Mr. Greathead.

tested, the fact that at the stations about 2,000 feet in length of the tunnels had been taken out was referred to in the Paper, and the perfect condition of the grouting behind the iron lining described. Within half-an-hour of its injection the grouting was generally as hard as the clay, and in a short time it became much harder, and it was therefore capable of taking the pressure transmitted by the clay. The cases of damage to property on the railway had been occasioned by the construction of the brick-lined tunnels, and were not due to any enlarged iron tunnels. As regards pumping, the success of the system of tunnelling described was due to the avoidance of that source of expense and danger.

Correspondence.

Mr. Armer.

Mr. JAMES ARMER stated, with reference to the tunnelling in connection with the metropolitan sewerage system, under the River Yarra in Melbourne, that, a former section of the work having been abandoned on account of the difficulties in driving through the silt formation, a shield had been made and sent from England early in 1894. It was 11 feet in diameter, and was in other respects identical to those employed on the City and South London Railway. The length adopted for the rings of the tunnel lining had been 2 feet 9 inches. During August, 1894, the rate of advance by this shield had been 11 feet 8 inches per shift of eight hours, an increase of 18 inches in the rate being anticipated with the addition of segment-lifting arrangements. The progress made in the same time by a shield constructed in the colony and working under similar conditions had been 2 feet 9 inches. The work under the Yarra was of a more dangerous character than that described in the Paper; but the accident in April, 1895, would appear to have been in no way attributable to the shield.

Mr. Bellamy.

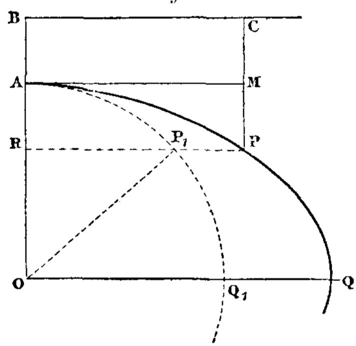
Mr. C. J. BELLAMY observed that the "hydrostatic arch" was well known to be the form suitable for sustaining the pressure of a perfect fluid, provided that its weight might be neglected, as being very small compared with the pressure of the fluid. This arch was not a closed curve, but a succession of loops. If, however, the weight of the arch itself was taken into account the curve became considerably modified, and there was a particular relation between the weight of the arch and the pressure of the fluid, for which the curve became a circle, as would be shown. In *Fig. 32* A P Q was a cross-section of the semi-arch at right angles to its length, and B C the surface of the fluid. The vertical forces

Mr. Bellamy. which kept the portion of the arch A P in equilibrium were the weight of the fluid A B C P, the weight of the portion of arch A P, and the vertical component of the thrust at P. Hence, equating the resultant of these forces to zero—

$$\int_o^x w\,(a+y)\,d\,x + v\,s - t\,\frac{d\,y}{d\,s} = 0 \quad . \quad . \quad . \quad (1)$$

where A B $= a$, A M $= x$, M P $= y$, A P $= s$, $w =$ weight per cubic unit of fluid, $v =$ weight per square unit of arch surface, $t =$ linear thrust at any point P per unit length of arch, and T $=$ linear thrust at A the highest point of the arch, where the curve was horizontal. The horizontal forces acting on A P were the thrust at A, the

Fig. 32.



horizontal pressure of the fluid on the vertical plane M P, and the horizontal component of the thrust at P. Hence

$$\mathrm{T} - \int_o^y w\,(a+y)\,d\,y - t\,\frac{d\,x}{d\,s} = 0 \quad . \quad . \quad . \quad (2)$$

Differentiating equations (1) and (2) with respect to s—

$$w\,(a+y)\,\frac{d\,x}{d\,s} + v - \frac{d\,t}{d\,s}\cdot\frac{d\,y}{d\,s} - t\,\frac{d^2\,y}{d\,s^2} = 0\,. \quad . \quad (3)$$

$$-\,w\,(a+y)\,\frac{d\,y}{d\,s} - \frac{d\,t}{d\,s}\cdot\frac{d\,x}{d\,s} - t\,\frac{d^2\,x}{d\,s^2} = 0 \quad . \quad . \quad (4)$$

Multiplying (3) by $\frac{d\,y}{d\,s}$ and (4) by $\frac{d\,x}{d\,s}$ and adding them together the resulting equation became—

$$v\,\frac{d\,y}{d\,s} - \frac{d\,t}{d\,s} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Mr Bellamy.

therefore $\frac{d\,t}{d\,y} = v$,

and $$t = \mathrm{T} + v\,y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Inserting this value of t in equation (2) and performing the integration in that equation, there resulted—

$$\frac{d\,x}{d\,s} = \frac{\mathrm{T} - \frac{w}{2}(a+y)^2 + \frac{w}{2}a^2}{\mathrm{T} + v\,y} \quad . \quad . \quad . \quad (7)$$

If b be the value of y, when the curve became vertical as at Q, at which point $\frac{d\,x}{d\,s} = 0$,

$$\mathrm{T} = \frac{w}{2}\{(a+b)^2 - a^2\} \quad . \quad . \quad . \quad . \quad (8)$$

Substituting this value of T in equation (7)—

$$\frac{d\,x}{d\,s} = \frac{(a+b)^2 - (a+y)^2}{(a+b)^2 - a^2 + \frac{2\,v}{w}\,y} \quad . \quad . \quad . \quad . \quad (9)$$

If now a particular value be given to v, viz., $\frac{w\,b}{2}$, equation (9) reduced to—

$$\frac{d\,x}{d\,s} = \frac{b-y}{b} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

If in *Fig. 32* the horizontal line Q O be drawn, and with O as centre the circle $\mathrm{A\,P_1\,Q_1}$ be described with radius O A, and the horizontal line $\mathrm{P\,P_1\,R}$ drawn, then at the point $\mathrm{P_1}$ on the circle

$$\frac{d\,x}{d\,s} = \cos \mathrm{A\,O\,P_1} = \frac{\mathrm{O\,R}}{\mathrm{O\,P_1}} = \frac{b-y}{b};$$

therefore the curve of the arch A P Q coincided with the circle $\mathrm{A\,P_1\,Q_1}$. This particular value which had been given to v, viz., $\frac{w\,b}{2}$, implied that the weight of any portion of the circular arch as $\mathrm{A\,P_1}$ was equal to the weight of fluid corresponding to the sectorial area $\mathrm{A\,O\,P_1}$, so that if the curve comprised the entire circle the weight of the cylinder was equal to that of the fluid it displaced; and with this condition the circular cross-section was a curve of equilibrium; and there was no bending stress on the cylinder, whatever be the depth of its immersion.

Mr. Brightmore.

Mr. A. W. BRIGHTMORE wished to add a few details in connection with the Vyrnwy Aqueduct tunnel under the River Mersey. The tunnel shafts were built of cast-iron, and were 800 feet apart from centre to centre. The depths of the shafts to the invert-level on the Cheshire and Lancashire shores of the river were 46 feet and 52 feet respectively. The external diameter of the tunnel was 10 feet, and that of the shafts 10 feet 9 inches, the latter being widened at the bottom to 15 feet. The minimum height of the river-bed above the tunnel was 20 feet, and the invert-level was about 50 feet below high water. The shafts were built of flanged cast-iron rings, 4 feet deep, varying in thickness between 1 inch and $1\frac{1}{16}$ inch, down to the widened part, which was built of smaller segments. The tunnel was built in rings, in each of which were ten segments, 3 feet by 1 foot 6 inches and $1\frac{1}{16}$ inch thick, weighing 4 cwt. each, and a key-segment, 1 foot by 1 foot 6 inches, weighing 1 cwt. The shafts had been sunk by loading the cylinders and excavating with a grab in the ordinary way, and nearly four-fifths of the tunnel had been driven by means of an improved shield; ten hydraulic rams, 7 inches in diameter, and working at a pressure of 1,000 lbs. to 2,000 lbs. per square inch, being used to force it forward. As the shield had usually a tendency to droop at the cutting-edge, it had been seldom necessary to employ the upper rams—a circumstance, no doubt, due to the greater resistance at the bottom of the shield. When there was no unusual obstruction, the friction in the shield amounted to about 4 cwt. per square foot, and sometimes to somewhat less.

The pressure of air in the tunnel was usually between 12 lbs. and 15 lbs. per square inch above the atmosphere, often about two-thirds the hydrostatic pressure of the water outside. As a rule it had been necessary to pump into the tunnel 500 cubic feet of air per minute (measured at atmospheric pressure), and in exceptional cases more than double that amount. Two methods of working had been employed. When, owing to the fairly uniform permeability of the strata, the air escaped evenly through the face and kept it dry, except quite at the bottom, the men, while standing in front of the diaphragm, excavated for about 18 inches beyond the cutting-edge; the pressure being then turned on to the rams, the shield advanced into the space so prepared. When the air escaped unevenly, the face, or a portion of it, was wet, and the men excavated standing in the pocket between the two diaphragms, the pressure being kept on the rams, so that the shield crept forward as each spadeful of material was removed, until it had advanced 18 inches. The time taken to advance the shield this distance and get out the excavation was practically the same with both methods. The next ring of segments was then fixed for the excavation to be resumed as before. It was worthy of remark that, after the improved shield had been put to work, the time taken for the excavation and advance of the shield was fairly constant, at the rate of about one hour and a half for each ring, unless there was some unusual obstruction. On the other hand, the fixing of a ring of segments took at first four hours; but when the men were well drilled to the work, this rate was greatly increased, and before the completion of the tunnel it had been found possible to fix a ring in one hour and a half. The leakage of water into the tunnel during the driving had varied between 30,000 gallons and 40,000 gallons per day. Mr. Brightmore.

Mr. E. G. Carey remarked that the rapid development of the system of tunnelling described in this Paper had led to the design of special plant, for the manufacture of the cast-iron segments of the lining. Those for the Glasgow District Subway were almost identical with those for the City and South London Railway, and were moulded in specially designed machines consisting of a 4-inch hydraulic ram working both the pattern and the box. A pair of side levers, actuated by a second hydraulic ram 2 inches in diameter and of 11 inches stroke, held the swing-head in position, the latter consisting of a cast-iron girder, with a hard wood ramming-block bolted to its lower side. Four guides, $4\frac{1}{2}$ inches in diameter, were secured to the cast-iron bed-plate to direct the actions of the ram which was counterbalanced. The empty moulds were conveyed beneath the machine on bogies and were transferred to it by the outline plate which was swung over. The ram then brought the pattern into place, sand being fed in from a hopper above, and the swing-head was then raised, and the ram caused to bring a final pressure to bear on the sand. The ram was then lowered, withdrawing the pattern and the swing-head being thrown back, the mould was turned over on to the bogie beneath by the outline plate. A hand-screw withdrew the pattern ends from the mould. The hydraulic pressure was 1,500 lbs. per square inch. Each of these machines produced $1\frac{1}{2}$ ring per hour (9 segments per ring). The total quantity in the Glasgow District Subway was 20,000 tons. Mr. Carey.

The Blackwall Tunnel segments had been machine-moulded, their size prohibiting hydraulic moulding. The moulding-machine consisted essentially of a main framing of cast-iron, carrying both pattern and moulding-box, and capable of turning completely over on side hinges. The pattern flanges were operated by four hand-wheels, 24 inches in diameter, to enable the mould to leave the

Mr. Carey. pattern, which was of mahogany, brass bound at the edges. The pattern with flanges in position, and mould-box being in place, sand was shovelled-in and rammed, the lid was then clamped on and the main framing thrown completely over. The flanges were then withdrawn and the mould received the hand-moulded top portion. This machine would make between thirty and thirty-three segments in the working day of nine and a half hours, the maximum attained in this time being thirty-six segments. The segments of the Edinburgh Mound Tunnels, and the Glasgow Central Railway sewers, were hand-moulded, the quantities required not warranting the construction of special plant. Special milling plant had been designed for machining the ends and sides of the segments. Two types had been adopted, viz., the work stationary and the tool travelling, and *vice versâ*. The milling heads, whether travelling or not, were essentially the same in each type and were furnished with cutting tools about 3 inches apart on the circumference. More than 50 miles of milling of 10 inches wide planing was thus performed. The patent moulding and milling plant had been constructed from the designs of Mr. Stephen Alley, Glasgow, at the works of the British Hydraulic Foundry Company, Limited, Whiteinch, Glasgow.

Mr. Fox. Mr. Francis Fox, of Westminster, had had considerable experience with the Greathead shield and grouting machine, and desired to bear his testimony to the great value of these appliances, which together formed one of the greatest improvements that had been introduced into the art of tunnelling during the last thirty or forty years. They had, to a great extent, deprived subaqueous or submarine tunnels of the risk formerly attending their execution, and had also, under many circumstances, much reduced their cost. Such tunnels could now be driven safely and rapidly through silt, gravel and sand, previously impassable at any reasonable cost. It might be true that the idea of a shield was not a new one; and the late Sir Charles Fox, M. Inst. C.E., had employed cement grout under hydrostatic pressure for the repair of cracks in brickwork, as early as 1865. The system of blowing in the grout by compressed air, introduced by the Author, was, however, a great improvement upon the hydrostatic process; and, having employed it upon several occasions, and under varying circumstances, he had formed the highest opinion of its efficiency, and commended it to the attention, not only of engineers, but of architects, for the grouting of masonry or brickwork showing cracks due to settlement, or other causes. For the repair of cathedral or church towers, or tall chimneys, he considered that it would prove of the greatest value, the cost of its efficient application to ensure the safety of the structure being probably not one-fiftieth part of the expense which would be incurred in rebuilding. He would not attempt to express an opinion as to the probable originator of a shield, for which several claimants had been put forward; but he considered that the credit of introducing, practically applying, and working out to a satisfactory completion the system under review was undoubtedly due to the Author, and that his name would be inseparably connected with this most important addition to the resources of civil engineers engaged in the construction of tunnels. Mr. Fox.

Mr. Druitt Halpin observed that a useful Table of costs of construction of various underground railways was given in the Zeitschrift des Vereines deutscher Ingenieure of the 26th October, 1895. Mr. Halpin.

Mr. J. C. Hawkshaw considered that the process of tunnelling by means of a shield and compressed air, which had been so successfully used and so well described by the Author, was, and always would be, of great value in driving tunnels through water-bearing strata at no great depth below the surface of the water which determined its pressure. But the limiting depth at which the shield process could be used was soon reached; probably 80 feet would be a maximum depth. The cylinders of Londonderry Bridge had been sunk by compressed air under a water-pressure of 80 feet, but five men had lost their lives owing to the severity of the work under such a pressure. That the process described in the Paper could be used only in tunnels at a comparatively shallow depth must be sufficiently obvious. It had been inferred that the Severn Tunnel could have been, or could now be, more cheaply constructed by using a shield with compressed air, and that similarly the Channel Tunnel and the Irish Tunnel could be more cheaply constructed by the same means. Compressed air could not be used in connection with a shield to keep back water at the tunnel faces in any one of the three cases mentioned. The least depth of the rail-level below high water, in the Severn Tunnel, was 80 feet close in shore; and it increased to 160 feet below the shoots and to 200 feet at the drainage heading. In the English Channel there was a depth of 120 feet of water, and the tunnel itself would have to be at a much lower level, probably between 250 feet and 300 feet below the surface of the water. In any tunnel to Ireland the depth would be greater still, as there was a sounding of 500 feet in the channel between the two countries. In the cases of the three tunnels mentioned, therefore, the process Mr. Hawkshaw.

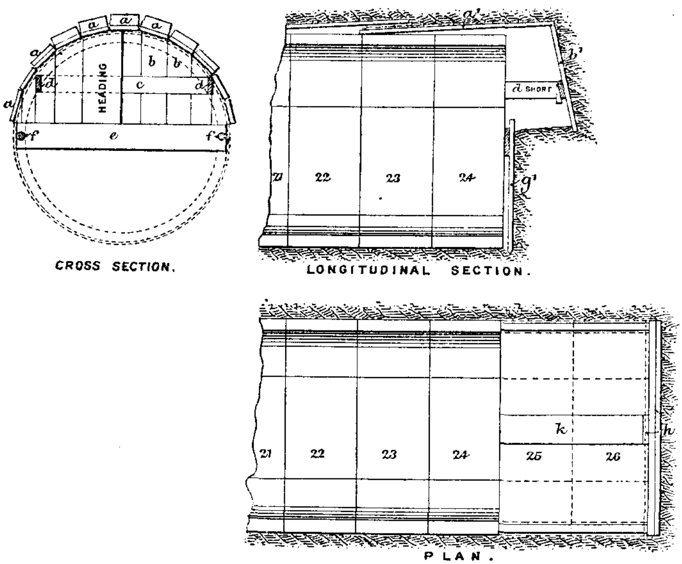
Mr. Hawkshaw. adopted with such success on the City and South London Railway could be of no avail. If a second Severn Tunnel were made, all the water penetrating into the working would have to be pumped, and so it would be if tunnels were made beneath the channel between England and France, or between England and Ireland. The practicability of making such tunnels depended on whether the whole of the water entering the workings could be dealt with by pumping. If it could not there was no known process by which such tunnels could be made.

Mr. Hay. Mr. DAVID HAY stated, with reference to the alignment of the tunnels described in the Paper, that, in order to determine their exact positions, an accurate survey had been made, showing the main roads to be followed and the buildings fronting upon them. This survey having been laid down to a scale of 10 feet to an inch, the centre lines of the tunnels had been marked, and points in the straight portions measured off from prominent buildings. These points had been established in the road, either by driving thin steel wedges between the setts where the road was paved, or by iron pins 12 inches long where it was macadamised, a centre-punch mark being made in either case. The lines had then been measured to the nearest curb, so that the marks might be easily found or reinstated if destroyed. The base lines thus fixed had been extended, and where they intersected each other the angle had been read off with a theodolite, the lengths between the points of intersection being carefully measured. In consequence of the heavy vehicular traffic all along the route of the railway during the day, it had been found possible to do this work only at night or early on Sunday mornings. In the former case a tissue-paper screen, held in front of an electric lamp driven from a primary battery, had been found most useful for sighting. In consequence of the shafts having been at some distance from the tunnels, the lines fixed on the surface could not be directly transferred to the tunnel. It had therefore been necessary to ascertain the angle between the line of the cross-passage and the line of tunnel. After the shaft had been sunk, the line of the cross-passage had been set out on the surface and the point of intersection, with its angle, fixed and read in the usual way. Two plumb wires had then been sighted into line in the shaft, to which the cross-passage had been driven the requisite length. The wires had been again sighted, and the distance, from the intersection to one of them, accurately measured on the surface. The theodolite had then been taken below and set up in the line of wires at a distance from them corresponding with that measured on the surface, and the angle read off, thus determining the line of tunnel to be driven. This operation had been repeated two or three times at each station until a sufficient length of tunnel had been driven to admit of a reliable base line being established. The most convenient method of establishing points had been found by filing nicks in staples driven into hard-wood wedges fixed between the cast-iron rings at the top of the tunnel. When sighting a plummet line in the staple, the tissue-paper screen had been placed behind it; and when the atmosphere in the tunnel was clear extreme accuracy had been possible, the smallest variation of the line being easily detected. A clear sight, however, could seldom be obtained with the theodolite for more than 250 feet or 300 feet, on account of the smoke from the candles, &c.; recourse had therefore to be had to a long steel piano-wire $\frac{1}{32}$-inch thick to produce the straight lines. This wire had been sometimes used for lengths up to 700 feet and had been stretched along the roof of the tunnel out of the way of traffic. By the use of plummets with fine steel points and thumbscrews for adjusting the wire great accuracy had been obtained, and after the first base line had been established it had never been found necessary to use the theodolite until a curve was reached. The line staples had been driven about every fifty rings, but never close to the shield, as there was a danger of the lining moving slightly. Daily checkings of the portion of the lining fixed had been made with a shorter wire, one end being attached to the third staple from the face, and the other end fastened to the shield. It had then been adjusted by the other two staples, a light plummet line being hung upon it opposite the last ring, and measurements being taken to check the position. A 7-inch theodolite had been used by Troughton and Simms. No special rings of cast-iron lining had been used for the curves; consequently iron packings had to be placed between the rings to make the joints radiate from the centre point of the curve. When approaching a curve the side of shield on the outside was made to lead a distance corresponding to the iron packing to be inserted, and at the same time the cutting edge of shield was freed on the inside of curve. This latter was a very important point and must be insisted upon, otherwise the men would neglect it, as it gave them a good deal more trouble. Mr. Hay.

Mr. W. A. P. Tait observed that the tendency appeared, from Table II of the Appendix, to be in the direction of an increase in the internal diameter of subways for electric or cable railways. It would be useful if the Author would not only state the cost of the lines of 10 feet 2 inches and 12 feet 6 inches internal diameter, Mr. Tait.

Mr. Tait. but the probable cost in similar circumstances of lines large enough to take the ordinary railway rolling-stock and satisfy Board of Trade requirements. It appeared a short-sighted policy, even though there might be a small saving, to construct subways of such small diameter as to cause the equivalent of a break of gauge. The permanent way was of the ordinary gauge, but there could not be reciprocal running powers. He understood that the air of the District Railway contained between twenty-two and thirty parts in 10,000 of carbonic acid, a somewhat larger ratio than found in an

Figs. 33.



Scale, ½ inch to 1 foot.

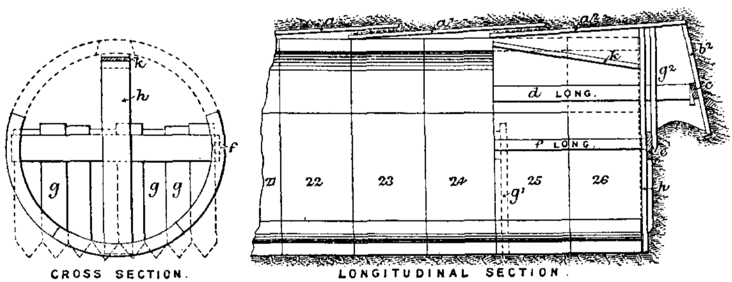
average theatre. Analyses of the air in the tunnels worked by the electric engine would be interesting.

Regarding the driving of the tunnels, he had had charge during construction of two of the small tunnels under the streets of Glasgow referred to by the Author. One of 4 feet internal diameter had been driven through wet sand, gravel and ballast, without a shield, and had proceeded at the rate of 1½ yard daily at each face. The progress of the other with a shield had been less satisfactory. It had been usual to take out, at one time, excavation for two complete rings of cast-iron, each made up of six segments, representing an advance of 3 feet. Eleven poling boards, *aa*, *Figs. 33*, supported at their

Mr. Tait.

leading ends by *bb*, had been used to support the roof until the two rings of the lining were finally erected. The other ends of the polings had been supported on the last completed length. The crown polings rose 3 inches in their length forward to allow for subsidence, and still permit the placing of the poling for the next length beneath. In order to "get in the top" for the rings Nos. 25 and 26, for example, the miner first removed a leg *b*, under a crown poling a^1 and drove a heading, shown in the section, the full length, about 4 feet, of the new poling board, a^2, and immediately propped it with the old leg, b_2, *Figs. 33* and *34*, and so on, widening the heading out to either side until all the new polings, a_2, were inserted and supported by legs, b_2. Great care had been taken to cover each of the polings before they were inserted with a layer of well-tempered clay. This had occupied the time of two miners, who in the limited space could only work

Figs. 34.



Scale, ¼ inch to 1 foot.

alternately, and a labourer about four hours. The legs, b_2, were then secured by a waling *c*, *Figs. 34*, held by two rances, *d d*, butting against the flange of the ring last erected. Next a waling *e* (held in same way) was set up so as to be somewhat more than 3 feet from the last ring, in order to let in two rings of 18 inches each. A series of piles, g_2 and *g*, *Figs. 34*, were set up and worked home as a little excavation was taken out. Little by little the dumpling had been removed, until at last one half of the length had been bottomed. Some difficulty had occasionally arisen at this stage, if the air-pressure was not maintained, and great care was necessary in taking out the last of the muck. In such a case the bottom plates had been laid in water. This second stage had occupied about three hours. After the bottom segment had been inserted, the trouble was much reduced, and the work became more easy. Before the second segment from the bottom could be

Mr. Tait. inserted, one of the rances, *f*, had to be removed, but it had been temporarily replaced by the soldier and stretcher, *h* and *k*, *Figs. 33* and *34*, but as soon as the second segment of ring 26 had been inserted, the waling, *e*, had been dwanged from the flange of that segment. The subsequent grouting had been as described by the Author. While all the polings used were allowed to remain, the rest of the timber was used again and again, the long and short pairs of rances *d* and *f* being used alternately.

A curious paradox in connection with the driving of tunnels in compressed air under the River Clyde had been noticed, viz., that a lower pressure often sufficed to keep the tunnel dry at high than at low water. This had been possibly due to consolidation of the silt by the increased superincumbent pressure. In view of the fact that excavation at a working face, unless supported, did not stand vertical, it occurred to him some years ago that in order to effect greater progress with a shield, the roof should be prolonged slightly so as to take the natural slope. This would, to some extent, obviate the present practice of working in advance of the shield; but care would have to be taken to prevent the shield from turning about its axis, a circumstance which occasionally happened.

Mr. Greathead. Mr. GREATHEAD, in reply to the correspondence, said that in fixing 80 feet as the maximum depth under water for tunnelling by shield and compressed air, Mr. Hawkshaw was not far wrong if he meant that the pressure of the air was to be, as usually in shaft sinking, such as to completely balance the head of water; but there were occasions when this was by no means necessary, and where compressed air could be used in tunnelling at much greater depths than 80 feet with great effect as regarded safety and economy. There could be no doubt that in cases where much water was encountered at great depths, whether compressed air were used or not, it would often be economical to put in cast-iron lining to avoid the permanent cost of pumping. The reduced quantity of excavation would generally in such cases balance the extra cost of iron over brickwork. It was stated by Mr. Carey that the cast-iron segments for the Glasgow District Subway were almost identical with those of the City and South London Railway. The design of the latter had, however, been departed from in the former in one respect which it was worth while to notice. The longitudinal joints, instead of being made with flat faces of the whole depth of the flanges, Fig. 16, Plate 2, had been made like the vertical joints in the City and South London tunnels, with a chipping edge or fillet along the outer edge of the flange. Where rigidity was required to prevent deformation and to secure the maximum efficiency of the iron this form of longitudinal joint, with a soft-wood packing between the flanges, appeared to him to be an unfortunate modification, because the bearing-surface of segment against segment was practically reduced to the width of the chipping edge with the result that there was very little resistance to outward movement, away from the centre, at any of these joints. Mr. Greathead.

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26 November, 1895.

SIR BENJAMIN BAKER, K.C.M.G., President, in the Chair.

The discussion of the Paper on "The City and South London Railway" occupied the evening.
