. Frank had been told by a geologist that there was a rather deep furrow there, and certainly that particular formation was actually found to occur near to the Westminster abutment of Lambeth bridge, under the foundation of the embankment wall, and a depth of 7 feet of gravel was encountered under one of the piers. He agreed with Mr. Griffiths that the sure and definite type of construction given by the compressed-air caisson was undoubtedly the right one for Lambeth bridge. The method proposed by Sir Harley, as Mr. Griffiths had pointed out, was dependent on the sealing effect between the cutting edge and the subsoil, and required a certain packing of clay and the services of a diver. **Mr. Frank.**

With regard to the roundabout, he did not wish to discuss its history, because it was lengthy, and numerous plans had been prepared. Others had had a say in its shape and size, besides those who were erecting the bridge. It had been suggested, however, that a car could hardly get round it without skidding. He did not know whether that was due to the make of the car or to some other reason, but the morning after that comment had been made he asked his chauffeur if he had ever skidded when going round, and was told he had not, although he went round it not less than a dozen times a week. The suggested inability of cars to get round without skidding should therefore be taken with a grain of salt.

Mr. Anderson compared the cost of the bridge with those of certain other bridges, and referred to two dimensions, the length (which Mr. Frank proposed to take as the length to the back of the abutments), and the width between the parapets. In the first place, it should be remembered that Lambeth bridge had a remarkable setting, with the Mother of Parliaments behind it, and engineers would agree that it would not have been possible to use in such a site the designs of some of the bridges whose costs had been compared with that of Lambeth bridge. He did not wish to detract in the slightest degree from the utility of the bridges over the Usk, the Trent, and the Wear to which Mr. Anderson referred. They were excellent in their own setting, but at Lambeth something more was required for the architectural treatment and had to be paid for; the granite, for example, was quite costly. It was hardly fair, moreover, to compare the cost of the bridge with that of bridges, one of which, at any rate, was built about 1860, and he found that even in 1886

Mr. Frank. the cost of excavation for one of the Thames bridges referred to was only 5*s*., instead of 26*s*. 5*d*. for Lambeth bridge, while concrete was 14*s*. instead of 33*s*., and granite 4*s*. 4*d*. instead of 18*s*. 10*d*. In one of the bridges which Mr. Anderson had mentioned the figures for each of those items were even lower. Wrought iron or steel was £14 instead of £27 10*s*. The figures given by Mr. Anderson, therefore, seemed to him to prove that Lambeth bridge was relatively a cheap and economical one.

Mr. Anderson gave the cost of Westminster bridge as £2 per square foot. Probably Mr. Anderson had taken that from "Kempe's Year Book" for 1932, where that figure was given; but in a more official publication he found the cost given as £4·5 per square foot. Mr. Anderson gave the cost of the bridge at Newport as £5·1 per square foot, but in "Kempe's Year Book" for 1932 the cost was given as £6·55 per square foot, and that figure should be corrected if it was wrong. For pre-war Thames bridges the average cost was approximately £4 10*s*. per square foot, and he had given some slight indication of the different rates ruling in those days. The cost of Southwark bridge, which was finished in 1921, was given by Mr. Anderson as £5·4 per square foot, but according to his own calculations based on the dimensions to which he had referred, its cost was £8·5 per square foot. In those comparisons two dimensions only were taken, but at Lambeth the depth of the members was limited by consideration of headroom, involving additional cost in construction. For Lambeth bridge, however, he calculated the cost as £7·6 per square foot, instead of the figure of £8·0 given by Mr. Anderson; he thought it would be agreed that that figure compared very favourably with the cost of the other bridges. The cost of the new Chelsea bridge, as anticipated on the tender, came out at just over £6 per square foot. It should be remembered, moreover, that Lambeth bridge had been designed for future loading. He agreed with Mr. Firth in thinking that it would be a great mistake to build bridges only for present-day loading, when engineers in other branches of the profession were preparing and producing machines which could work more economically when transporting larger loads than were yet permitted, and when bridge and highway authorities were being asked to allow exceptional loads. Those exceptional loads already reached 100 tons, and the loads that would be permitted in the case of ordinary traffic 80 years hence might well be imagined. It would be a great mistake to construct modern bridges for inadequate loadings.

Mr. Groves. Mr. Groves, in reply, remarked that Sir George Humphreys had referred in generous terms to the work done by all who were responsible for the construction of the bridge. He could only say that

Sir George himself had inspired that work from start to finish; no man could work under Sir George and not give of his best. For his own part, many factors had contributed to make the experience of constructing the bridge a very enjoyable one—the admirable organization of the contractors, and the first-rate way in which they served their job throughout; the zealous and unsparing co-operation which he received from those who worked with him at the site; and the ready help which, in any matter of difficulty, was always forthcoming from the very efficient engineering department of the London County Council. Sir Reginald Blomfield, in his most acceptable contribution to the discussion, had expressed clearly and fairly the relative importance of the engineer's and architect's responsibilities in regard to a work of the kind in question. Mr. Groves had learned much by being associated with a work in which engineer and architect collaborated. At the outset he had been inclined to be critical in his mind of the immense time and trouble which the architect spent in elaborating the minor features of his design, but as the work progressed and that design took shape he realized the importance of those details, and by the time the structure was completed he appreciated that there could be much more in the artistic finish of such a bridge than was dreamed of in the average engineer's philosophy. Mr. Groves.

Sir Harley Dalrymple-Hay had raised several points of interest. Dealing first with the traffic-circus at the Westminster end of the bridge, he agreed with Sir Harley that it was all too small. (It appeared from the discussion that Sir Harley travelled about London very much faster than Mr. Frank!) It had been very difficult to introduce that traffic-circus. The approach to Lambeth bridge had been planned many years ago, and when at a later stage the Ministry of Transport had requested that a roundabout should be made, it had been necessary to repurchase a certain amount of land and to give splay corners to the great blocks of Thames House and Imperial Chemicals House, which just allowed the circus to be tucked in. He thought the best had been made of a rather difficult job, but the result was not ideal.

He respectfully joined issue with Sir Harley regarding the suggestion that open instead of pneumatic caissons should have been used for the pier foundations. Sir Harley had quoted Barnes bridge as being a good precedent for similar construction at Lambeth. The Barnes caissons, however, were only 18 feet wide; the Lambeth caissons, as Mr. Frank had mentioned, were 37 feet wide. He suggested that the tendency of the material outside a caisson or cofferdam and the water above it to blow in at the bottom was to a certain extent, at any rate, resisted by an inverted arch of clay.

Mr. Groves. A small tunnel could be driven safely relying on the arch of clay at the top, but with a larger tunnel the top had to be poled; the difference between an 18-foot and a 37-foot caisson was, he suggested, just the same. An arch of clay of 18 feet span could be relied on to do very much more than one of 37 feet span. Mr. Frank had touched on the question of the depth of ballast at the piers. It was true that it was only a few inches at one point, and 7 feet at another, but, as mentioned in the Paper, the average depth of ballast for each caisson was about 3 feet. That depth represented 450 cubic yards of material within the area of each caisson, so that had Sir Harley's method been adopted 1,800 cubic yards of ballast, apart from any inferior clay at the top, would have had to be removed by divers, which would have been very expensive. Even if initial difficulties and cost were disregarded he did not consider that open caissons would have been suitable at any stage. For one thing, the caissons actually used never sealed themselves. That was known, because one week-end when a caisson had nearly reached founding level the compressor-driver went to sleep, the pressure was not kept up, and water came under the cutting edge into the chamber. That would have been an awkward contingency had the caissons been open. Further, apart from the danger of pockets of ballast in the upper surface of the clay, London clay itself could be very treacherous as a cut-off for water. One example had come under his notice at the time of the construction of Lambeth bridge. He had then been engaged also on the extension of the County Hall wall. That work had been done in open cofferdam, and he had been delighted to find a good clay bottom in the first section excavated at —23 O.D. The piles of the dam went 6 feet below that. Within a few hours of his having passed that bottom, however, the cofferdam was filled up to a good level with about 500 cubic yards of material which had blown in through the clay under those piles. There was a vein of sand in the clay which was not apparent when the excavation was bottomed up, and the rising tide found a weak point. Fortunately no lives were lost. Men had a better chance of surviving such a mishap in an open cofferdam than in a caisson such as had been used at Barnes, with only two or three vertical shafts to get out of. Sir Harley had commented on the ballasting of the caissons. Admittedly a considerable quantity of ballast had been used, but what would have happened under Sir Harley's scheme ? The ballast would have been brought to the site alongside the stagings in barges, hauled up in skips, put through the mixers and lowered into the caisson. Actually, it came alongside, was hauled up over the stagings and into the caisson, and from there was shot directly down, after having served its purpose as kentledge, through the mixers into its permanent position. He could not see much difference, especially with regard to cost; there was no more handling, and the cost of the bunker-floor was small. The props underneath were made more substantial than if they had been temporary only, but they would have been wanted in any case to support the sag of the bottom frame of timbering, and that bottom frame of timbering and the ballast-floor were one. In thinking over the vexed question of open versus pneumatic caissons, he could not help wondering what he would have done supposing that alternative designs for the bridge had been made by Sir George Humphreys and by Sir Harley Dalrymple-Hay, the only difference between them being that Sir George was going to use pneumatic caissons and Sir Harley open caissons, and that he had been appointed resident engineer with the choice of carrying out which scheme he liked. He would have said to Sir Harley: "I should like to see these caissons go down without using compressed air. It would be an interesting experience, and it might be an exciting adventure. Success would bring about a very substantial economy, but I do not feel sure of success, and I do feel the risk of a catastrophe. Well, being a married man with a wife and family, I am going to work with Sir George!" **Mr. Groves.**

Mr. Frank in his remarks had dealt, almost line by line, with the points that he himself had intended to put forward in reply to Mr. Anderson on the question of the cost of the bridge. The bridge was not, he admitted, a cheap one, but he thought that the cost was justified by reason of the site. He would like at once, however, to refute Mr. Frank's suggestion that the bridge over the Usk at Newport cost something over £6 per square foot. He had been resident engineer for that bridge, and he knew for certain that the cost was not so high as that.

Mr. Du-Plat-Taylor had asked why the piers were all the same depth. The reason was that the three central spans were all navigation spans, and the same anticipated maximum dredging-level of —22·50 O.D. applied to those three spans, and therefore to all the piers. Admittedly the springings of the short arches were low, but there was no alternative; the gradient and ruling levels and the necessary headroom for shipping determined the levels that were adopted.

Mr. Husbands had criticized the grading of the bridge, though he had not said how it might be improved. The grading was a very difficult problem, and Mr. Groves thought that the solution arrived at was the only one possible. The grades of the bridge were steep, but the headroom which had to be provided was laid down by statute, and the road had to come down to embankment-level at each end. At first he had thought that Mr. Husbands was going to make a

Mr. Groves. great point of the 7 feet of straight interposed between two curves in the profile of the bridge, but Mr. Husbands had forthwith answered his own criticism by pointing out the smallness of the effect of that straight. He felt inclined to offer Mr. Husbands a prize if he could find it; it existed on paper, but it was quite unnoticeable and had not the slightest effect on the design. Mr. Husbands was wrong in thinking that the caissons had been sunk with a staggering motion. The staggering motion applied only when the caissons were suspended in the air by jacks; the sinking proceeded normally.

In conclusion, he felt that his fellow-Author had been at some disadvantage in not being able to add the personal touch to his Paper on a very interesting piece of bridge work. Perhaps in the circumstances he might be allowed to couple Mr. Dean's name with his own in expressing appreciation of the very kind reception given to their Papers.

*** Mr. Dean's reply will be found at p. 248.—SEC. INST. C.E.

Correspondence.

Mr. Granter. Mr. ERNEST GRANTER observed that, having been Mr. Groves's chief assistant during the construction of Lambeth bridge, he would like to make the following comments on the work and Paper.

It was found that the vertical joints provided between the concrete and masonry of the abutments and river-walls were of little use, as relative movement between the abutments and walls occurred only during the early stages of the work, and after a few courses of the granite had been laid no further movement was discernible. On three sides of the abutments the river-walls cracked vertically at about 70 feet from the vertical joints, the probable explanation being that, as the joints failed to function as intended, the massive abutments, while settling, dragged the lighter river-walls downwards, thus causing the cracks. The settlement of the walls probably varied from zero at the cracks to a maximum at the abutments. The vertical joint was merely a joint between two masses of concrete, without any soft intervening material which would allow relative movement between the abutments and walls. Apart from the difficulty of obtaining perfectly plane vertical surfaces to the concrete at the joints, the magnitude of the frictional forces between the two surfaces would probably preclude any relative movement. It appeared, therefore, that, for such a joint to be effective, it was essential to interpose a plastic material between the adjacent surfaces.