Discussion.

Mr. Trench. Mr. E. F. C. Trench observed that the work described was of interest not only to engineers but also to the many millions who travelled by the tube railways in London. When he heard in 1913 that it was proposed to enlarge the tunnels without closing the railway, it appeared to him to be a work of almost insuperable difficulty. Like all works, however, it seemed much easier when accomplished than when contemplated in the first instance. The many difficulties that had been encountered had been admirably overcome. He was not entirely disinterested, because the extension of the Euston tube was practically under his office at Euston, and he knew that wet sand was likely to be encountered there. That portion had eventually been dealt with in compressed air, which, of course, necessitated the suspension of the train services. The enlargement had been no light undertaking. First an extremely ingenious shield had been designed to support the ground between the removal of the old tunnel and the construction of the new, through which a train could run. Between the running of the last train at night and the first train in the morning an immense amount of work had had to be accomplished. That work consisted in taking all material for a certain number of rings to all the different faces at which work was in progress, the removal of the permanent way, the preparation of grouting-apparatus and the compressed-air supply, excavation, the rebuilding of the composite lining, replacing the track, and leaving all in apple-pie order. Knowing the way in which an engineering job was usually run, and the untidy state it was in until the final clearing up, he imagined that it had been no easy task to leave everything in order for the running of the trains after each shift. Not content with enlarging the tube, the engineers had decided to improve the line and level, which had not in all cases been ideal in the original tunnels. He had no doubt that the necessity for great accuracy in driving had not been so fully appreciated when the railway was made as it was now. The trains fitted the tube so closely that there was very little chance of adjusting the track, any irregularity in driving the tunnel being reproduced in the track. There had been some rough places; between the Angel and Euston, for example, there was a spot where the train gave a jump. This was known to regular travellers as "Becher's Brook." All that had gone now, and the trains ran with admirable smoothness. It might seem that the operation of tunnel-enlargement was not likely to recur; that, however, was by no means certain, for with the growth of congestion of traffic on the tubes some of those present might live to see the day when all the tubes would have to be enlarged. Mr. Trench.

Mr. DAVID HAY remarked that when the Paper was presented to The Institution, the railway-company had not given permission for the costs to be published, but permission had since been obtained, and he would give figures for a few of the principal items of the work. He had got out figures per mile of double track, including sidings and crossovers, in order to make a comparison between the enlarged tunnel and the latest tube that had been made, namely, the Morden extension. The figures excluded such items as land, surface stations, lifts, escalators, staircases, and passages. The permanent way had been laid by the railway-company, and, except for the concrete road-bed, was also excluded. The cost of enlargement of the portion let by contract, where traffic was suspended, was £175,816. On the southern section, where traffic was kept running, the cost rose to £201,290. The average for the whole line was £192,096. Adding that to the cost of the original line, which was £145,000 per mile, the total came to £337,096 per mile. The cost of the Morden extension was £307,000 per mile, so that the enlarged line with lengthened stations had really cost £30,000 per mile more than the latest tube. The disparity between the figures would have been a great deal wider but for the fact that the original line had been driven before the war. He thought that the directors of the railway-company had shown great courage in undertaking such a work. It was not usual to give contractors' prices, but there would be no objection to giving details of the costs of the excavation, iron lining, and grouting, carried out by administration. In the enlargement of the tunnels by shields to 11 feet $8\frac{1}{4}$ inches, the average price of excavation at sixteen shields was 39*s*. 3*d*. per cubic yard. Erection of the iron lining cost 17*s*. 1*d*. per ton, and the materials £7 12*s*. 6*d*. per ton. The cost of labour and materials for grouting was 4*s*. 3*d*. per square yard. In the small hand-driven tunnels the average cost of excavation amounted to £3 17*s*. 7*d*. per cubic yard, which relatively high figure, he thought, was largely accounted for by the fact that there had been very little excavation in some places, and the cost of taking out the road and putting it back had largely increased the cost of excavation per cubic yard. The iron lining had cost £1 4*s*. 3*d*. per ton for erection and £7 12*s*. 6*d*. for material. The grouting (labour and materials) had cost 4*s*. 9*d*. per square yard. Excavation for the lengthening of the 21-foot station-tunnels and crossover roads came to £1 16*s*. 4*d*. per cubic yard; the erection Mr. Hay.

Mr. Hay. of the iron lining cost £2 12*s*. 3*d*., and material £7 17*s*. 6*d*. The grouting rose to 10*s*. 1*d*. in that case, which was accounted for by the fact that it included the temporary pilot headings, which had always been grouted. Average figures for the whole of the work done by administration were: excavation, £2 7*s*. 6*d*. per cubic yard; iron lining, £1 4*s*. 8*d*. per ton for erection and £7 15*s*. for material; and grouting (labour and materials) 5*s*. 3*d*. per square yard. It had been possible to re-erect 48,000 tons of the old lining, and the saving effected thereby probably amounted to £400,000 or £450,000. He thought the Author's statement that that had made the scheme economically possible was justified. The number of points at which work had been carried out at one period was stated in the Paper to be sixty-two for the running-tunnels and sixteen for the station-tunnels. That referred to the administration portion carried out from Stockwell, the Borough, and Kennington. At that period most of the construction of the part let by contract had been finished, but, a short time before, work had been carried on at 120 points simultaneously over the whole line. When consideration was being given to the question how best to get the job done, a schedule was got out showing the times of departure from and return to Stockwell of the works-trains. The greatest number of points thought of at that time was fifty; by the closing of Kennington and the Borough stations, that had been raised to seventy-eight, but the original plan as far as Stockwell went had been closely followed. A subsidence had taken place at Stockwell during the enlargement of the south-bound tunnel. It was known that the tunnel had been originally driven through gravel and sand, and numerous boreholes were made to ascertain the level of the clay. Unfortunately, a minor depression which did not quite reach the old tunnel was missed by the bore-holes, and during the excavation it was penetrated. When he reached the site of the accident, soon after 3 o'clock in the morning, no trace of it could be seen in the road. In order to locate it recourse was had to a survey that Mr. Mott and he had made nearly 40 years before, and a hole about 2 feet square was cut in the concrete of the road. An examination showed that large gas- and water-mains were spanning a gap of about 28 feet without any support whatever (Fig. 14, Plate 4). The cavity was dealt with in a manner similar to that described in the Paper for a similar occurrence in Newington Causeway—fortunately, before further damage resulted. He would like, in conclusion, to say how much his firm appreciated the services of the staff in what must be described as a difficult and anxious work. The shield described in the Paper had been suggested by a member of their staff, Mr. H. Heseldin, who, unfortunately, had not lived to see his idea carried out on the work. Mr. Hay.

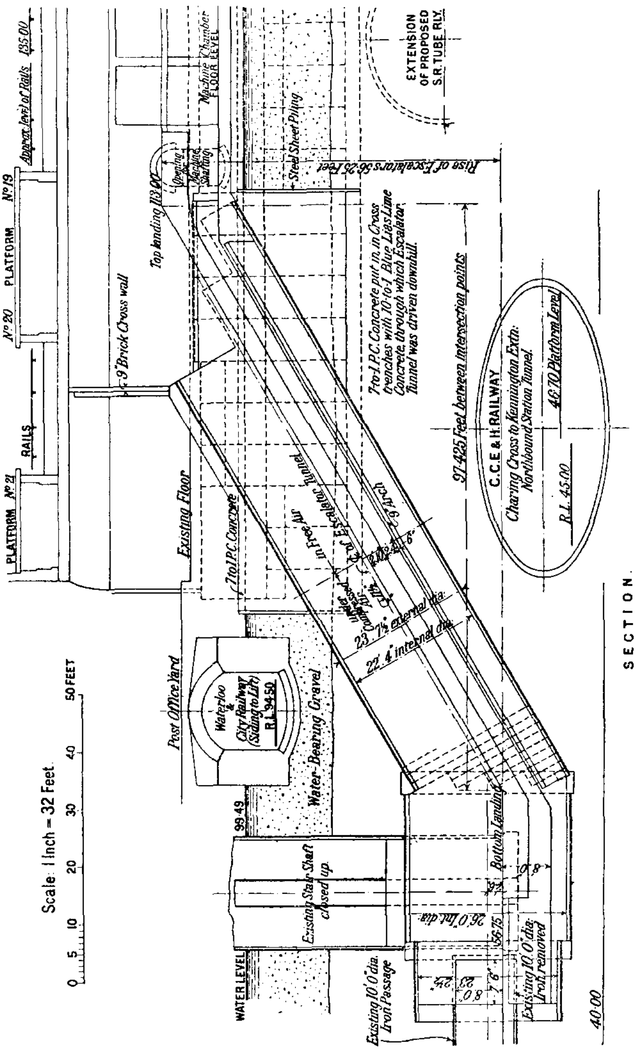
Sir ERNEST MOIR remarked that as a contractor, and therefore a constructor of works, he had read the Paper with great interest, because it dealt rather with the constructional than with the academic or scientific aspect of engineering. The job was clearly a miner's job, and the railway-company were fortunate in having at their service the experience of engineers who had done so much mining, namely, Messrs. Mott and Hay. There was nothing to criticize as far as he could see. The Paper was a history of a difficult work, well carried out under extraordinary circumstances, such as had never existed before. If there was any engineering criticism, it was that such small tunnels had been made in the early days. He agreed with Mr. Trench that it would be necessary to adopt the 16-foot tunnel, which had been used on the Great Northern and City Railway, a tunnel that would comply with the Board of Trade regulations and carry any rolling stock; but it would require a great deal of pluck to face the financial side of the work. In referring to finance he would like to bring to the notice of the members a matter that had not been mentioned, namely, that Mr. C. G. Mott, the uncle of Mr. Basil Mott, had been largely instrumental in finding the money for the first City and South London railway, and had had the pluck to extend the tunnels in order to produce not one but two railways, to the heart of the City. The system was not so much a through railway as two railways meeting in the centre, an arrangement which had resulted, he hoped, in the levelling of the peak load—which was such a difficult task—by attracting through traffic in the middle of the day. He thought the 8-hour day had had the result that manual labourers accentuated the peak in morning traffic. The manual labourer was now going later to work and thus joining those who were going to shops and offices, so that both traffics were taking place at the same time. While some of the extensions described in the Paper were being made he had been carrying out the Great Northern and City Railway, and therefore had been interested in all that was being done. The railway he had been engaged upon ran from Moorgate to Finsbury Park, and it had been hoped that some day it would become a great through-traffic line carrying trains from the North-Eastern system to Dover and the South Coast. Although that hope had not yet been fulfilled, he thought it would be some day. The object of making the tunnels 16 feet in diameter had been to enable through traffic to cross the Thames. Another thing which he thought would come home to roost was the shortness of the platforms on the City and South Sir Ernest Moir.

Sir Ernest Moir. London Railway. On the railway he referred to the platforms were 420 feet long, except at Moorgate, and he believed that longer platforms would be needed before very long, and the City Railway stations would need further extension. The acceleration gradients at stations had added to the complication of the work at those points, and it would be noticed that a falling gradient of 1 in 50 had been substituted for one of 1 in 30 at the end of the original short station. When the Central London Railway was opened, not very long after the City and South London, very small locomotives with the armatures on the driving-axles were employed, a system which rapidly destroyed the track; he believed points lasted only 6 weeks at the Bank terminus. He remembered saying in the Institution to the promoters of that railway that sooner or later they must come to the multiple-unit system, which was being installed in the Great Northern and City Railway; but they said it could not be done. The originator of a practical multiple-unit control-system was Mr. Frank J. Sprague, M. Inst. C.E., of America. That system allowed of high rates of acceleration with low axle-loads, and would carry more useful weight; and he thought the system would be the saving of the railways financially in the future. He believed that some day it would be used for goods-traffic, so that goods-trains could be linked up into a solid block without loose couplings. For a great many years the speed of railway traffic had not been increased, and that was why road transport was beginning to compete with the railways, which did not deliver goods as speedily as they should. The adoption of the multiple-unit system would enable goods-train traffic-speed to be increased; and, until the average speed of goods-trains on railways was increased from 12 or 13 miles per hour to 30 or 40 miles per hour, they would not be successful, and their traffic would be taken largely by road transport. He did not think sufficient stress had been laid on the consideration that the multiple-unit system (whilst there might be, and doubtless had been, improvements in the methods of its application) was a basic idea of great importance and ranked among the great advances in electrical traction schemes. It had first been introduced in London by him on the Great Northern and City Railway; though there, he believed, the system adopted was a modification of Mr. Sprague's original patents. It had been a success from the start, and was now universally practised on all suburban electrical work. He did not think it would be many years before it became universal practice throughout all electric traction systems. In the Great Northern and City Railway the tunnels had been lined with iron throughout during construction, to enable excavation to be done rapidly by a shield. By taking out the lower half of the iron for re-use and replacing it by 16 inches of blue vitrified brick, £30,000 had been saved. The tunnel was quieter than an all-iron type, and, incidentally, the difficulty of obtaining the iron at a reasonable price had been circumvented. He would like to give a meed of praise to the soft-ground tunnel-miners of this country. In a case where every operation was one of experience, of essential care, and of personal knowledge and skill, it was impossible to say too much on behalf of those miners. There was a great danger at present of factory-inspectors being appointed to supervise engineering works; but how would it be possible to deal with such a problem as the works described, if a set of rules written in Whitehall had to be utilized to instruct the miners in their work? British miners went all over the world, and were of the greatest possible help to engineers who were engaged upon tunnelling. He had been very pleased to hear particulars of the costs from Mr. Hay, but he was afraid there was a sorry side to some of the figures. He had heard that some contractors had lost a good deal of money, and he hoped those losses would be included in the published figures for the guidance of those who would have to pay for future work. He would like to give great praise to the traffic-control which had had to be organized and carried out in connection with this very difficult job, and also to draw attention to the fact that no accident whatever seemed to have arisen out of the daily lifting of many sections of the track and their replacement, work having been done in the interim in a great number of places. Sir Ernest Moir.

Mr. H. H. Dalrymple-Hay remarked that it was a great pleasure to him to be present that evening, because Mr. Jones had worked as his resident engineer, first on the Queen's Park extension of the London Electric Railways, and subsequently on the Post Office tube. He thought it was appropriate to mention his old master, Mr. Greathead, who was the originator of the tube system of railways, because engineers to-day owed him a deep debt of gratitude. Mr. Greathead started the ball rolling, and they had only kept pushing it along slowly. The enlargement was a splendid piece of work, which had been boldly undertaken. The description of the enlarged composite lining (p. 180) was given in a few words and easily comprehended. Mr. David Hay told him about the section long ago, and at the time he had thought that the proposal was a very bold one. The section was admittedly of a bad shape and unfortunately had wood packings in the cross joints, but he was convinced that, taking everything into account, it was quite a Mr. Dalrymple-Hay.

Mr. Dalrymple-Hay. proper section to adopt under the special circumstances. Had the old iron been rebuilt, of that particular section, in virgin clay, he thought the tunnel would certainly have collapsed. In all tunnel operations through solid ground there was a general flow of the clay towards the working-face before the grout was put into the annular space round the lining and had become hard, and consequently there was a general "draw" of the ground round the tunnel, and a settlement at the surface. That "draw" squeezed the tunnel-joints together, as he had frequently verified by putting a spanner on the longitudinal joints; he had found that it was possible to keep on tightening the bolts, which were always getting loose on account of the squeezing. In that condition there was formed what he might term a concealed arch in the ground immediately above the tunnel. That condition had existed on the City and South London Railway before the alterations were made, the superincumbent load being taken by that concealed arch. The comparatively weak, but sufficiently strong, section of lining which was now in place was, on account of the concealed arch, a good enough section for the purpose for which it was used, namely, to save money by using up the old 10-foot 6-inch diameter segments in the composite form adopted for the lining. He thought it would be of interest to give some information about cementation, to which reference was made on p. 188. It had been necessary to drive an escalator-tunnel 23 feet $7\frac{1}{4}$ inches in external diameter inside one of the arches on the northern side of the Southern Railway viaduct at Waterloo station, the span of which was 24 feet (*Fig. 15*). There was 14 feet of water in the ground, which contained sand and gravel, and it was necessary to pass under the small brick tunnel which he had built 30 years ago on the Waterloo and City Railway. Owing to the presence of the water it was necessary to enclose the viaduct in a steel dam before the piers could be underpinned and the escalator-tunnel driven. A series of cross trenches were constructed between the piers, and the water was pumped out. The piers were underpinned before the escalator-tunnel was constructed within the dam and before tunnelling outside the dam and below the small brick tunnel was begun. The Southern Railway Company's engineer had considered that the brick siding-tunnel should be underpinned, but Mr. Dalrymple-Hay thought that that was not possible because it was at right angles to the viaduct and would involve a great deal of pumping. He therefore asked to be allowed to cementate it, with a view to solidify the ground. The railway-company agreed, and about sixty-three cementation-holes were driven into the ballast in order to crystallize the ground immediately under the abutment of the siding-tunnel adjacent to the viaduct, so that it would be possible when mining through the ground to cut through solid material and not loose ballast. The cementation work Mr. Dalrymple-Hay.

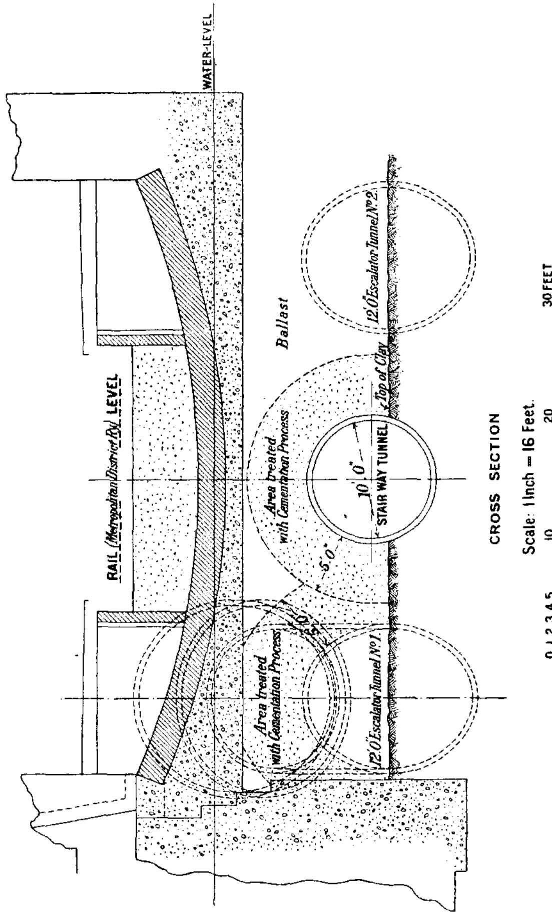
Fig. 15.



was done by the François Cementation Company, not by the silicatization process, but by the ordinary process under about 300 lbs. per square inch air-pressure. After about 12 tons of cement had been injected, which the Cementation Company considered to be ample

Mr. Dalrymple-Hay. for success, the steel piling was drilled through under compressed air, so as to form a series of slotted holes, through which steel channel piling was inserted with the flanges downward and the table upward. Some pocket-holes had previously been formed ahead of the channel piling and filled with clay. When an attempt was made

Fig. 16.

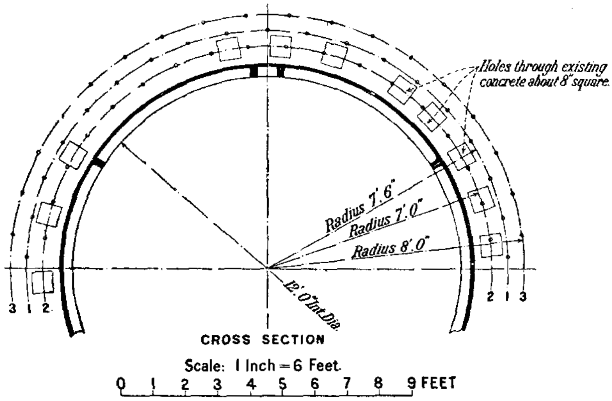


to jack the piles forward, it was found that there was no cementation at all—nothing but sand. That experience clearly proved that if there was sand in the ground the cement would not penetrate it. In that case the cementation was a complete failure, although it must have crystallized the adjoining gravel-bed. Another case which was perhaps more interesting occurred at Charing Cross station (*Fig. 16*), where three tunnels had to be built. His idea had been to form a band of cementation about 5 feet thick in the ballast. The water was pumped out and the Cementation Company drove numerous holes through the face of the tunnel. Their advice was that the holes should be driven through the central portion of the face of the tunnel, because the cement would rise gradually and an arch of stronger material would be formed above the lining. When the ground was mined out later, no cement was found immediately above the tunnel except in patches, and where the ground was sandy the cement would not penetrate the sand-bed at all. It must have gone somewhere outside the tunnel; and as 28 tons of cement had been put in the first tunnel and little was found at the face, he was satisfied that the ground had been crystallized where he wanted it to be strong, namely, outside the tunnel, although not immediately outside, as he had intended. The Cementation Company stated that the cement always rose gradually through the ground; he thought that it would not do so. If cement was forced into water-bearing ground with high-pressure air it would no doubt go upwards, but if cement grout, which was in a very liquid state, was forced into dry ground, as in the present case, it would tend to go, under the action of gravity, down into the ground through the interstices of the gravel, unless, of course, there was any other easier line for it to travel along. It would always follow the line of least resistance. Only a small quantity of cement was found on the line of the staircase tunnel; but, as it had been put in under high pressure, it must have gone outside (as was ascertained in a few cases by prickings), and from that point of view he was quite satisfied. He decided to deal differently with the third tunnel, and put in three sets of holes—about eighteen in each set—as shown in *Fig. 17* (p. 212). The central holes were driven first by the Cementation Company, and hollow perforated rods were left permanently in them. The inner and outer rows were ordinary cementation boreholes. When the tunnel was driven downhill it was found that for a short length there was an excellent piece of cementation where he desired to have it. It had buried the rods and formed a concrete arch which simplified the mining, because there was nothing but gravel at the face. As excavation proceeded downwards, however, only strips or bands of cementation were found, and where there was sand there was no cementation at all. Mr. Dalrymple-Hay.

Mr. Frank Pick remarked that the old City and South London Railway had been a tube of narrow diameter, inefficient, but forming a part of the Underground system as a whole, and it had been necessary for the railway-company to choose between enlarging Mr. Pick.

Mr. Pick. the line, thus making it a part of their system, and scrapping it. It took a great deal more courage to scrap it than to enlarge it, and therefore in the end the company ventured on the difficult engineering task of enlarging the tunnels. They had had to try and keep the railway working while the enlargement took place, because while the line was unprofitable, the goodwill—the only thing left—might have been lost if the railway had been closed during the enlargement, and then there would have been nothing at all of the original railway. He was glad to say that there had been no serious accidents to the trains while the work was in progress. Mr. Hay had given figures of the cost of the work which showed that on the whole the policy of enlarging the old tunnel had not been unduly expensive, owing to the skill with which the old materials

Fig. 17.



had been re-used. The company were fortunate in getting a new tunnel at what was practically the current price after allowing for the original expenditure. But there was a much more serious problem than the engineering problem, namely the economic problem. No tube railway in London at the present moment was self-supporting. The tube railways required for their support a traffic which had a density of not less than 30 to 36 million passengers per mile per annum. There were short sections of tube railways which had that density, but the tube railways generally had only about two-thirds of the required density. He admitted that in recent years the cost of constructing tube railways had fallen relative to the cost of materials; and the recent costs had been cheaper than those of former years. At the same time, he thought that more consideration should be given to the question whether the construction of tube railways could be standardized, so that it would be possible by mass production to build lines much more cheaply still. In all tube-railway works a good many men were employed in getting clay out of place by brute force and in attempting to get heavy blocks of metal into place, and he thought that could be avoided by having some system of mass production, which would be essential if many more tubes were to be built in London. So far, labour-saving devices or mechanical aids had not proved successful. If tubes were to be built, either they must be subsidized or their cost must be low. He had never understood why 11 feet $8\frac{1}{4}$ inches had been chosen for the size of the tubes; it was an odd size like the 4-foot $8\frac{1}{2}$-inch gauge of railways; and now it was stated that 16 feet was the proper size. He was grieved to hear that at this eleventh hour. A diameter of 11 feet $8\frac{1}{4}$ inches was certainly too small to take rolling stock with side doors high enough to enable a person to enter a car without stooping. The company received many complaints on that score. Finally he was glad to have an opportunity of saying how much the railway company appreciated the way in which the work on the City and South London Railway had been carried out. In the last few years the company had secured a large extension of the underground system without any serious mishap or disturbance. They could congratulate themselves on the skill and care shown in so arduous and difficult a work, and still more the engineer. They wished to thank all those who had had a part in carrying it out. Mr. Pick.

Mr. A. R. Cooper remarked that the Paper not only formed a record of an interesting engineering work but also provided valuable data for future use. One visit which he had paid to the new siding-tunnel at Kennington had particularly impressed him, as showing the intricate nature of the work and the care which had to be taken in carrying it out. A tunnel, 27 feet 6 inches in diameter, had been put round the existing running-tunnel so as to enable a junction to be formed with the siding-tunnel. He had stood in that junction tunnel, and, putting his hand on the running-tunnel, had felt passenger-trains going through it. His main interest in the work had concerned the safety of the train-service and the re-equipment of the line. An outstanding feature of the enlargement which had made an already difficult task more difficult was the fact that for about 13 months trains had run for about 13 hours every day. For reasons of economy the contractors had been given the task of taking up and replacing the track, because otherwise the railway-company would have had to employ a large staff for the work, which would only have occupied a short time. Naturally, responsibility for the safety of the Mr. Cooper.

Mr. Cooper. train-service had rested with the company's staff. Representatives of the permanent way, signalling, and electrical departments had acted jointly in the examination of the work at the end of each shift. The first man's duty had been to see that the track was safe for service and that the necessary clearances had been provided. The signalling representative had had little work to do, but that little had been of importance to safety of running. The electrical representative had been concerned with various cable-connections and the rebonding of the track. Those men had worked together and had covered as many faces as possible—usually four or five. For the rest of the night they had been engaged on their ordinary duty of inspecting the track and the equipment. That had worked satisfactorily, and he was glad to record that during the whole of that special train-running (and there had been much wrong-road working for ballast-trains) there had been no accident or collision, or injury to men. Transport had been a vital feature of the work; there was only one depot—Stockwell—and, further, the single line from the tunnels was connected to the surface by means of a lift. On that account serious difficulties had had to be overcome to provide transport for the work throughout the whole of the railway; as many as sixteen work-trains, having an average of four or five trucks each, had run at night. Arrangements had been made for at least one truck to be transported to each working-face, and each truck had contained the material required for a particular job on the particular night. The railway company appointed a liaison officer with offices at Stockwell depot, adjoining the chief resident engineer's offices, and those offices, therefore, had become a sort of nerve-centre for transport arrangements. That liaison officer had been responsible for co-ordinating the various requirements of the consulting engineers, the various contractors, the departments of the railway-company, and the contractors engaged on station alterations and escalator work. The whole experience of the work had shown how necessary it was to prepare programmes of work to be carried out and schedules of material at as early a date as possible, although those schedules and programmes had had to be modified and reviewed day by day. As many as seventy-eight faces had been worked at once, which would give an idea of the transport that had had to be provided for. The company had decided that the line should be re-equipped throughout on modern standards; escalators had been provided at suitable stations; the station structures had been modernized; bull-headed rail had been substituted for the flat-bottomed rail; and the old arrangement of an earth return had been changed to an insulated return, Mr. Cooper.

making it necessary for a fourth rail to be installed. The old trains had consisted of a locomotive and five coaches. The lengthened platforms permitted standard seven-car trains to run; and, with the higher speeds and the improved signalling (the line had been resignalled throughout), the capacity in seats had been increased from about 4,600 to 12,000. The total expenditure on the work was about £3,000,000, of which about £2,000,000 covered the main work described in the Paper. The other £1,000,000 had been spent on equipment, and it could be roughly divided into three: one-third of a million on rolling stock; one-third of a million on modernizing stations, including escalators, equipment, lighting, telephones, and other small services; and one-third of a million on new permanent way with electrical equipment. Towards the later stages of the work the need for bringing in material for equipment, and in particular the permanent-way material, had caused somewhat serious congestion at Stockwell. Owing to their length, rails could not be brought in otherwise than by a track connection; they were too long for the lift-shafts. A heading 50 feet long and 4 feet in diameter had therefore been constructed at King's Cross station between the City and South London Railway and the Piccadilly Railway, which enabled the Lillie Bridge depot and the Piccadilly Railway to be used to bring in heavy material such as rails and sleepers. Two or three thousand tons of material had been taken in by that means, and the heading had relieved the congestion and facilitated the carrying-out of the work. Laying track equipment in a tube was difficult in comparison with similar work on a surface line. It was all end-on work, and the clearances were very small. There were three stages. The contractors for the tunnel left a concrete formation about 2 inches below sleeper-level. The sleepers were next brought in, already chaired, put in position on wooden blocks, and lined up to give as good an alignment as possible—that was important, because when the track was once set it was very difficult to modify—and finally the whole was concreted in, and rendering was placed for about 15 inches up the side of the tunnel with the object of avoiding any likelihood of an earth connection between the current-rails and the tunnel-lining. Hanging shoes (with one link broken) did occur on trains, and they would touch the tunnel iron and cause a partial short-circuit if that were not prevented by means of the rendering. Laying the track had been done by gangs of eighteen men, each of which in an $8\frac{1}{2}$-hour shift had laid about 90 yards. The concreting had been done by gangs of twenty-eight men, who could do 170 yards in an $8\frac{1}{2}$-hour shift, and a twenty-eight-man gang would do 85 yards of side rendering, which

Mr. Cooper. was quite an expensive item, in the same time. The Authors had referred to the co-operation existing between the various parties concerned in the work. He would like to associate himself with their statement, because he realized that it had been largely on account of that co-operation that many difficulties had been overcome and the conditions made more pleasant for everyone who had been concerned with the work. He congratulated the consulting engineers on the carrying-out of a very fine piece of engineering work, and also the Authors for the part they had taken in it.

Dr. Lowe-Brown. Dr. W. L. LOWE-BROWN remarked that any work in connection with the City and South London Railway must always be of great interest to tunnel engineers or to anybody connected with the transport of urban passengers, for it had been the pioneer line in so many things, and would always be associated with the name of Greathead. It was not only the pioneer tube railway, but it was also the pioneer of accelerating and decelerating gradients at the stations. In addition it was a pioneer in electric traction, and it was the pioneer in the fight for the right of the railway-companies to occupy the subsoil of the streets. The line had been started with courage, and with not a very large amount of capital. It might almost be said that the varying diameters of tunnel showed the varying financial confidence which it inspired. If it had been another kind of engineering work, the pioneer nature of which had been more generally understood, he was sure that there would have been a great deal of opposition to modernization. Fortunately, the public had not understood the pioneer nature of the work, and therefore, instead of being an interesting historical relic, it was now one of the most up-to-date lines in London. He congratulated the Authors on their clear description of a very difficult piece of work. Mr. Hay and Mr. Cooper had indicated what an almost overwhelming amount of detail had had to be dealt with; and that the work had been carried out very rapidly was to the credit of everybody concerned. The Authors' frank description of an accident was commendable, because often more could be learned from an accident than from work which went without a hitch. To carry out the work and keep the traffic running had been a difficult task, and he was quite sure that an undertaking to do it in that way must have been one of the fundamental conditions imposed upon the engineers; for the expense must have been much greater and the time much longer, and the very shape chosen for the enlarged tunnel might have been determined by that consideration. While he could sympathize with their misfortune in having an accident after 80 per cent. of the work had been successfully done, he thought

Dr. Lowe-Brown.

that perhaps their mortification might have been somewhat assuaged by the fact that as a consequence the traffic had been stopped, with the result that they had been able to complete the work better and more expeditiously. He could not help speculating whether, if the work had to be done again, the same condition would be imposed. It was rather curious, having regard to its title, that the Paper did not contain a sketch of the enlargement, and he suggested that cross sections of the enlarged 11-foot $8\frac{1}{4}$-inch tunnel as made up from the 10-foot 6-inch rings, and also of the oval section, be given. There might be some special features connected with the former which made it a stronger section than would be gathered from the brief description in the Paper. As the mining features of the work had been dealt with at some length by previous speakers, he would not go over the same ground, but having spent much of his time in recent years in studying the economic side of engineering, he could not help looking at the modifications to see how they had affected the railway as a passenger-carrying machine. He had visited the works twice during the reconstruction, and had been greatly struck by some of the improvements which were hardly mentioned in the Paper; so, after reading it through, he had spent part of two afternoons in travelling over the line to see the working of the improvements noticed during his previous visits, and he would recommend anybody who wanted to enjoy an interesting afternoon to spend a few hours in travelling over the line and visiting some of the better stations, such as the Oval, or some of the new stations on the Morden line. The enlargement had, of course, been essential to enable the line to take its place in the system of which it now formed a link. But there were other changes which were of great importance to its increased efficiency. Mr. Cooper had already indicated the extent of that increased efficiency. Mr. Hay had given some interesting figures about the cost which would be of the greatest value to engineers; but the total cost of the structure was a long way from being the total cost of the railway as a going concern, which included parliamentary expenses, cost of land, equipment of the line, rolling stock, provision for the supply of electric current, etc. In the early days, tube railways had cost about £500,000 a mile. He thought that in the capital accounts of the companies to-day the cost stood at about £750,000 a mile, and a competent authority had given the cost of new lines at £850,000 a mile. It took a large amount of traffic and careful working to enable a reasonable profit to be earned on such a large capital, and everything had to be arranged so as to attract as much traffic as possible, and then to run the line in the most economical way.

Dr. Lowe-Brown. When the first tube railways were constructed, the speed of travel was so much faster than that of their principal competitor, the horse-bus, that a loss of a few minutes at stations and in lifts and passages did not count for very much in journeys of 2 or 3 miles; but with the advent of the motor-bus that had been completely changed, and they had begun to lose passengers—more particularly the short-distance passengers. It then began to be realized that the question of convenient access had become of vital importance. Sir John Aspinall, in his James Forrest Lecture, had stated[1] that it was little things that made perfection in the handling of London traffic, and he had pointed out how the access to the stations was one of the most important factors. The difference between the old City and South London Railway and the new, in that respect, was most marked. The old-fashioned booking-office had given place to a new arrangement, which he believed was called the "passimeter." Instead of lifts there were escalators, and from the moment the passenger entered the station doorway from the street, he could move forward without interruption until he reached the platform. That had made the tube so much more attractive to the public that the necessary increase in the number of passengers had been obtained. At the same time the new arrangements had given the additional capacity necessary to handle those increased numbers. The escalator had the further advantage that, if account was taken of the fewer number of men required, it would be found that the working-cost was usually not more than one-half, and in certain places not more than a quarter, of that of lifts. Ease of interchange at stations was another important factor affecting the convenience of the passengers. In the old railways the interchange had very often been arranged after the line had been built, and such interconnections were frequently very inconvenient, although they were doubtless the best that could be made under the circumstances. In the linking up of the Hampstead with the City and South London Railway, there was an interchange station at Kennington which was of a very different character. It was, he thought, as perfect an interchange station as could be made for tube-railway work. In 1912 he designed an interchange station in Buenos Aires,[2] between the Buenos Aires Western Railway and the underground Anglo-Argentine system, which was very similar to Kennington. The passenger left one train, walked across the platform and got into

[1] Minutes of Proceedings Inst. C.E., vol. ccxiv (1922), p. 237.
[2] *Ibid.*, vol. ccv (1920), p. 189.

the other train. It was more or less the same arrangement as at the express stations on the New York Subway. He thought that showed one of the great advantages of having all means of transport under one authority, because proper arrangements could then be made, instead of belated attempts to link up lines planned by different interests. It was necessary to make the tubes not only attractive to the passenger, but also as economical as possible in working. An important economic feature, which depended upon the design, was the provision of reversing-sidings. A line which radiated from the traffic centre to the suburbs would be worked very wastefully if all the trains were run to the end of the line; because when that was done only a fraction of the accommodation was occupied for the last part of the journey. The solution was to turn back a proportion of the trains at intermediate points. There were many examples on surface lines, as at Wood Lane, Hammersmith, and Golders Green; but he thought Kennington station was the first example of such an arrangement in purely tube construction. It was true that on the Central London Railway there was such a siding at Marble Arch, but it was not sufficiently far out to be used as a sub-terminus, for which it had never been intended; it was used, as intended, for emergency working only. On a line with the train-frequency which this line ought to have within a few years it was absolutely necessary to provide either a reversing-siding situated between the tracks, or else a loop. The former had the advantage that a train could be stored there, or the order of trains could be inverted. A loop, on the other hand, had the advantage that the motor-man could remain at one end of the train and make a continuous run. In both cases interference with the through traffic was reduced to the minimum. Dr. Lowe Brown.

Mr. H. J. DEANE observed that during the driving of the old City and South London extension from the Angel to Euston, sand had been encountered between the blue and the mottled clay. Between Euston and King's Cross that material had been obviously surrounded on all sides by clay, and there had appeared to be no means for the escape of the compressed air under which the tunnel was being driven. When that band of sand was first struck it was charged with water. The immediate effect of applying compressed air was to drive the water back. After stabilization of the pressure the water returned, and on reducing the air-pressure again the water came out in still greater volumes. For every increase of pressure the quantity of water was reduced until stabilization had been attained, when the water began to flow again as fast as ever it had before. The obvious reason for that was that there was Mr. Deane

Mr. Deane. a large pocket of sand, and the air had been escaping into that pocket, pushing the water before it, until stabilization occurred. After stabilization, of course, the water had come back as before. Mr. Greathead's Paper showed that the head of water which had been met with in the portion of the tunnel constructed under Clapham Road in compressed air was 35 feet. That was, he thought, above the crown of the tunnel. In the same Paper it was stated that normal air-pressure was used, but there was no reference to what that normal air-pressure was. In the enlargement at that place the pressures had been 3 and 4 lbs. per square inch when two faces and one face respectively were being worked. It seemed that there must have been some reduction in the water-level over those tunnels, otherwise the air would have escaped, and much water would have come into the tunnel. Perhaps the Authors would give some information on that point. With regard to the same section of the tunnel, the Authors inferred from the experience of No. 1 and No. 3 runs that, since the air could be kept in where the sandy material was very compact, there must have been a dividing ridge between the different strata found in the two runs. He would like to know how that very positive conclusion had been arrived at. His own view was that a greater pressure had been maintained in the one case because the air had difficulty in getting away through that close material, and he believed that there was a definite hydraulic connection between those two strata. The unfortunate experience to which reference had been made emphasized the necessity of being very careful to what extent reliance was placed on borings. Borings might be very close together, and at the same time they might miss an important pocket or pot-hole which would cause trouble. To what extent had administration covered the work carried out by that particular method ? Had any contractors been employed on the southern section, and, if so, what had their responsibilities been ? Possibly they might have merely supplied the labour and certain of the materials, such as ballast and cement, and carried out the directions of the engineers who were controlling the work.

Mr. Wilson. Mr. J. S. Wilson regretted the absence of a cross section of the tunnel-lining. He had devoted a great deal of time to the study of the strengths of tunnel-linings, and, seeing that the enlargement of the tube railway had been carried out perfectly satisfactorily, and that a great feature in the economical execution of the work was the re-use of the old segments, he thought the inclusion of a drawing, showing the cross section of the tunnel, would greatly add to the value of the Paper. He was gratified to think that, in spite of the alterations made, a great deal of Mr. Greathead's pioneer work remained untouched. Mr. Wilson.

Mr. H. Berridge remarked that about 30 years ago he had been the contractors' engineer on the completion of the Waterloo and City Railway and the commencement of the first extension of the City and South London Railway (from the Borough to Moorgate Street). The resident engineer on the Waterloo and City Railway had been Mr. Dalrymple-Hay; and he thought all engineers owed Mr. Dalrymple-Hay a great debt for the system he had introduced in setting out the tube railways, namely the use of the steel tape, the 7-inch theodolite, and the radius rods for guiding the shield round the curves. The systematic use of those instruments had made the setting-out and driving of the tunnels much more rapid and reliable than had been the case previously. The methods and appliances which had been used in the present work were very much the same as those in use 30 years ago. The Greathead shield and the grouting operations seemed still to be the backbone of tunnelling in London clay. There was no doubt that grouting, by means of which the earth was prevented from beginning to move, was one of the most important operations. In the old days steam cranes hoisted the spoil from the shafts, the shields were pumped by hand, and horses and carts moved the spoil. Disposal of the spoil was a very important matter in tunnel work, and he would be glad if the Authors could say something about it. He did not see any reference to mechanical excavators or to other modern improvements, such as quick-setting cement and oxy-acetylene cutting, which he thought would be useful for getting out steelwork which was in the way. He would appreciate further information regarding the step-plates. He did not think the clay-pocket system could be used except at a low pressure and in small tunnels. He had tried that method on the New York approach tunnel, which was about 17 feet in diameter, with a pressure of about 17 lbs. per square inch, and the difficulty of making a hole, overcoming the escape of air, getting the puddled clay, and getting it into the hole, had precluded its use. With regard to grouting, he had had considerable experience of such work in connection with pouring neat cement grout down pipes into the sea, in order to consolidate the foundations of quay-walls. There were two or three points about that operation which, he thought, explained the discrepancies that were found to exist in regard to grouting. In the first place, the grout had to be made in a certain way, namely, the neat cement must be made into a paste and thinned with water to the necessary consistency. The bottom of the pipe had to be submerged in the cement grout, that was to say, the Mr. Berridge.

Mr. Berridge. grout had to displace the water upwards; it must not go down into the water. A third point was that grout would go into very small fissures. It would go into shingle, or rubble, or block work; and if the proper precautions were taken to limit the travel, a thoroughly solid job could undoubtedly be made. The foundations of the breakwater at Jersey, the Rosetta barrage, and several quay-walls on which he had been employed, had been grouted up solid in that way. It was hopeless, however, to expect to get a solid job by putting the grouting-pipe into a bed of sand, or mud, or mixed material, and blowing grout into it; the grout would not travel through very fine material.

Mr. Hay. Mr. DAVID HAY observed that Dr. Lowe-Brown and Mr. Wilson had referred to the cross section of the tunnels. He thought a diagram could be added to the Paper if necessary. The section was, however, described in the Paper, and anyone who cared to take the trouble to draw it out could see exactly what the shape was.

Mr. Taylor. Mr. F. N. G. TAYLOR remarked that it had never before been necessary to enlarge an existing tube railway, and now that running-tunnels were practically standardized at 11 feet 8¼ inches, he thought it would be a very long time before anything in the nature of the present work would be done again. The Paper dealt mostly with work done underground, but from the contractor's point of view a good deal had depended on how the work was organized on top. Large quantities of material had had to be handled, in most cases from very inadequate sites. At Kennington, for instance, a very small garden in front of a block of buildings, about 5 yards by 6 yards, had been handed over to the contractors. Most of that garden had really been a coal-cellar, through which the shaft had been sunk. At Euston the contractors had been given the old station building. There they had set up the cranes on the roof. The whole of the material had been handled through the old lift-shafts, the lifts having previously been removed. The enlargement of the crossover tunnels, sidings, and running-tunnels, as far as King's Cross, had been dealt with from that site. Air-compressors for low and high pressures had been installed in the cross passages leading into the bottoms of the old lift-shafts. Air-locks had been built into the original temporary access passages. Approximately 30,000 tons of iron and excavated material had been handled during a period of about 12 months at that site over the roof of the station building. The great difficulties of handling large quantities of material were often forgotten. In the extension of the City Railway from Clapham Common to Tooting Broadway, 300,000 tons of excavated material had been handled by the contractors in about

Mr. Taylor.

16 months; and a fleet of twenty to thirty motor-lorries had been continuously employed night and day in dealing with that material. Discharging those lorries had been quite a contract in itself. Special gantries had been set up, special roads made, and petrol locomotives utilized for dealing with the excavated material as it arrived at the shoot. The mechanical erector referred to in the Paper had been set up at King's Cross for handling the heavy station segments. After erecting five or six rings, the contractors had taken it down, because they found that it required a special squad of men to handle it, and that it greatly interfered with the work of the men at the face. In its place they had put up a little "tugger" hoist worked by compressed air and snatch-blocks fixed to the roof portion of the finished rings. That had hauled the plates into position more quickly, and the men had rapidly got accustomed to handling the plates themselves. Those hoists were wonderfully portable and could be lifted by a couple of men and put in position in about an hour. They were also very economical to work. The work described by the Authors, being the first tube work to be done after the war, had brought into use a number of new tools which had never before been used on tube work. Amongst them might be mentioned heavy pneumatic concrete-breakers, which had been invaluable in breaking up the old concrete invert; the excavation in hand-driven tunnels had been, for the first time, carried out by pneumatic "spaders" instead of the old hand picks; old bolts taken out of the original tunnels had been rethreaded by pneumatic thread-screwing machines; and the pneumatic hoists, already referred to, had been very useful also in hauling wagons up steep gradients and round sharp curves. The contractors had had great difficulty in getting men for the enlargement, because the miners had been accustomed to real mining work, and two things were involved which they disliked most, namely, building iron and grouting; and to this was added the fact that it involved the pulling down and rebuilding of the old iron, which, being very dirty, was more unpleasant than new iron. Previously they had been accustomed in a new shield-driven tunnel to handle about 6 tons of iron and excavate about 32 cubic yards of material, for an average of four rings per shift. The contractors had asked their men to do six rings of enlargement per shift, which involved the dismantling and re-erection of 9 tons of iron, and only about 9 cubic yards of excavation. That work had been very unpopular, but if the men were asked to drive a new tunnel, or even a big station enlargement, they were quite pleased to undertake it. In order to meet their objection, the contractors had made an electrically-driven

Mr. Taylor. iron-erector. It had been quite a useful machine, but by the time it was ready the work was proceeding fairly steadily, and it had been thought better not to stop the men and put up the erector. It was wonderful how the men could so easily and quickly handle the segments; in fact, so much so, that any mechanical appliance seemed out of place. He was sorry that the cross section of the enlargement had not been shown, since it had given the contractors a good deal of trouble to build it. It was an odd form, difficult to trammel, and constantly getting out of shape. The enlarged tunnel-lining had twelve horizontal joints with wood packing at each, and the earth-pressure coming on the tunnel after it had been built had caused the bolts to become slack: the contractors had been repeatedly accused of not tightening them up sufficiently. He admitted it was difficult to get them tightened, but the numerous wood packings had been largely responsible for the slack bolts. He considered that in all iron-lined tunnels the horizontal joints should be iron to iron.

Mr. Jones. Mr. JONES, in reply, observed that the Paper was a description of an unusual work, and would probably not be of much practical utility, unless at some future time, as had been foreshadowed, it should be decided to enlarge the whole of the underground system of tube railways in London. Sir Ernest Moir had given a meed of praise to the miners engaged on the work, and they deserved it; for in addition to the usual mining work of driving the shield, erecting the iron lining, and grouting, they had been responsible for the re-instatement of the track, clearing up all loose plant and material, and leaving everything in a safe condition for the resumption of traffic at the scheduled time in the morning. That work was so harrassing that the men would leave the shields whenever an opportunity occurred of working in a large face with plenty of excavation to go at, where bonus could be earned. He would like to give a meed of praise also to the resident engineers and their assistants on the various sections; they had had a very trying job. They had surveyed the tunnels, which were in an extremely dirty condition through years of accumulated dust, had set out the improved lines and levels at night, and had plotted the results of the surveys and worked out their calculations for the improvements to be effected in the day time. He thought it highly creditable to them and to the men driving the shields that, although on many occasions in effecting these improvements advantage had been taken of the maximum possible deviation of the shield, either vertically or horizontally, when an error in setting-out or in driving the shield might easily have resulted in the trains not being able to pass through the shield on the resumption of traffic, there had been no instance of this occurring. Mr. Dalrymple-Hay considered that the engineers had been justified in putting in the composite lining, and that it was strong enough for the job. Those concerned had never had any doubt about that. In a tunnel where the grouting was done immediately the shield had advanced, any movement of the ground was due to a general drawing of the ground at the face, or round about the heading where an advance heading was in use, such movement continuing for some time after the lining had been erected, and throwing weight upon it. In the case of the 11-foot 8¼-inch composite tunnels, there was no face to speak of, the width of clay in the annular face being nowhere more than 12 inches. Measurements taken in the composite tunnel had shown that, notwithstanding the larger number of joints, no more movement had occurred than in the new tunnels with similar joints. With reference to the opinion expressed by Mr. Dalrymple-Hay that, if used in virgin clay the composite lining would certainly have collapsed, several hundred yards of 11-foot 8¼-inch tunnel had been constructed in virgin clay with the same composite lining as was used in the enlargement, with equally satisfactory results. Mr. Dalrymple-Hay had given examples of his experience in the application of the cementation process. That had been of great interest to Mr. Jones, because there had been several cases, in addition to the slips referred to, where cementation had been used. Mr. Jones's experience also was that the cement would not travel in close sand or silt; in disturbed ground it would fill the finest fissures. In pervious ground, such as gravel or ballast, it required to be used with caution, because it followed the path of least resistance and travelled far beyond the point where it was required, with the risk of its entering drains, sewers, or other underground structures. At one time the contractors for the compressed-air section in Clapham Road contemplated the possibility of using cementation there in lieu of compressed-air working, but he thought they had been well advised not to do so. Had the cementation been successful, the ballast in the annular face between the 10-foot 6-inch iron and the cutting edge of the shield would have been turned into concrete of uncertain quality, which would have been extremely difficult to excavate in so confined a space. It had been asked why 11 feet 8¼ inches had been adopted as the diameter for tube-railway tunnels. Mr. Mott had touched upon that in his Presidential Address,[1] where he stated that in one of the tube-railway contracts—the first in which that

Mr. Jones.

[1] Minutes of Proceedings Inst. C.E., vol. ccxix (1925), p. 8.

Mr. Jones. size of tunnel was used—contracts had been let for an 11-foot 6-inch tunnel (12 feet 6 inches externally), and that before the work had been started some doubt arose whether that tube would allow sufficient latitude for the small irregularities in driving, in conjunction with the rolling stock it was proposed to use. As it had been undesirable to increase the external diameter, and therefore the contract price, it had been decided, after careful consideration, to reduce the depth of the flange to the minimum. Mr. Pick had suggested that the cost of tube-railway works might be reduced by the employment of mass-production methods, particularly with regard to the erection of the cast-iron segments. No doubt such methods were in use in the manufacture of materials such as segments and bolts, but with regard to savings in labour at the shield, Mr. Jones did not hold out much hope. With the ordinary Greathead shield, the usual piece-work progress was four rings of 11-foot 8¼-inch tunnel per 10-hour working-shift. As the time occupied in the erection of one ring was about 20 minutes, the total time occupied in the erection of the iron lining would be 80 minutes per shift. Assuming that 50 per cent. of that time could be saved by the use of an erector—which was a very sanguine estimate—the net saving in time would be only 40 minutes per shift. Against this, he feared that the erector would be very much in the way of the other operations in a place where all available room was required for the handling of the excavation. Where the ground and all other circumstances had been favourable, Price rotary excavators had been used in conjunction with the shields on the Morden extension. Those machines were very efficient, and whereas the progress made had been more than doubled, the personnel of the gang had been reduced by one-third. In that case the whole of the excavation and loading of spoil had been done by machinery, but the erection of the lining had still been done by hand and had occupied the same time per ring. Thus when nine rings were put in per shift, the erection occupied 3 hours. He thought it worth consideration, in this case, whether a considerable portion of that time could not be saved by means of an erector mounted upon an extension of the axis of the rotary cutter. With such an erector in use, heavier segments could be handled. Economy in cast iron and bolts could be effected by increasing the width of the rings from 20 inches to 24 inches; and he was of opinion that the same number of rings would be put in per shift, with a corresponding reduction in cost. There was no difficulty in the application of a mechanical erector for dealing with the segments in the larger tunnels, where they were long enough to warrant it.

An erector fixed to a working-stage travelling on brackets at a little above the axis-level of the tunnel would probably be the best pattern, but those used for the lengthening of the 21-foot $2\frac{1}{2}$-inch stations were as shown in Fig. 7, Plate 3, and were designed to clear the passing trains. With a higher speed of operating, he was of opinion that the balance of economy would have been in favour of the erector, as against the small pneumatic hoist used by Mr. Taylor and also largely used by him. Those erectors had been used throughout the construction of the new station tunnels at Stockwell. He did not quite follow Mr. Taylor's statement that the enlarged tunnels had constantly got out of shape, unless he referred to the small movements due to the slight squeezing of the wood packings in the joints. The flanges of the old 10-foot 6-inch iron were unplaned, and therefore in re-erection wood packings had had to be used, as in the old tunnels. Where the composite lining had been used in hand excavations every ring of iron had required very careful trammelling and strutting from the ground until grouted. If the iron was built out of shape, the tendency was for each succeeding ring to get worse. Ordinarily this tendency was checked by the rings breaking joint, but the design of the composite lining had not permitted of this being done. In the 10-foot 6-inch to 11-foot $8\frac{1}{4}$-inch shields the middle of the 10-foot 6-inch segments rested on the shield-skin; the ends of the segments and the additional casting were $1\frac{1}{2}$ inch away from the skin and were supported on packing-plates permanently bolted to the skin. The composite lining was therefore firmly supported in the shield; so long as the tail of the shield kept in shape, the composite iron was bound to be in shape also, and there was no more necessity to trammel the iron in those shields than in the case of the ordinary 11-foot $8\frac{1}{4}$-inch lining. Mr. Taylor had referred to the smallness of the working-sites provided for the contractor. It was, of course, difficult in London to give a contractor all the facilities he would like, but he had no cause for complaint when such facilities as were available were stated in his contract. Mr. Taylor's reference to a site of 5 yards by 6 yards as a working-site handed over to him was rather misleading. That area was the site of the temporary shaft only; permission had been obtained from the local authority to enclose an area of the footpath and roadway adjacent thereto, on which the contractor erected his crane and spoil-gantries, machinery-sheds, etc., as had been done in the case of the five temporary shafts shown in Fig. 3, Plate 3, three of which had been sunk in the public roadway. In Mr. Greathead's Paper[1]

Mr. Jones.

[1] *Loc. cit.*

Mr. Jones. it was stated that in the section of tunnel through water-bearing ground at Clapham Road, Stockwell, the pressure in the invert of the tunnel was that due to a head of water of $36\frac{1}{2}$ feet. That was in 1889. Since that date the level of the water in the ground had been so lowered by the construction of new main sewers, paving of areas, etc., that at the date of the enlargement works in 1923 the water-level was only 1 foot above the invert of the tunnel. He thought the lack of water in the gravel accounted for the high air-losses referred to on p. 191. The gravel-filled depression in the clay extended to about 18 feet below the invert of the tunnels. Sandy clay had been met with 300 yards north in the section referred to as runs Nos. 2 and 4, where a pressure of 10 lbs. per square inch was required to keep back the water. It seemed obvious that there was a dividing ridge or barrier of impervious clay between those sections, and that there was no hydraulic connection as suggested by Mr. Deane. He had experienced several instances, as far apart as Tooting and Clerkenwell, when tunnelling in the Woolwich and Reading beds, of enclosed pockets of waterlogged sand, sometimes of considerable area, in the clay, where of course the water could not be driven away by air-pressure. In setting-out for the reconstruction of the tunnels no extreme accuracy had been necessary. An interesting account had been given[1] by Mr. David Hay, in the Correspondence on Mr. Greathead's Paper, of the methods adopted, using a 7-inch theodolite, in setting out the main lines under very difficult conditions, the results comparing favourably with those on the latest tube extensions. He could not agree with Mr. Berridge's contention that the clay-pocket method could be used only at a low pressure and in a small tunnel. That method had been used very successfully on the river crossing of the Baker Street and Waterloo Railway, described in the late Mr. A. H. Haigh's Paper,[2] in pressures up to 35 lbs. per square inch, and he saw no difficulty in applying it in much larger suitably designed shields-provided with a hood. No mechanical excavators had been used on the enlargement of the tunnels, because the shields easily had broken down the whole of the excavation, and they would, in any case, have been inadmissable, owing to the necessity of clearing the tunnels for through running. On the Morden extension of the railway they had been used where the ground was suitable. Pneumatic spades had been very extensively used for the hand tunnel-excavation, and pneumatic concrete-breakers for breaking up the old concrete road-bed and

[1] Minutes of Proceedings Inst. C.E., vol. cxxiii (1896), p. 118.
[2] *Ibid.*, vol. cl (1902), p. 25.

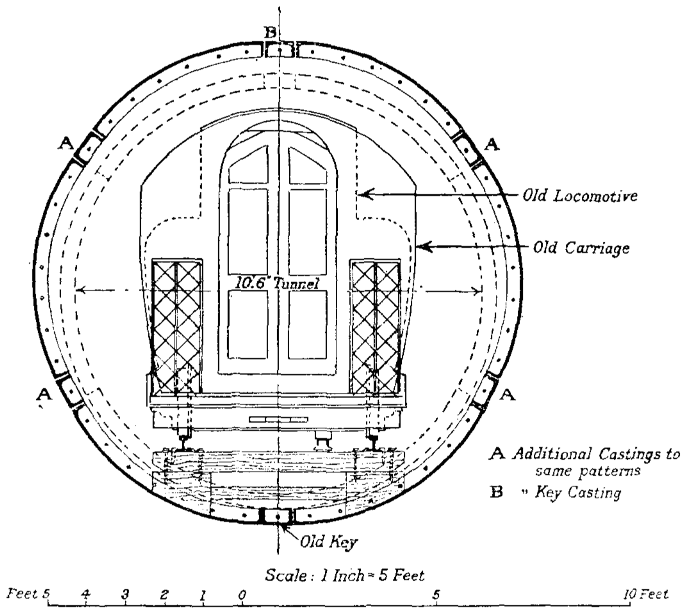
generally in breaking out concrete and brickwork in the reconstruction work. Oxy-acetylene cutting-apparatus had also been an exceedingly useful adjunct for the cutting-out of the old shield-skins which had been buried in the ground, and in cutting away girder work, etc. The extent of the work carried out by administration was described on p. 179. For carrying out this work the mining labour at the tunnel faces had been supplied by a contractor, who had been paid a percentage on his wages bill; and he had provided his men with ordinary hand tools. All other labour and plant, including pneumatic hand tools, and all management and engineering had been dealt with by the engineers, the purchasing of plant and materials having been done by the railway-company on the requisition of the engineers. Mr. Jones.

Mr. Curry, in reply, referring to Mr. Pick's suggestion that tube-railway construction might be cheapened by standardization and by mass production, remarked that Mr. Jones had pointed out the present limitations of speed in shield-driving and the possibilities of an increase in the speed of driving the rotary excavator shield with the assistance of a segment-erector. Those shields at present could reach a speed of eleven rings per shift in good ground. To achieve a progress of nine rings per shift, grouting of the rings was only required to be done every two or three rings. A limit of nine rings per shift had been imposed upon progress by the engineers, to allow time for the grout to set. When the speed exceeded about nine rings per shift it was frequently at the expense of keeping to good line and level. The Underground Railway Company allowed only a small clearance between their structure gauge and the iron lining. At one period during the enlargement that allowance was $1\frac{7}{8}$ inch near the haunches of the 11-foot $8\frac{1}{4}$-inch lining. On a curve of 20 chains radius the overhang of the rolling stock absorbed $1\frac{1}{2}$ inch of that clearance, leaving a very small allowable deviation from the correct line, level, or shape of ring. The company, however, found that they were able to increase that particular clearance to 3 inches. For the fast driving of a shield that clearance was still a handicap on a 20-chain curve, especially where a vertical curve had to be taken into account at the same time. With reference to Mr. Taylor's remarks, in addition to the use of the station building and roof at Euston, the contractors had been able to enclose the footpaths on two sides of the station building in their hoardings in Drummond and Seymour Streets. The importance of tightening bolts in the horizontal joints of the cast-iron lining increased in proportion with the number of joints per ring. Bolts in a horizontal joint no doubt tended to slacken Mr. Curry.

Mr. Curry. slightly soon after building, especially when wood packing was used. Neglect to tighten the bolts to a reasonable extent on completion of the building of a ring was the first means adopted by some gangs to gain time. Such neglect also tended to increase with the number of joints per ring; it varied from the obvious to the slightly doubtful, but usually could not be mistaken. With regard to the pocket of wet sand encountered between Euston and King's Cross during the original driving of the tunnels, Mr. Deane had not said how the difficulty of encountering wet sand had been dealt with when compressed air was of little use. During the enlargements in the neighbourhood of Euston station water-bearing strata had been encountered on which compressed air had had a useful effect, in some cases more noticeably than in others. Mr. Curry was of the opinion that many of the so-called pockets of wet sand were pockets with one or more holes in them, which, however small, allowed the water to be blown back by the same passage through which it had made entry. In some cases the rate at which the water could be blown back through, say, a narrow vein of sand might be very small, but still of some assistance. The true wet pocket, without any means of egress for the water, could be made by the tunnel itself cutting off and entirely isolating a portion of wet sand from its main bed. Unless that artificially-made pocket was large, it should drain itself in due course. In dealing with the shape and strength of the 10-foot 6-inch to 11-foot $8\frac{1}{4}$-inch diameter composite lining (*Fig. 18*), it would perhaps be best to consider first the true circular 11-foot $8\frac{1}{4}$-inch diameter lining. The line of the ellipse of pressure for a tunnel built in clay showed the circular lining to be in tension on the outside of its section at the springing and on the inside of its section at the crown. The shape of the section of the segment of cast iron being more favourable to its being put under tension on the outside than on the inside, the lining at the springing was therefore more able to withstand the stresses on a well-constructed tunnel in clay than was the lining round the crown; but the design of the circular 11-foot $8\frac{1}{4}$-inch lining had stood the test of time, and therefore the factor of safety at the springing might be considered high. In the 11-foot $8\frac{1}{4}$-inch composite lining all the joints, with the exception of the key joints, lay, to all intents and purposes, on a circle 11 feet $8\frac{1}{4}$ inches in diameter, the key joints being situated $\frac{3}{4}$ inch above the circle. The segments at the springing took a course amounting to a maximum of 1 inch outside the circle at springing level and away from the line of pressure, and were therefore placed slightly more in tension on the outside of their section than if they had followed the line of the circle.

The portion of the lining round the crown followed more closely the line of the ellipse than did the true circle, and the tension on the inside of that portion of the crown lining was lessened. In other words, owing to the shape of the composite lining, a slight sacrifice of strength was made at the springing where it could be afforded, and a slight increase of strength was given to the crown where it was most needed. He thought that the additional number of joints (which should be avoided, if possible, as being an element of weakness) was compensated for in this way. Mr. Jones, in his Mr. Curry.

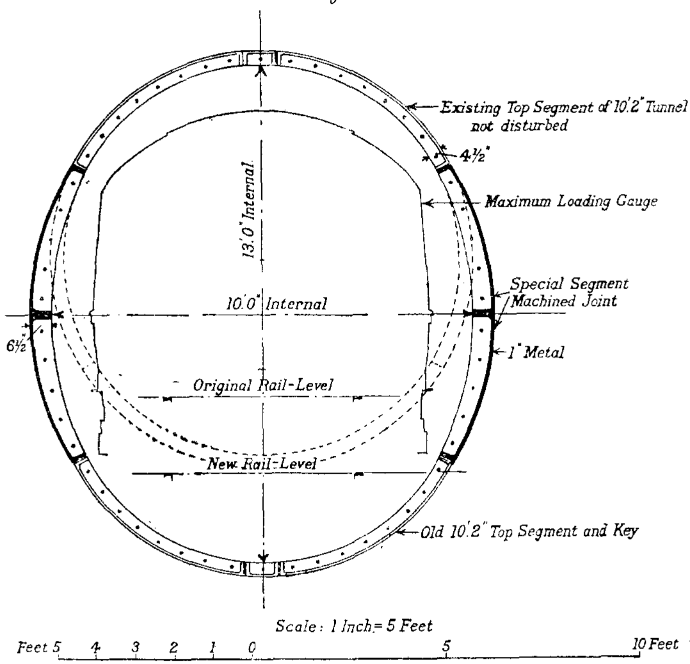
Fig: 18.



reply, had pointed out that no more movement had occurred in the composite-lined tunnels than in tunnels with new lining. Gaugings taken at intervals of approximately 1 week, 3 weeks, 2 months, and 9 to 11 months, after building, showed that any appreciable movement took place usually within the first 3 weeks. Many thousands of gaugings had been taken, and the maximum movement had in no case exceeded $\frac{1}{4}$ inch. That seemed to show that the composite lining had been subjected to much the same condition of external pressures as, and had behaved in a similar way to, a new tunnel with truly circular lining driven in virgin clay, referred to by Mr. Dalrymple-Hay. The section of the oval tunnel at

Mr. Curry. Newington Causeway was shown in *Fig. 19*. Referring again to Mr. Pick's remarks, it had always appeared to Mr. Curry to be unfortunate that when the trouble and expense of running a railway 40 feet or more underground was incurred, it should be made to follow the tortuous windings of the streets. That was apparently a necessity caused by the cost of easements and the difficulties of obtaining powers to run under properties. If straight lines could be made for the greater parts of the distances between stations, not only would the lengths of tunnel be reduced, but the reduction in the number

Fig. 19.



and lengths of the curves and the longer radii of those remaining would tend to cheapen and simplify the driving of the shields, and especially of the rotary excavators. It would perhaps be possible for the Underground Railway Company to promote legislation to enable powers to be obtained more easily than at present for tunnelling under private property. That would especially benefit any scheme for running express tubes with stations at longer intervals than generally existed at present. As an instance of an endeavour on the part of the manufacturers of the cast-iron segments for the

Morden entension of the City and South London Railway to cut down expenses, he cited their attempt to use in their foundry sand-throwing machines, which had been largely used in America. Several of those machines had been installed but, whilst each of them was capable of ramming moulds at quite four times the rate at which it could be done by manual labour, difficulties and obstacles had been raised against their use to such an extent as to render them ineffective, and they had been discarded. He would like to join with Mr. Jones in his praise of the work of the assistant engineers. On the northern section they had been fortunate in having less night work, but excellent work had been done by the assistant engineers of both the engineers' and the contractors' staffs. Mr. Curry.

Correspondence.

Mr. W. C. EASTON remarked that, from the short references (pp. 180, 185, and 189) to the enlargement of the tunnels under the river Thames at London Bridge, apparently little difficulty had been experienced there. The reference on p. 177 would appear to be the first record in the Proceedings of the 11-foot 6-inch tunnels driven in 1900. The late Mr. Greathead's Paper fully described the original 10-foot 2-inch tunnels under the river, now mentioned as being used only for storage of rolling stock. From Mr. Greathead's drawing,[1] the cover of the original tunnels under the bed of the river, mainly in London clay, was about 25 feet. What was the cover and the nature of the strata over the 11-foot 6-inch tunnels under the river-bed? The Authors referred (p. 189) to the fact that the clay in the roof at one point under the river Thames was very wet and unreliable, and they stated that as a consequence compressed-air working had been resorted to. The pressure used, 10 lbs. per square inch, indicated that the strata, although very wet, were strong enough to prevent the direct pressure of the river above from coming on the tunnel—a somewhat different condition from that experienced in one of Mr. Greathead's original 10-foot 2-inch tunnels[2] under the river. In view of Mr. Greathead's experience with one of the 10-foot 2-inch tunnels there, it was natural to expect that the greatest trouble would occur in the Mr. Easton.

[1] Minutes of Proceedings Inst. C.E., vol. cxxiii (1896), Plate 1, Fig. 4.
[2] *Ibid.*, p. 44.