The imposition of such a heavy load on the comparatively green concrete of the walls called for considerable care. Further, owing to the variable depth of the filling under the jacking bases there was a strong tendency to tilt, which had to be checked immediately. Some small cracks developed in the wall in one instance as a result of tilting, but they closed up immediately when the pressure was relieved.

The tensile steel of the cross beams was pre-stressed by similar methods to those

Fig. 25.

SUBWAY—TYPICAL CROSS SECTION.

mentioned in the Paper. The deflexion of the longest beam, which had a clear span of about 42 feet, was measured after it had been relieved of support from the stanchions in the east wall of the old subway and was found to be inappreciable. Tell-tales placed across the junction between these beams and the old brickwork show that no differential settlement has taken place since their construction. Although the condition of the arches was such that careful observations had to be made continuously throughout the work, the underpinning was carried out without mishap of any description.

Discussion.

Mr. E. J. Buckton introduced the Paper with the aid of a series of lantern slides. He observed that it had been written and printed under difficult war conditions, and some of its shortcomings might be attributed to that fact.

It would be noted that the title of the Paper was "The New Waterloo Bridge": had it borne the shorter title of "Waterloo Bridge" the subject could not have been properly dealt with at one meeting. "Waterloo Bridge" as a subject dated back 120 years and would require further technical Papers, and possibly also a political treatise, to do it justice. Owing to limitations of space, a good deal had had to be omitted and some sections had been unduly abbreviated, but he hoped that the Paper covered most of the salient features of the work.

The actual construction of the bridge had been dealt with very briefly. He had hoped that the Contractors would submit a companion Paper, as it was obvious that the execution of the work had entailed much of constructional engineering interest.

Under the L.C.C. By-laws welding of reinforcement was, in general, prohibited, but special permission might be granted for its use.

A bridge in the heart of London called for close collaboration between engineer and architect. It was difficult to see how one or the other alone could meet the needs of the public for a serviceable structure which was also attractive to the eye.

The new bridge was an example of effective and friendly co-operation between the two professions, in which each had done its utmost to meet the other's requirements.

Sir Peirson Frank observed that Mr. Buckton had been very modest in reference to his own work, but complimentary in regard to the work of others.

The matter included in the Paper had been carefully selected and attractively arranged, and The Institution was greatly indebted to the Authors.

Of the others who had been closely engaged in the work, and whose names were given at the end of the Paper, he would like to mention particularly Mr. Nolans, the Resident Engineer, Mr. Allin, Mr. Peter Lind, and Mr. Prior. He congratulated all of them on the way in which they had set about the work and faced the difficulties that had arisen.

The principal differences between the old bridge and the new one were that the latter had almost twice the surface area, in plan, of the former, yet its weight was only about three-quarters that of the old structure. It was supported, so far as the river portion was concerned, on only four bearing walls, each of which was only 2 feet 3 inches in thickness, whereas the old bridge had been supported on eight piers, each 20 feet thick. He thought there were some advantages in making use of the services of consulting engineers, because the bearing walls might not have been 2 feet 3 inches without them. Provision had been made, as stated in the Paper, for preventing the damage which might occur to such a slender bearing wall from river shipping. That damage might be greater than had been anticipated, and perhaps the addition of an inch or two more to the width would have had a stiffening effect. That would not have been a parti-

cularly good feature, and it would have increased the size of the foundation slightly, but it would have helped in the case of any possible future enemy damage from particularly heavy bombs.

A point which he thought was worthy of notice arose in connexion with *Fig. 24*. In the upper central portion of that figure appeared what he used to call the floor joists, but which could be called the cross girders. Strange to say, of all the work shown in that picture they had been constructed first and they had been constructed in position. That would give an indication of the difficulties experienced in undertaking any large engineering work in the centre of London, where there was not the area or the yard-space that was required by a contractor. On one occasion when the London County Council were dealing with the repair of enemy damage in Charing Cross Road and the Royal Engineers were called in, they were asked, as usual, what they required, and in one of his first reports a member of that Corps said: "A large central depot required." Where could that then be found in the centre of London?

The rubber block paving referred to on p. 166, *ante*, might have been quite suitable, but he thought it was only fair to say, in addition to the Authors' statement, that besides being considered too experimental, it was also rather more costly, and it had not been adopted for those two reasons. One of its most useful properties was that it deadened the noise of traffic, but in the case of Waterloo bridge most of that advantage would have been dissipated, owing to the absence of buildings on either side of the roadway.

The material used for the carriageway of Waterloo bridge was the same as that used on Wandsworth bridge, but there a public utility service had, after the bridge was completed, been threaded through under the deck. That would not be the case on the new Waterloo bridge, because ducts had been provided under the footpath. Wandsworth bridge had been opened since the war started, but the new provision was required on account of war-time conditions which could not have been foreseen by the public utility undertakers.

It would be recollected that the failure of the old Waterloo bridge was due to a settlement of pier No. 5 of just over 2 feet 4 inches, by 1924. Pier No. 3 of the new bridge was in close proximity to that pier: the settlements at pier No. 3 were shown in the bottom left-hand corner of *Figs. 22, Plate 7*. He had plotted the latest settlements on each of the diagrams in that figure, and he was glad to say that in the case of pier No. 3, which was so near a severe settlement on the old bridge, the latest figure, given for the end of March 1943, was $3\frac{7}{32}$ inches, which was only $\frac{5}{16}$ -inch more than the estimated settlement; and from that figure of $3\frac{7}{32}$ inches there had to be deducted the figure for swelling shown on the extreme left of the diagrams, which, in the case of pier No. 3, was $1\frac{1}{8}$ inch. He thought that that degree of settlement showed the stability of the construction, and it accorded with the settlement noted at about the same time after the opening of

Wandsworth bridge, after traffic had been running for three or four months, and he believed also with the settlement at Chelsea bridge.

With regard to Appendix IV, he thought that, as the contract had not been quite completed, the heading should have been "Tender Price, 1937" instead of "Cost."

In conclusion, there was one important subject which he felt he ought to mention. About ten years ago a Sub-Committee, consisting of three members of The Institution, was appointed to consider the improvement of the old Waterloo bridge. As he was the only remaining member of that Sub-Committee, he felt sure that if the gentlemen who had submitted tenders and schemes for the reconditioning of the old bridge had seen the difficult conditions which existed under its piers they would have agreed that the London County Council had done the correct thing in bringing the new bridge into being.

Mr. Peter Lind observed that he wished to thank the President for inviting him to attend the meeting, and to congratulate the Authors on their very well prepared Paper. He also wished to express his thanks for the gracious compliment made to his firm and his staff by Sir Peirson Frank.

He admired the courageous way in which the engineers had embodied so many innovations in their design. They had certainly succeeded in creating the most up-to-date reinforced-concrete job in Great Britain. He would like to pay a special tribute to the engineers for the thoroughness with which they had carried out tests before adopting the innovations, and for the highly scientific manner in which all stresses and strains in the structure had been taken care of in the detailed designs. He did not think that an ounce of concrete or steel had been put in which could not be held to serve a useful purpose.

He thought that the best contribution he could make to the discussion was to state frankly some of the problems that the Contractors had had to face in carrying out the work.

The first problem they had encountered was the swelling of the clay inside the first cofferdam while the steel reinforcement for the foundation slab was being welded to the steel sheet piles. He wished to thank Dr. Faber for the very ready and sound advice which he had freely given to the Contractors during the execution of the work.

The next problem had been to make the special box foundation transmitting the load from the bearing pier walls on to the 6-foot thick foundation slabs. That was illustrated in *Fig. 6 (a)*, which showed the steel reinforcement going down into the 6-foot raft. It was a very difficult job to suspend that reinforcement accurately in mid air before the slab was concreted, and he wondered whether the engineers could not have thought out a simpler method of transmitting the load. He also wondered whether it was really necessary to round off all internal angles inside the box, where a slab met a girder, instead of using straight splays.

When the Contractors started on the superstructure they found that the engineers expected them to build both the top and the underside of the reinforced-concrete deck slab to the same drainage slopes and contours as the finished road surfaces and foot pavements. He believed that arrangement had saved 2-3 per cent. in weight, which, of course, was important, in avoiding mass concrete laid to falls on top of the reinforced-concrete work, but it had added considerably to the cost of the shuttering work.

He considered that the welding was a very useful and interesting innovation, whilst another was the vibration of the concrete while depositing it in the formwork. By vibration and by using a small slump it was possible to obtain concrete of the highest possible crushing strength; whilst in many cases concrete could not have been made to flow round the steel reinforcement without vibration.

Vibration of concrete had many good points, but he felt that attention should also be drawn to the risks entailed and that engineers should not specify vibration for the whole of a job indiscriminately. It should be borne in mind that vibration caused concrete to flow to a practically level surface and considerably increased its pressure against the formwork, which therefore had to be made considerably stronger, whilst the heavier it was the greater the power required for the vibrator in order to give efficient vibration. It was not an easy matter to decide how to construct the formwork and how and where the vibrators should be fixed to the shutters. Furthermore, to make construction joints grout-proof when the concrete was vibrated called for very special attention. In a vertical joint of a wall holes in the stop-end shutter had to be drilled to fit the bars very accurately.

The Contractors had also found that it was necessary to use top shuttering to the vault slabs, although they appeared very flat, and it had been very difficult to make top shuttering for the construction joints between the vault slabs and ribs A, B, and C indicated on Fig. 9, Plate 5. In fact, a special method had had to be devised, using small pieces of wood with sponge rubber nailed on, which could be squeezed tightly round all the steel bars sticking out of the joint and fastened to the starting shutters for the walls.

When vibration was adopted it was necessary to use concrete with a small slump, but he considered that it might be very dangerous to insist on too low a slump. In any case concrete with a 1-inch slump was very difficult to discharge from a concrete mixer, and if it had to be transported 1,000 feet or more before being put into the forms it would settle so tightly in the skips that great difficulty would be experienced in discharging it.

Other problems arose in concreting the "Z"-pours indicated on the cross-section of Plate 5. Those were the inner girders carrying the cross-girders. The engineers had asked the Contractors to concrete a section of the vault slab and to carry on immediately with the girder, and thereafter with part of the deck slab, all without interruption. That made the shuttering work very awkward, and the difficulties were increased by the

fact that the vault slab was arched and it was necessary to provide top shuttering to it as the concreting proceeded. He would like to express the hope that engineers in future would not find it essential to specify "Z"-pours.

The fixing of each stone facing block to the outer girders, as illustrated in *Fig. 18*, by means of four bolts taken right through the girder, was very difficult, on account of the many reinforcing bars in the girder which had to be avoided, and he wondered whether it was really necessary to fix the stones so securely.

The expansion joints were certainly very ingenious, but the construction was not quite so simple as *Fig. 13*, *Plate 6*, would suggest at first glance. It was the considered opinion of the Contractors that all such joints to be built into reinforced-concrete work should be provided with means of adjustment.

The work in connexion with the jacking operations was carried out quite smoothly, but it required very considerable planning beforehand. Of course, it facilitated considerably the decentering of the superstructure.

Last, but not least, his staff had had to invent a new type of extracting gear mounted on a large pontoon in order to enable them to withdraw all the 1,200 odd timber piles which they had driven 25–35 feet into the river-bed for carrying the formwork for the concrete. About 1,000 piles had been drawn successfully so far, and the last two rows of piles close to the pier bases were now being dealt with in such a way as to avoid reducing the valuable skin friction between the steel sheet-piles protecting the pier bases and the surrounding clay. It would be remembered from the description that the steel reinforcements in the foundation slab were welded on to the steel sheet-piles, and that the steel piles therefore helped to carry the load of the bridge.

Having mentioned some of the Contractors' difficulties, he would like to mention one operation which it was thought at the outset would be difficult, but had proved in reality very easy, namely, cutting off the steel sheet-piles in the cofferdams at level –23 feet, which was 8–16 feet below the river-bed. A great deal of difficulty had been anticipated from water squirting in if attempts were made to cut the piles from the inside; but the Contractors had found, to their delight, that, although they had to cut under 20–40 feet head of water-pressure, as there was clay outside the steel piles at level –23 feet, the water-pressure squeezed the clay through the gap made by the cutting plant and practically sealed the gap, so that very little water came through. Therefore the total cost of cutting off all the sheet-piles in each cofferdam was very small, whereas if water-bearing ballast had been present at level –23 feet it might have been found necessary to employ divers and under-water cutting plant from the inside of the cofferdam.

His staff and he were naturally very proud of having surmounted all the difficulties, in spite of war conditions. They hoped that the bridge

would be a source of pride to Londoners for centuries to come, and that its unique design would be admired at least as much as that of the old bridge.

Sir Giles Gilbert Scott, R.A., expressed his appreciation of the Paper ; he could not understand all of it, because the very technical engineering language was beyond him, but he thought that the Authors had given an extremely interesting description of the construction of the bridge.

He would confine himself to one aspect of the work which he thought concerned not only the structure in question but also many other civil engineering structures, namely, the collaboration of architects and engineers. There seemed to be a growing public demand for greater beauty of line and form in all structures, even of the most prosaic nature erected for purely practical purposes. It was interesting to notice that more attention was devoted to line and form in Telford's time, in the earlier period of what might be called the modern civil engineering age than later. He did not know why that was so ; he would have thought that the reverse would be the case. Attention to line and form, however, had now spread from civil engineering to mechanical engineering. Engineers now designed motor cars with a keen eye for line, and that was also the case with aeroplanes and ships. He remembered some years ago, before the war, remarking to a naval architect that he thought some of the German liners, such as the "Bremen", had extraordinarily beautiful lines, much more beautiful than those of British vessels, and asking why that was the case. The reply was that German engineers relied more on the eye than did British naval architects. After functional conditions and requirements had been satisfied a margin of latitude always remained where the eye could come in. The British naval architects were satisfied with fulfilling the practical requirements, whereas the Germans used their eye to improve the line and appearance of the ship.

He thought that clean simple solutions not only provided greater beauty but also were usually more efficient than untidy and complicated solutions. He had not time to discuss the question of whether the complete solution of functional requirements automatically gave a fine-looking result, but he would say that the experience of the industrial age, during the Victorian era, when factories and other industrial buildings were erected without any consideration at all being given to their appearance, showed that that resulted in such complete ugliness that he doubted whether pure functionalism and mere consideration of practical requirements gave a beautiful result. He thought it was necessary to have a conscious striving for the simple solution.

In view of the very happy collaboration of the engineers and himself in the building of the new Waterloo bridge, he would give a brief outline of the procedure adopted there. The collaboration started at the very beginning, and not after the main lines of the engineering solution had been settled. Too often architects had been called in to provide what were called the trimmings. Modern architects did not use trimmings, but they tried to

obtain effects with proportion, shape, and arrangement of parts ; those, of course, were matters of primary importance—much more important than trimmings. Therefore, early collaboration between architects and engineers was essential.

In the case of the new Waterloo bridge, the first thing which had had to be decided was the type of bridge to cross the river at that point. Mr. Buckton had shown slides of the engineers' drawing and the architect's drawing, but he had not gone back far enough, as the collaboration had begun long before those drawings were made. The first design was of a more monumental structure, with pylons at the entrances at both ends, and it was much more of an architectural solution ; but even before that design was produced it had been necessary to decide upon the type of bridge to be erected. Mr. Buckton had shown him a sheet containing a large number of possible solutions for carrying the road traffic and satisfying the navigation requirements. Those were the primary practical objectives, and they could be met by about twenty types of bridges. Therefore, it was necessary to decide which type was the most suitable. He had felt strongly that the constructional elements of the bridge should be below the road-level, owing to the view down the river, with St. Paul's in the background, and the general character of London and its bridges. It had seemed to him that anything in the shape of a suspension bridge or a bowstring bridge, or any type of bridge with a large quantity of superstructure, would be unsuitable for the position in question. It was also necessary to consider the question of the navigational headroom. A good height had to be provided for large barges, so that not much room was available for constructional work underneath the roadway, and that factor influenced the selection of the design and type. The positioning of the piers was dictated largely by the position of the navigation channel, which was a comparatively narrow part of the river ; and another consideration which had to be borne in mind was the relation of the appearance of the bridge to that of the adjoining buildings. All those considerations led to the adoption of the type which had been so interestingly described in the Paper.

The great width of roadway would naturally give a very tunnel-like and heavy effect to a bridge of the kind in question, and the treatment of the soffit became an important one. The double arch with a flat soffit in between enabled a good view to be obtained right through the bridge from the north embankment to the south ; and as the embankment road ran under the bridge it was very important that the soffit appearance should be interesting and attractive.

With regard to the surface treatment of the bridge, the stone facing had been adopted because concrete was a very difficult material to render satisfactory in appearance. In his opinion, the only way to make it tolerable was to chisel off the skin of cement and expose the aggregate. In the case of Waterloo bridge there were certain practical difficulties in doing that, and it was not possible except on the rim of the arch. The main

surfaces of the concrete could not be treated in that way, owing to the vibration damaging the surface of the concrete, so that moisture could enter and injure the steelwork. Moreover, all the buildings in the neighbourhood were of Portland stone. Therefore, it was decided that the facing of the spandrels should be of Portland stone, which would weather in the same way as the neighbouring buildings and blend with them.

In conclusion, he would like to express to Mr. Buckton and to the members of his staff and all others with whom he had been privileged to work on that interesting job his appreciation of their helpful and sympathetic attitude towards his suggestions and proposals. It had made their collaboration smooth working and easy, and he had derived a great deal of pleasure from that collaboration.

Dr. Oscar Faber considered that not only had the London County Council been very fortunate in their consulting engineers, but also the consulting engineers had been very fortunate in their contractors; and all had been very fortunate in the architect who had collaborated with them in producing what was an extremely beautiful bridge. He had been very pleased to hear the gracious remarks which Sir Peirson Frank had made about the Contractors, because there could be no doubt that the Contractors had carried out an extremely difficult job, and had done it extremely well.

He proposed to refer only to a few technical points which arose on the Paper. If he disagreed very slightly with the consulting engineers on some features, he was sure they would realize that he was in agreement with them to the extent of 99 per cent., and if his observations appeared to be "disagreeing remarks", it was only because he had selected those points, and had not indicated the many matters with which he was in entire agreement.

With regard to the rising of the clay in pier 4, which amounted altogether to about 3 inches, the explanation given in the Paper was that the rise of the clay was due to water getting into fissures loosened by pile-driving; and he believed that the pile-driving referred to related to the temporary timber piles used for carrying the arches rather than to the sheet-piling. Those timber piles were at a considerable distance, of the order of 50 feet, away. In his view, there was another explanation, which he believed was the right one. On the outside of the cofferdam there was at high tide about 20 feet of water and 37 feet of ballast and clay, which represented at the bottom of the cofferdam a pressure of about $2\frac{1}{2}$ tons per square foot. On the inside of the cofferdam, when the excavation was nearly completed, there was about 10 feet of sand, representing a weight of about 0.5 ton per square foot. Accordingly there was a difference of pressure there of roughly 2 tons per square foot. The cofferdams consisted of steel sheet-piling and projected down a considerable distance below the level at which the bottom frame of struts could, in the nature of things, be put in; and in fact that bottom frame of struts was approximately 16 feet from the bottom of the sheet-piling and there was about 10 feet of clay below the

bottom excavation, so that on that lower 16 feet of sheet-piles they were overhanging as cantilevers, with a difference in pressure of about 2 tons per square foot for the whole of the 16 feet. In his opinion those sheet-piles bent in at the bottom under that cantilever 16 feet long, with a difference in pressure of 2 tons per square foot between the inside and outside, and squeezed the clay on the inside, and therefore it rose inside the cofferdam.

He was strengthened in his view that that was the real explanation by the following fact. There was a difference in procedure between pier 4, where the rise was 3 inches, and the other piers, where it was only about 1 inch. In the case of pier 4, the excavation had proceeded right down to the bottom level over a very large area, and then 3 inches of concrete was placed to seal the surface; the reinforcements were then placed in position, and the concreting followed. All those operations took a considerable time, during all of which the clay was rising. In the case of the other piers, the work was done differently. A certain level having been reached, the clay was excavated in strips across the cofferdam, and in a strip an 18-inch concrete slab was then cast which acted as a strut between the two sides of the cofferdam and prevented the cofferdam from moving in under that cantilever action; and in all the cases where that procedure was adopted, the rise was only about 1 inch, instead of about 3 inches.

It might be of interest to mention that in the original contract drawings the sheet-piles were shown as going down only 6 feet below the base of the foundation, but the contractors, at his suggestion, had asked to have that increased to 10 feet, to which the engineers had kindly assented. That was done because he had already given consideration to the effects of that differential pressure, and had come to the conclusion that with only 6 feet they would be reaching a condition where a considerable rise in the clay might be expected—and indeed a condition where the factor of safety inside the cofferdams might be inadequate. There could be no doubt that in foundations of the kind in question there was a very definite time element and that everything depended on speed; and when the excavation reached the bottom the foundation was stable only if it was followed up with concreting within a few days. It would not be stable if left indefinitely in that condition.

Another matter of very great interest in connexion with the bridge was the very extensive use of welding. It might be of interest to mention that there were in the work 54,000 butt welds, 222,000 junction welds, 100,000 spreader link welds, and 1,110,000 spot welds in places where bars crossed—a total of 1,486,000. He did not think that there could be the slightest doubt that that use of welding had made it possible to overcome some intricate problems, which it would have been very difficult to solve otherwise. Having said that, he would like to add, with great respect and humility, that he thought that some of those welds could have been omitted, and that at some places other and cheaper methods could have been adopted.

The welding had also introduced considerable difficulties, apart from the many difficulties which it solved. One difficulty was that with bars practically continuous and 600 feet in length, rises and falls of temperature caused the rods, which were fixed at both ends by welding, to buckle, and arrangements had to be made to free them in that respect before they were concreted in ; and in fact it had been necessary to leave a concreting gap to deal with that difficulty.

He would like to compliment the Authors on the degree to which the bridge, although of reinforced concrete, was free from cracks. The Authors had stated that it was entirely free, but he thought that that must be a slight misunderstanding, because he had seen some very fine cracks, which had been marked with a red pencil—possibly by the engineers' inspectors. That was only to be expected, and he did not think that they were in any way detrimental to the structure. But in the interests of strict accuracy it should be mentioned that there were in fact some extremely fine hair cracks¹. He believed that the great freedom from cracking which had been obtained was due principally to the care with which the structure had been cured, first of all by the use of low stresses, and secondly by the use of extremely careful curing methods. The Authors had suggested that it was also due to the welding ; but he did not think that the welding had had any effect on the crack control.

With regard to the design generally, reference to *Fig. 24* would show that the longitudinal strength lay on the two sides of the bridge, partly under the pavements, which were, of course, relatively lightly loaded, and that the weight over the centre of the road had to be transmitted to those side girders by cross-beams. That form of construction, which he understood was imposed from aesthetic considerations, must have added a great deal to the difficulties of the engineers, and to the cost of the bridge. Instead of the weight being dealt with directly where it occurred, it had to be carried by the cross-girders on to the big box beams at the sides, which were thereby subjected to torsion and very considerable additional stresses. In fact the weight was concentrated on two widths of 25 feet where a total width of 80 feet was available. That had produced very heavy concentration of reinforcement, and he thought had also imposed the necessity of welding, because it had forced the engineers to adopt reinforcement of the order of 2-inch rods at $4\frac{1}{8}$ -inch centres, which was, of course, extremely heavy reinforcement, very difficult to fix, and which could be jointed only by the butt-welding which was actually adopted.

In his view the bridge was an excellent one from every point of view, architecturally and scientifically, and it was sound engineering. He wished to thank the Authors, the architect, and the Contractors for the excellent work which they had added to London and its beauties.

¹ Since the discussion Dr. Faber has stated that he has examined the cracks again, this time with Mr. Buckton. He agrees that they are no more than "fine hair cracks"—the term used by him in the discussion.—SEC. INST. C.E.

Mr. R. V. Allin described a new device for automatically registering settlement as and when it occurred, which had been improvised on the job, and had produced results which were extremely helpful (*Figs. 26*). It would be recalled that 6-inch borings were carried down under all the piers and abutments for the purposes of soil analysis, and advantage was taken of those borings to instal datums. On the completion of each boring, a 2-inch sleeve-pipe was lowered and centralized inside the boring, and was driven a few inches into the clay. Inside this again a $1\frac{1}{4}$ -inch pipe was lowered with a shoe attached, and driven until its resistance to further penetration ensured that no settlement would occur under its own weight. The space between the outside of the sleeve-pipe and the inside of the boring was filled with cement mortar or sand: the latter was found to be the better material. The sleeve-pipe was then cut off at the level of the foundation and carried on again with an enlargement attached to it deep enough to allow of the full estimated settlement of the pier. That enlargement entered the annular space which was filled with crepe rubber. Thus settlement did not impose any weight on the mortar which might in time vitiate the results by pressing down the datum. Both the sleeve-pipe and the datum were carried up and finally housed in compartments over the pier.

It was obvious that the settlement of the pier consisted of the differential movement between the sleeve-pipe, which was concreted into the foundation, and the datum. That called for an indicator, and a "Capstan" dial was fixed which recorded the settlement of the foundation. Very careful checks with precision instruments were made during the full settlement of $4\frac{1}{4}$ inches of that foundation and no observable error was found. Readings were obtained to an accuracy of one or two thousandths of an inch.

As the de-centering operations imposed about 6,000 tons extra weight on the piers, an excellent opportunity was afforded to obtain load/settlement relationships. The chief points of interest were what was known as the "immediate" settlement and the settlement of consolidation. The "immediate" settlement was chiefly due to the reduction of the swelling of 3 inches which had been referred to in the Paper. The settlement due to consolidation which succeeded it was, of course, that due to the pressing out of the water from the clay, and would continue for many years at an ever-decreasing rate.

With regard to the diagram of the observations at point "B" (see Plate No. 7), about 6,000 tons came on the foundation fairly rapidly, owing to the jacking, and in the first $3\frac{1}{2}$ months it settled about $1\frac{1}{2}$ inch. Then a bomb was dropped a little up-stream of it, and the pier settled about 0.016 inch. Whilst that was of no practical importance, it rather fortified the theory of the effect of fissures underneath the foundation; he could not otherwise conceive of a fairly elastic soil such as clay jumping down and staying down, as it were, under quite a slight vibration. Then

two separate 1,000-ton loads were put on, in order to gain some idea of the effect of the road surfacing, which had yet to be put on. The first loading showed greater effects than the second, and the recovery when the water ballast was taken away was very striking. There appeared to be almost no recovery when it was taken off at the end of the second period of loading, and that permitted the engineers to assume that the bridge under its full load had practically taken up all its "immediate" settlement. When that load was actually put on, no appreciable increase in the rate of settlement occurred.

Another interesting feature was the effect of pile-drawing. Obviously there was a slight lag between drawing the piles and a slightly higher rate of settlement. The effect was clearly due to the fact that the holes left by pulling out the piles, of 24-foot penetration, drew the clay away from the sheet-piling and reduced the skin frictional resistance which contributed in some measure to the resistance of the foundation to load. That was purely temporary, and even now showed signs of ceasing.

A satisfactory relationship was found between the estimated slope of settlement and the actual settlement due to consolidation.

The general inference to be drawn from what had occurred was the importance of dealing with the rise of the clay, and curtailing it as much as possible, especially where it was fissured and possibly compressed by piling, because the settlement would depend very largely upon its rise during excavation.

Mr. P. R. Alderman congratulated the Authors upon their masterly selection and condensation of the mass of interesting material available as a result of the construction of the bridge.

Ten years ago, such an extensive use of welding in connexion with a bridge of that nature would have been regarded with considerable suspicion. It was a tribute to the advance which had been made in welding technique that such an important design should contain such novel and ingenious features involving extensive welding with complete confidence in the ultimate result. Reference had been made to the reasons which governed the application of welding to the main bars, and he agreed entirely with the reasons adduced by the Authors. Dr. Faber had referred to the problems which arose from about 600 feet of continuous steel bar restrained at intervals of about 250 feet at the piers. As a result of that experience it was hoped that it would be possible to make provision for laps in the reinforcement at reasonable intervals and at points of minimum stress in the structure if similar problems arose in a design in the future.

With regard to the secondary welds, there could be no doubt that the use of welding had resulted in a clean and workmanlike appearance of the reinforcement; but resistance to displacement was not an unmixed blessing and when welding was applied to reinforced concrete each weld should be considered on its merits. The opinion of his firm was that the wholesale application of welding might not result in ultimate economy.

From *Figs. 17* it would be observed that special shapes were required for the ends of bars which were to be welded, unless the "Secrom" method were used: but the apparently simple job which was obtained with the "Secrom" weld was vitiated to some extent by the necessity for cleaning off the very irregular cropped ends of bars received from the rolling-mills. Approximately 60 per cent. of the bars used for "Secrom" welding had to be oxy-acetylene cut square. It was a question for the future whether bars should be ordered to exact length, cut by cold sawing at the mills.

It should not be assumed that the wiring up and fixing costs of steel would be reduced by welding. Often the wire ties were cut by the welder at the first striking of the arc, and the spring of the bars forced them away from contact. It was necessary to restore that contact to obtain a proper weld, which required stand-by labour for that purpose, thus adding to the cost.

A further complication was that the welding trade was interposed between the steel-fixing trade and the concreting trade. When there were (as would be seen by reference to *Fig. 9, Plate 5*) three layers of main bars and four layers of transverse bars, it was necessary to have as many as ten alternating steel-fixing and welding operations before getting down to the concreting. Good access must be given to the welders, as a first essential in obtaining good welds.

It was found that welders would not collect the waste ends of electrodes, so that somebody had to find those electrode ends later on, under a mass of welded up reinforcement. He had already mentioned the cut wire ties; they dropped down into most inaccessible positions on the shutters, and it had sometimes been necessary to use magnets to remove them. Moreover, in the case of the vault slab a very highly finished surface was required, and accordingly the shutters were provided with a polished lining. Unfortunately, weld splash and burning occurred, with unhappy results to the shutter lining and the finish of the concrete.

The rays from the arc could be very damaging to the eyes, and it was well to remember that other tradesmen could not work in close proximity to welders without risk of suffering from "arc eye", which was very painful and disabling.

Very thorough and painstaking inspection of the welding was required, and that could not be obtained without cost.

For horizontal work, spreader-links or spacer-bars welded in were very advantageous and gave a rigid support for the upper layers of steel, but shutters had to be erected to vertical steelwork after it had been welded. Commercial bars were not straight, and, however carefully the steel might be set out and fixed, any slight error in the straightness of the bar would be perpetuated by welding, so that in fixing the shutters, the carpenters had rather a heart-breaking struggle to obtain correct line and cover. There was no "give" in the reinforcement, and the shutters tried to come up hard against a solid, inflexible cage. In many cases it had been neces-

sary to break the welds, make the necessary local correction, re-weld, and then fix the shutters.

He considered that the contractor should have complete control of welding on the site, in order to eliminate sources of delay and consequent increase in cost. It was a question whether contractors should not have their own welding organization, if welding were to be used more generally in reinforced concrete in the future.

The problem of cleaning out the debris remaining after welding needed very careful consideration when the shape of sections for concreting was considered, as an undue complication of shape would inevitably cause more trouble in cleaning out. When it was necessary to clean out in a deep and complicated section, traps had to be formed in the shutters, and, if the concrete were vibrated, the possibility arose of leakage at such traps.

Mr. L. F. Cooling congratulated the Authors and their engineers on the exceptional value of the settlement records which had been taken. He knew of very few published records in engineering literature which could compare in accuracy and completeness with those summarized in Figs. 22, Plate 7; the actual observations were really better than was indicated in those diagrams. By starting observations at an early stage in the excavation, and by taking accurate measurements during construction and after completion of the bridge, a very complete history of the movements had been obtained. Such complete records were not only of value in themselves, as forming a permanent contribution to foundation engineering, but also were essential for the development and progress of knowledge of soil mechanics. At present it was necessary to rely entirely upon comparisons between theoretical estimates of settlement and actual observations on structures to test the degree of reliability of existing theories. As the subject developed, it should be expected that those theories would be modified and altered; but comparison with practice would still be necessary, and records of careful field observations such as those quoted would always supply a valuable background for progress.

In the problem under consideration, in carrying out the theoretical analysis it was found necessary, owing to the very complicated conditions, to adopt a number of simplifying assumptions; nevertheless, the degree of agreement between the calculated and observed values shown in *Figs. 22* might be regarded as encouraging. However, as stated in Appendix II, a truer check on theory would be possible after 5 or 10 years, since by then the consolidation settlements would have become relatively more important. For that reason, he hoped that the observations which had been begun so well would be continued for the necessary period, so as to enable those comparisons to be made.

The rise of clay in the cofferdams during excavation, and the pronounced influence of that effect on the subsequent settlement, had been mentioned both by the Authors and in the discussion. Without going into that point in detail, he thought that it was well worth emphasizing that in

dealing with stiff fissured clays such as London clay, rise during excavation was likely to be important in very many problems, and the only way in which reliable information on the question could be collected was by taking field observations such as those described in the Paper. He considered that such records should be made whenever it was possible to do so.

* * **Mr. H. E. Steinberg** observed that the bridge was undoubtedly an elegant solution of a difficult problem, but so far as the structural design was concerned the outstanding features were the complexity of some of the details and the prodigious use of welding. The bridge bore several points of similarity to the George V bridge, Glasgow, which formed the subject of a Paper read before The Institution by Mr. Thomas Somers, M. Inst. C.E., in 1929¹. Both bridges consisted of continuous beams having curved soffits, and in addition to the usual provisions for expansion and contraction precautions were taken to offset the objections to continuous beams where unequal settlement of the piers would engender large bending moments.

In Mr. Somers' Paper a comprehensive statement was made of quantities of materials, and if similar information could be given in respect of Waterloo bridge it would enable a useful comparison to be made between the two structures.

The cost of the concrete in the superstructure had been given as £27,500, but the cost of the reinforcement, together with the welding, kentledge, etc., amounted to £164,000. That seemed a very large sum in proportion to the concrete.

The use of welding as a means of holding essential bars in correct position was, of course, justifiable, but Mr. Steinberg considered that there were objections to welding the ends of the longitudinal bars, and as an indication of the differences of opinion which existed between engineers, it might be useful to state that in the George V bridge, in order to avoid buckling, a gap of 3 inches was specified between the ends of all longitudinal bars. Those gaps were carefully staggered so that by the addition of a few extra lines of reinforcement it was possible to maintain the requisite sectional area of steel at all points. He considered that was a simpler and more practical solution.

The welding of the stirrups to the longitudinal bars, top and bottom, would prevent the natural shrinkage of the concrete in hardening and obstruct the usual accommodation for slip and creep.

The Authors had asserted that by their methods cracks had been prevented. Mr. Steinberg thought the bridge would have to be in use for some years before such a claim could be substantiated, and that given good design of the details of reinforcement, other less elaborate and less costly methods would have been equally successful.

He found it rather difficult to understand the principles underlying the arrangements for expansion and contraction.

* * This contribution was submitted in writing.—SEC. INST. C.E.

¹ Min. Proc. Inst. C.E. vol. 227 (Session 1928-29, part I), p. 155.

It had been stated that piers Nos. 1 and 4 were to be regarded as fixed points, and only a nominal clearance of $\frac{1}{8}$ inch was provided between the flexible wall and the rigid enclosures to the piers. The other fixed point was obviously at the centre of the suspended span, at each end of which accommodation was provided for $\frac{3}{4}$ inch of movement. That $\frac{3}{4}$ inch had, therefore, to serve for the expansion of a length of 379 feet—the distance from either pier No. 1 or pier No. 4 to the centre-line of the bridge.

That accommodation seemed to be on the small side and if the expansion exceeded $\frac{3}{4}$ inch in that length, then pier No. 4 would bend, and would not remain rigid, as stated in the Paper, and the outer shell to the piers would then be subject to an overturning moment.

In any case, the clearances did not seem in accord with the statement that 6 inches of movement (3 inches at each end) had been provided for. It was appreciated that that estimate had been based upon a temperature-variation of 60 degrees, which would never be realized, and Mr. Steinberg had no doubt that the Authors could furnish a simple explanation of that apparent anomaly.

He wished to express his pleasure that reinforced concrete had been adopted for London's latest and most important bridge, and to thank the Authors for placing such full details of their work before The Institution.

Mr. E. J. Buckton, in reply, thanked Sir Peirson Frank and other speakers for their very kind remarks. He was not altogether in agreement with Sir Peirson's views on rubber block paving, because it was only fair to compare like with like, and recent developments of rubber, with its non-skid surface, provided a first-class material. Although asphaltic paving and roads had given excellent results, there was really no comparison between the surface of such a block as the rubber block and the ordinary asphalt road. He did not think cost should be decisive, because it was not a matter of comparing like with like.

The building of a bridge to the slopes of the road surface was not unusual; when dealing with a high-grade structure of the kind in question, one would want to build it to the surface slopes that were required, and that was, of course, clearly indicated on the contract drawings.

Vibration of concrete was a good servant, but a bad master. The facing stone slabs were fixed as shown at the request of the Contractor. The original design had provided for dowels in the stone, building the stone wall up and using it as a shutter, and then concreting behind. That had the difficulty that it had to be kept very true and that a considerable weight had to be supported, and the contractor had therefore preferred to shutter the concrete and add the stone afterwards. That was agreed to, and he thought that the result was quite satisfactory. When listening to Mr. Lind's balance-sheet he was glad to find that there was one item on the credit side, namely, the cutting of the steel piles. There had been innovations in the job as a whole, and of course they had meant trouble for both engineers and the contractors.

Sir Giles Gilbert Scott had referred to the bridge being functional. There was a difference between utility and function, and one of the characteristics of a functional structure should be that it was "eyeable", whereas the utility structure might be really hideous. Sir Giles had referred to the monumental design including the twin girders which were copied in the engineer's sketch. In a drawing prepared by Sir Giles for a six-line Waterloo bridge, and adopted by the L.C.C. in February 1932, the bridge consisted of five spans of elliptical arches, crossing the river between Victoria Embankment and an assumed future extension of the existing embankment on the Surrey side. In addition there were two flat spans, one on either side, to cross the embankments. The piers were of mass concrete and granite up to cutwater-level; above the outwaters, the bridge structure was to be of reinforced concrete with Portland stone surface treatment, the towers and parapets being of Portland stone. The design was for twin arches supporting the deck. Sir Giles had firmly insisted upon the twin arches. The engineers knew the trouble that meant to them, and the contractors had since found out the trouble entailed from their point of view. All kinds of suggestions were made to Sir Giles to see whether he would accept anything simpler and easier, but he had insisted upon twin arches: and Mr. Buckton was now certain that that was the right thing to do. Without the twin girders there would have been a bridge, but not the bridge which had, in fact, been provided.

As Sir Giles had pointed out, collaboration between Engineers and Architect was arranged from the start, which was all to the good. With regard to Sir Giles' comment that the Authors had not gone back far enough, the change over from the monumental to the functional design was as follows. At the time of the submission of the monumental design in 1932 the Engineers and the Architect seemed to be the only parties in agreement about Waterloo bridge. Outside controversy ran high and the hoped-for abatement, when the proposed design for the new bridge was published, did not occur. Time went on, tender drawings were in abeyance, and the prospects of agreement seemed remote. At last, as a further effort, the Engineers tried out a functional design.

The chief differences in that, as compared with the monumental design, were:—

- The siting of the piers—the first span jumping the Victoria Embankment.

- Girder-cantilever design instead of arches.

- Five equal segmental spans, instead of five graded elliptical spans with two special spans, one over the Victoria Embankment and the other over an assumed future south-side embankment.

- The elimination of massive construction on the edges of the embankments as abutments for the arches.

- Extreme slenderness, giving maximum openings to river traffic. No pylons.

Level bridge.

Continuous parapet.

Tram tunnel entrance sited centrally.

and the similarities were :—

Superstructure in form of twin “arches” with central strip of decking.

Reinforced-concrete construction.

Portland stone and granite surface-treatment.

As the functional design seemed to offer a possible solution the Engineers sought, with the concurrence of the London County Council, the collaboration of Sir Giles. The differences were accepted and improved upon by him, and the Highways Committee of the London County Council unanimously recommended for adoption the functional design when officially submitted.

Sir Peirson Frank had pointed out that the claims were not settled yet, but the Authors' view was that the Contractors had done a fine job ; they had attempted to produce a really good bridge, and had succeeded.

Dr. Faber had mentioned cracks in the bridge. There was none, or at least the Authors had not found any. Since the meeting the Authors had further examined the alleged cracks, portions of concrete had been cut out, the parts removed, and the in-situ concrete carefully examined by them and, at their invitation, by Dr. Faber. The cracks on the surface appeared no more than hair cracks and the cutting out of sections of the concrete showed that they extended inwards to a maximum depth of 1 inch, but mostly much less.

Mr. Alderman had made a most helpful contribution to the discussion, and had been able to give much information of value to those interested in carrying out such work, as he had been in close touch with the construction throughout. The matters such as control of welding, collecting electrode ends, protecting the shutter lining, and the effect of rays from the arc on other tradesmen, all gave the contractors trouble, but such troubles should grow less as high-grade reinforced-concrete work became more common.

The Building Research Station had been most helpful and there was little doubt that the Chief Engineer of the London County Council would continue the recording of observations of settlement, as suggested by Mr. Cooling.

In conclusion, he wished to thank the President and members for the reception they had given to the Paper. The cordial relationship which had prevailed between all those concerned with the bridge was appreciated by no one more than the engineers during the whole six years of its construction.

Mr. John Cuerel said that the twin girder construction, which had given Mr. Lind's firm trouble, had also caused the designers trouble. It

had necessitated the Z-pours, with the consequent difficulties during construction, and had led to a disposition of the main supporting members which was not ideally related to the loading. It had also required denser reinforcement and had considerably increased the amount of welding. He thought that it was all worth while. Obviously it was not the type of construction which an engineer would choose if entirely unfettered by other considerations than carrying a simple bridge across a river. The new bridge had to be a particularly specialized article to fulfil the functions set out in the Paper and to be worthy of its setting. He thought that the contractor had been fairly treated in the way that the original arrangements were revised for his convenience, and he did not think that the difficulties experienced were greater than might have been anticipated at the time of tendering.

With regard to cracks, the cause of some apparent ones was a slight crazing, probably only $\frac{1}{8}$ inch deep, resulting from bomb damage. Sand-blasting was carried out after that slight crazing had occurred, and the weakness at the craze permitted the sand-blasting to break down the edges, and except on very close examination there seemed to be a crack there. Those apparent cracks had, however, been tested not only visually but also by filling the space inside with water.

Sir Peirson Frank had suggested that a few more inches on the bearing walls might be desirable. Probably another 2 or 3 inches would not interfere with their function, but if the construction were to be made so robust as to be able to withstand impact from ships without suffering damage they would not do their primary job. Moreover, with any increase in width the flexural stresses would be increased and the direct stresses reduced, with the result that the tension set up by flexure would become greater than the compression caused by the direct load, and therefore there would be a tendency to cracking and to deterioration of the structure.

Dr. Faber had given his theory of the cause of the rise of clay in pier 4, but Mr. Cuerel did not think that it could be the correct one. Had the rise been due to the giving in of the sides of the cofferdam, it would not have disappeared so quickly. It must have been mainly caused by water between the laminations in the clay; otherwise many years would elapse before it was taken out by the action of the load. Had the clay to be consolidated, to lose 3 inches of swelling would have taken many years, whereas it had disappeared already.

Consideration of the volume of the swelling showed that it would have been necessary for a very definite narrowing of the cofferdam to take place had the rise inside been due to deflexion of the sheet piling. Taking a probable shape for the deflexion curve, the narrowing at formation-level would have amounted to some 6 inches, and, since two-thirds of the swelling took place after completion of the excavation, 4 inches of that narrowing would have occurred with the concrete mat in place and during the welding up of the reinforcement, with consequent bursting of the

concrete and buckling of the bars. There were no signs at all of such action, and no evidence of appreciable deflexion of the sheeting during or after bottoming up. The difference in the amount of swelling at the other piers, as compared with pier 4, was due to the greater waterproofing value of the 18-inch concrete mat and of the procedure adopted, combined with the absence of heavy pile-driving near the other piers during the carrying out of the foundation works.

Further, the values of the cohesion and the internal friction for the clay obtained by the Building Research Station were respectively $k=0.63$ ton per square foot and $\alpha=18$ degrees. Applying those values in Bell's equations, it would be seen that the active pressure of the outside clay was small, that the passive resistance of the first few feet below formation-level was adequate to take the reaction, and that a considerable factor of safety existed against upward movement of the inside clay at the toe of the sheet-piling. The contract drawings showed a penetration for the sheeting of 6 feet minimum below formation-level, thus leaving it open to the contractor to propose a precise value.

The suggestion had been variously made that some of the welding was superfluous. With one and a half million welds it might be possible to find one or two which should not be there; but generally speaking all the welds shown on the drawings and put in the work were considered necessary. As previously mentioned, the twin-girder type of construction had greatly increased the amount of welding; all such junction welds as typified by Fig. 16, Plate 6, were, for instance, imposed on that account. The "blob" or spot welds were provided mainly for the purpose of crack control, and inasmuch as shears in the deck and vault were increased by the twin form of the superstructure, some of those welds were also due to that cause. Blob welds, although they amounted to three-quarters of the total in number, represented only about one-fifth of the total cost of welding and the crack control afforded by their use was worth that sum. He could not agree that the freedom from cracking was due to low stresses and extremely careful curing. Stresses were normal, and there were frequent difficulties during the course of the work, which interfered with extended curing.

There had been references to expansion difficulties caused by the welding up of steel bars into lengths of about 600 feet. Certain difficulties were to be expected from the temperature effects, particularly with the sun shining on the bars. Dr. Faber had suggested that the concreting gaps were provided especially to overcome that trouble; that was not the case, though they had enabled a solution to be found.

Mr. Alderman had expressed the hope that in future lapping of the reinforcement at points of minimum stress would be adopted in lieu of welding throughout. That had been considered in the design, but a solution on those lines was undesirable in the particular case, since at and near the points of dead-load contraflexure there would be considerable reversals

of stress under the action of the live load, and the effect of that, through bond slip, would be to cause appreciable cracking. In view of the care taken generally to control cracking in the interests of the toughness and durability of the structure, it was thought worth while to carry the principles of the design to their logical conclusion and accept the additional difficulty involved.

Mr. Lind had referred to the connexion between the cellular base of the pier and the foundation-block. Bonding in of the pier base reinforcement was, of course, an essential engineering requirement. The approved method of temporarily supporting the steel involved the use of "stools" resting on the bottom steel of the foundation, so that it was perhaps hardly correct to describe the reinforcement as suspended in mid-air before the block was concreted.

The use of a cove instead of a straight splay at corners was decided on in some instances as giving a better stream-lining of the stresses. The gain, with a material like concrete, was not great; but since the additional cost was very small it was worth having.

The extent to which vibrating should be specified was given careful consideration. It was found that throughout the work there would be no major section in which vibrating could be dispensed with entirely, except the foundation-block, where it was not specified. In small parts of some sections the concrete could possibly have been compacted by hand; but the whole was required to be a monolith with the same properties as regards strength, modulus, shrinkage, and creep throughout. It was, therefore, most undesirable from the design point of view to vary the types of concrete, and, considering that hand compaction would generally have had to be used together with vibrating in the same pour, the practicability of a variation was doubtful.

The circumstances leading to the introduction of adjustment at the expansion joints were described in the Paper. The adjustment proved most useful in the correction of the effects of bombing. It was hoped that provision for similar war conditions would not be required in future.

Mr. Steinberg had rightly observed that the bridge was similar to the George V bridge at Glasgow in that it consisted of continuous beams having curved soffits; but the points of dissimilarity were perhaps more outstanding. In its foundations, the pier and abutment construction, the twin girder superstructure, the length and number of spans, the arrangements for the accommodation of expansion, and in its setting the new bridge differed radically. The flexibility of its construction was such that many inches relative settlement of the piers would not appreciably affect the bending moments, although it might be objectionable aesthetically.

A comparison of cost between concrete, excluding formwork, and an "omnibus" item including reinforcement, was apt to be misleading; but it should be realized that by taking advantage of welding, scantlings

would be reduced, and therefore the net cost of concrete would bear a smaller relation to the total for the reinforced work.

The use of virtual splice bars formed by extra lines of reinforcement was considered, but was rejected in favour of welding, for the reasons given in the Paper and mentioned previously in connexion with the possibility of using laps.

The control of strains due to shrinkage and creep and the elimination of slip by means of welding were definitely advantageous; the benefit by way of prevention of cracking would be permanent.

The allowance for total change of length and the corresponding range of temperature were correctly given in the Paper. The 6 inches of total variation was afforded by a movement of $1\frac{1}{2}$ inch at each of the four expansion joints— $\frac{3}{4}$ inch each way from the mean position. A range of temperature of 60° F. would produce, on the 379-foot length from pier 1 to the centre of the bridge, a movement of about $1\frac{5}{8}$ inches— $\frac{13}{16}$ inch each way, the slight excess being taken up in the nominal clearance at pier 1. It was necessary to provide sufficient clearance at the joints to allow for a bare-deck condition, that was, the road and footway surfacings not laid, and during the time that such a condition obtained the range of body temperature approached 60° F. and a total movement of $5\frac{1}{2}$ inches was actually recorded. Measurements taken subsequently indicated that even with the deck clothed by the surfacings the movements would not be substantially less.

Finally, he wished to thank the President and members for their reception of the Paper, and the various speakers for such a stimulating discussion.