The Charing Cross, Euston and Hampstead Railway

With Special Reference to the Methods Adopted in the Construction of the Tunnels

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The success of the first underground railways, worked by electrical power, in London, the City and South London Railway, the Waterloo and City Railway and the Central London Railway, led to similar lines being projected and carried out during the decade 1900 to 1910. The existing facilities in the older underground steam railways and vehicular traffic had long been overloaded during the morning and evening rushes between the suburbs and the heart of London and it was evident that additional underground Railways, electrically worked, along routes which were then badly served, which could be constructed without involving the high cost of the acquisition of land and buildings, would meet the needs of the travelling public and would prove to be a sound financial proposition.

The Charing Cross, Euston and Hampstead Tube Railway was one of these undertakings and was constructed between the years 1902 and 1907, being opened for traffic about the end of the latter year. This work comprises about 7½ miles of double tunnel of cast iron section with contingent works, between Charing Cross and Golders Green and the branch line Camden Town to Highgate, as shown on the diagram map Fig. 1. The running tunnels are of 11 feet 8½ inches and 12 feet 7 inches internal diameter. There are
seventeen stations, each having two tunnels 350 feet long by 21 feet 2½ inches diameter, the shafts for lifts being 23 feet in diameter and the staircase shaft 18 or 16 feet in diameter with the necessary connecting passages.

The terminal station at the suburban end of the line, which is in the open, is situated at Golders Green where running sheds, workshops, sidings for marshalling trains and other facilities are provided. Between Leicester Square and the Strand stations and near Highgate station, the running tunnels converge toward and diverge from "crossover" tunnels 100 feet long by 23 feet 2½ inches in diameter which provide room for a scissors crossing which allows for the working of trains from one line of track to the other.

The works comprising the tunnels and contingent work in shafts and passages, between the Strand station and Golders Green and the branch line Camden Town to Highgate, the underground station at Tottenham Court Road and the yard at Golders Green were designed and the construction supervised by the firm of Engineers, Messrs W. R. Galbraith and R. F. Church, M.M. Inst. C.E., in association with Sir Douglas Fox and Partners, the cost amounting to about £1,750,000. The contractors for these works were Messrs. Price and Reeves of Westminster. The station buildings above ground, permanent way, signalling, electrical equipment, lifts, staircases, and the provision of the rolling stock were carried out by other firms. The author was employed on the staff of Messrs. Price and Reeves and was for the first few months in charge of various sites and afterwards, until the end of the work, Senior Assistant in charge of the section Euston, to the Strand under the Chief Engineer to the contractors, Mr. J. Brown, M. Inst. C.E. In addition to employing the services of the above engineering firms, whose Resident Engineer was Mr. A. W. Donaldson, M. Inst. C.E., the Underground Electric Railways Company of London, Ltd., had their own staff, their Chief Engineer being Mr. Harley H. Dalrymple-Hay, M. Inst. C.E.
ALIGNMENT AND GRADIENTS

Under the powers taken for the construction of this Railway, the tunnels, as far as possible, were to be located at least 6 inches outside the building lines of the streets traversed and the levels fixed, having due regard to the possibility of future extensions and the provision of footway connection to certain other railways. The position of the Golders Green terminal station and yard being settled, the necessary surveys were made, plans prepared and the alignment and gradients of the Railway determined. In the earlier tube, the "Central London Railway," which traverses London parallel to the River, advantage was taken of the fact of the surface being practically level to dip the gradients between the stations to assist the acceleration and retardation of trains when leaving or approaching stations and thereby effect economy in current, but as the suburbs of Golders Green and Highgate are at a much greater elevation than the Strand, the same arrangement in the case of the Railway under description would have greatly increased the cost. The station tunnels are in every case placed on the level, the gradients between them rising generally towards Hampstead and Highgate, the ruling gradient being 1 in 120. At the intersections of gradients to ensure ease in running the tunnels were driven on vertical curves, consisting of flatter gradients. Owing to the Railway being under main thoroughfares for the greater part of its length the curvature is easy, but near Euston and the Strand stations, owing to the layout of the streets, it was necessary to take the tunnels under buildings and also to introduce sharper curves. The minimum radius allowed was 5 chains with compound transition curves, the latter being formed of successive circular arcs increasing in curvature up to the commencement of the main curve.

SHAFT SINKING

The shafts, which are of varying depths, being 60 feet at the Strand to 230 feet at Hampstead are, as stated above, of 23, 18 and 16 feet internal diameter and are formed of
cast iron segments 4 feet deep bolted together along the circumferential and vertical joints, 12, 10 and 8 segments respectively forming a ring. The ordinary method of sinking this type of shaft through the London clay, where no water occurs in the top strata, is simple. The top ring is first built, carefully levelled and trammelled and the excavation taken out for four segments of the next ring below, two of each of these segments being opposite on square lines intersecting the centre of the ring; these are then lowered by crane, bolted into position and temporarily strutted. The excavation is carried on for four more segments, each being next to one of those already built into position so that square lines as above again intersect them and so on. The ring is built slightly larger in diameter before tightening the bolts to avoid any difficulty in placing the last segment. Each ring when built is carefully trammelled and the bottom of each segment checked from plumb lines. To avoid continuous vertical joints in the iron lining of the shaft, each ring is built so that the vertical joints at the junctions of its segments come under the centres of the segments of the ring above. Before operations are commenced a grouting plant is installed on the site and on the completion of each ring the space between the "iron" and the clay is grouted up under pressure with a mixture of three parts blue lime to one of sand, the segments being cast with a hole through the centre for the purpose. Between each ring and cross fitted for packings are inserted to make the joints watertight and to provide a means of adjustment for keeping the shaft plumb. At the bottom of the shafts special castings are built into position where the passages are afterwards driven and a concrete invert is placed on which the concrete beds for the electric lift machines are built. A section of one of the 23 feet diameter shafts is shewn in Fig. 2 giving the stratum through which it was sunk and the rate of progress, the average speed being about 2 feet a day. The strata vary very little along the route of the Railway, the tunnels being for the most part driven
through the London clay, which is a good medium in which to work, despite the occasional presence of small boulders.

At one site only was it necessary to depart from this method of sinking. At Goodge Street station the first shaft sunk was one of 23 feet diameter. On reaching a depth of 20 feet a layer of sand about 5 feet thick which contained water was encountered. There was a danger of the operation of sinking the shafts through this layer causing settlement of the surrounding buildings which were old and which it was ascertained by trial holes were founded on the sand. The walls of these buildings where they abut on the site were therefore underpinned, the underpinning resting on the clay 25 feet below the old footings and being made thick enough to carry the walls of the future station building, which were at the time built up against the walls of the existing buildings to second floor level as an additional safeguard.

The sinking of the shaft was then re-commenced, the method adopted through the layer of sand being shown in Fig. 3. A sump in timber was first made at the centre from which the water was pumped, struts were placed between the timbers forming this sump and the last ring built and the excavation taken out in sections by piling with 1½ inch boards. Two of the sections taken out provided room for one segment, which after being bolted into position was strutted and grouted up. It was found necessary to build one ring only by this method, but as a precaution the excavation for the next ring was close timbered as taken out, the remainder of the shaft being completed by the ordinary method.

The local authorities objected to this method on the ground that the pumping of water from the sand might cause settlement and damage to the buildings in the vicinity and it could not be used for the other two shafts on the site. It was realised that it might be necessary to sink them through the sand under
compressed air, but in order to avoid the expense of this method it was decided to fix cutting edges and if possible to sink them by weighting with cast-iron segments already on the site for the construction of the tunnels as illustrated in Fig. 4. The skin friction on the outside of the shafts as they were sunk varied from 2 to 3 cwt. per square foot and the time taken in sinking was considerable, but the method was attended with success.

**Hand-driven Tunnels**

The first operation after sinking a shaft consists of driving 8 or 10 feet diameter tunnels up to the position of the running tunnels and the latter tunnels up to the position of the shield chambers. These tunnels as well as the passages were driven by hand and the work being of a simple character in the clay calls for no special comment.

The shield chambers for the small shields which are of 15 feet diameter are large enough to allow room for fixing the tackle required in the erection of the shields and are built without any special timbering, the clay as a rule being stiff enough to stand.

The space between the cast-iron rings of the tunnel lining and the clay was grouted up with either neat blue lias lime which is highly hydraulic, or if the tunnel was wet, a mixture of half lime and half Portland cement. Each ring was grouted before the excavation for the next ring was taken out. The grout is forced through holes provided in the castings for the purpose, by a nozzle at the end of an armoured hose pipe which is connected to a grouting pan. This vessel is fitted with the necessary valves and is connected in turn to the service pipe in which an air pressure of 60 pounds to the square inch is maintained. When, for any reason, the construction of a length of tunnel was temporarily suspended the face was timbered and grouted to prevent any settlement of the clay which might cause a subsidence of the area above.
Included in the hand-driven tunnels are the large shield chambers for station and cross-over tunnels which are of 25 feet and 27 feet diameter respectively. Fig. 5 shows the method of supporting the roof while the excavation is taken out. A short vertical shaft is first driven at the end of the tunnel already built and after lines and levels are given, a horizontal heading is driven for the length of the chamber and the two H iron top crown bars placed in position on timber props and strutted. The heading is then widened out for the next bar on either side and so on, the floor being lowered at the same time and the props carrying the bars replaced with longer ones. On reaching the level of the top sills, these are placed in position and the props carrying the bars inserted as shown in the figure. The excavation is then carried down, the other sills and bars similarly placed and the poling boards grouted up as the work proceeds. The cast-iron lining of the chamber is then built, the crown bars being left in and the space between them and the iron rings packed tight with concrete.

**Shield-driven Tunnels**

While the hand-driven tunnels leading to the shield chambers were being driven, steps were taken to provide the machinery required for the construction of the tunnels and the disposal of the spoil. At each station, with the exception of Golders Green, Tottenham Court Road and the Strand, electrically-driven hydraulic-gushing and air compressing plants to work the shields and hoists for the shafts were installed, current being supplied from the local mains. A staging of squared timber was built over the shafts on to which the clay was dumped from the skips brought up in the cages and from which it was dropped through a shoot hole into carts which removed it from the sites, most of it being loaded into barges which were towed down the river, the clay being dumped in deep water.

At Golders Green the tunnels emerge into the open and the excavated clay was tipped to fill a low-lying portion of the site for the yard.
There are no shafts at this station, but the shields were driven from temporary chambers of special design at the mouths of the tunnels and the plant for driving them provided. At Tottenham Court Road and the Strand stations small air compressors for grouting purposes only were put down as the tunnels were driven from the adjacent sites.

The shields used in driving the tunnels for the Railway forming the subject of this paper, although of different diameter, were of the same type and similar in detail to those used for the earlier tube tunnels in London. The author has no drawings of these shields available, but as similar shields were illustrated and very fully described in a paper read before the Institution of Civil Engineers by Mr. Harley Hugh Dalrymple-Hay on the Waterloo and City Railway and printed in the minutes of Proceedings, Institution of Civil Engineers, Vol. CXXXIX., Session 1899-1900, these illustrations are reproduced in Figs. 6 and 7, and the following extracts are taken from that paper:

Extract from Mr. Harley Hugh Dalrymple-Hay's paper on the Waterloo and City Railway.

"The Greathead type of shield was used exclusively for tunnelling in the clay. The details of the shields for both the 12 feet 9 inch and 12 feet 1½ inch tunnels are the same, so the smaller machine will alone be referred to. Figs. 7, Plate 2 (Fig. 6 in this paper). The external diameter is 13 feet 2 inches, being 2 inches larger than the cast-iron lining of the tunnel, and the total length from the cutting edge to the end of the tail is 7 feet. There are seven 7 inch hydraulic rams placed within a cylindrical casing, to which they are connected by ¾ inch bolts. The stroke of the rams is 22 inches, and each ram is capable of exerting a maximum pressure of 34 tons. They are actuated by two hand-pumps placed one on each side of the shield. On the City section the pumps were worked by men with long lever handles; but in the compressed-air
portion of the work towards Waterloo, the contractors used electrically-driven hydraulic pumps with great advantage. The piston-rods of the rams fit into suitable heads, which thrust against a circular timber rib placed between them and the iron lining. The function of the rib, besides distributing the thrust of the rams on the circumferential joints, is to act as a stop to prevent the grout from pouring out into the shield when the annular space between the tunnel and the clay is being filled with lime under pressure. For this purpose the inner surface of the rib is covered with leather.

"The front end of the shield, against which the cylindrical casing containing the rams abuts, is formed of a stout casing made in four segments, the external diameter of which is slightly larger than the rest of the shield. This is splayed to receive the cutting edge, which consists of steel plates 1 inch thick forming a continuous conical ring. These steel plates are splayed to an acute angle at the front end so as to form a sharp edge, and are capable of being extended so as to cut wide of the shield when driving round curves. In the case of the 5 chain curves in the clay the cutters when extended their full length, i.e. 4 inch on an angle of 30°, did not cut wide enough to admit of the shield being driven properly, and it became necessary to chop wide of the cutting edge on both sides to the extent of some 2 inches before the shield could be turned. On the 9 chain curve, however, in the clay, when the cutters were put out to their full extent on both sides of the shield, it was necessary to excavate about an inch wide of the cutting edge on the inner side before the shield could be turned. A \( \frac{3}{4} \) inch plate diaphragm is placed at a distance of 15 inches from the cutting edge, and at its centre there is a rectangular opening 5 feet 6 inches wide by 6 feet 6 inches high, through which access to the working face is obtained. This opening can be closed in case of need by placing 4 inch timbers across it, the ends of the timbers fitting into steel channels riveted to the diaphragm on each side. The skin of the
shield extends from within a few inches of the cutting edge, to which it is secured by set pins, to the tail end of the apparatus, and is formed of two \( \frac{1}{4} \) inch steel plates connected by rivets countersunk on both sides. The plates are made to break joint, so that no butt covers were necessary, as would have been the case had one \( \frac{1}{2} \) inch skin plate been used instead of two plates each of half the thickness. The skin extends 2 feet 9 inches back from the end of the ram castings, and forms a tail to the shield, under cover of which the tunnel rings are erected. The external diameter of the shield being 13 feet 2 inches and that of the tunnel lining 13 feet, half the difference represents the mean depth of the annular space between the exterior of the tunnel and the clay. This annular space is filled with grout composed of blue lias lime or Portland cement mixed with sand and water, in the ratio of three parts of lime or cement to one part of sand.

"In tunnelling with this apparatus, owing to the extremely limited space, viz., 15 inches between the diaphragm and the cutting edge at certain stages of the work, it is not possible for more than one miner to work at a time Figs. 7, Plate 2 (Fig. 6 in this paper). Indeed, at most, only two miners can work together in this limited space, and that only after one miner has cleared a place for himself. Without recourse to other means of attacking the face, progress under these conditions would be extremely slow and the work costly. The method adopted therefore of finding more room for the men to work at the face, instead of extending the cutting edge, is to run out a heading in front of the shield and to keep driving it forward while at the same time it is being shortened at the back by the excavation at the face of the shield. Various types of heading were tried, and that shown in Figs. 7 was finally adopted as the best suited to the work. It consists of 11 inch by 4 inch head and side trees; the latter being placed on 9 inch by 3 inch foot blocks let into the clay. The side trees are spragged outwards at the bottom 3 inches on
each side, so as to tighten when the top is driven back. They are held at their upper ends by brobs driven into the head-trees. The heading usually consisted of eight or nine settings. Under the river the settings were kept close together, but elsewhere they were spaced from 2 inches to 4 inches apart.

"Shield for 23 feet Tunnels"

The apparatus used for driving the three large tunnels is shown in Figs. 14, Plate 3 (Fig. 7 in this paper). The vertical and horizontal external diameters are 24 feet 10½ inches and 24 feet 9½ inches, respectively. The extra inch in the vertical diameter was to allow for any sag of the apparatus when erected. Total length from cutting edge to tail is 10 feet. The outer skin is formed of 1 inch steel plates extending from back to front. There are eleven such plates, each 7 feet wide. A single butt-cover, 1 inch thick by 12 inches wide, connects the longitudinal joint between two adjacent skin plates. At the front end the edges of the butt-covers are splayed in the reverse direction to the cutting edge of the skin plates, so as to diminish the chance of their being deformed should the cutting edge come in contact with a claystone. Within and bolted to the skin are two cylindrical castings, one forming a stout blunt cutting edge, and behind it is another casting containing the hydraulic rams. The shield is divided by two horizontal and two vertical plate diaphragms into nine compartments or cells, which are entirely open to the face. The floors of the six upper cells were constructed with movable platforms actuated by hydraulic rams placed beneath them. These floors were always kept tight up to the face so as to give it as much support as possible. In addition to these rams the face was supported by a couple of timber struts placed against a waling at the face and by angle cleats riveted to the movable floor of each cell. During the operation of moving the shield forward the pressure in the platform rams was not relaxed, and had to be overcome before the shield could advance.
"There are twenty-two 7 inch hydraulic rams equally spaced round the shield. They were supplied by hydraulic power at 700 lbs. to 750 lbs. per square inch, from the mains of the Hydraulic Power Company, who sank a small shaft for the purpose from a lateral in the Queen Victoria Street subway to the level of the tunnels below. The pressure was increased from 750 lbs. to 2,000 lbs. per square inch by means of an intensifier which was drawn along on a track by the shield as the latter advanced. The large tunnels being straight throughout, the whole of the rams were brought into use, with the exception of two or three at the top. The pressure seldom exceeded 800 lbs. per square inch, although it sometimes rose to 1,200 lbs. just before the shield began to move. Owing to the large number of rams the shield could be manipulated very easily, and it was consequently run with remarkable accuracy, both as regards line and level.

"At the back of the shield there are two hydraulic erectors fixed to the main vertical diaphragms. The centres of the erectors are on the same level as the horizontal diameter of the shield, and are 8 feet 8 inches apart measuring horizontally. Directly above each erector and at the level of the upper floor there are two hydraulic cylinders with their piston-rods pointing vertically downwards. The lower end of each rod is connected to an endless chain passing over two pulleys—an upper one bolted to the main casting containing the two hydraulic cylinders referred to, and a lower one on the same axis as the erector proper to which it is connected. By admitting water into the upper portion of one of these cylinders and to the lower portion of the other, a circumferential motion is obtained by means of the endless chain and pulleys. The total time occupied in erecting a complete ring with both machines was generally about 40 minutes. In addition to the convenience of having two machines working at the same time, from their position they were entirely out of the way during the operation of excavating the face, when they were then placed in a vertical position behind the diaphragms. A novelty
introduced by the contractors, and one that is worthy of imitation, is the method of working the grouting rib. This was constructed of timber and iron, in short lengths fixed to every alternate ram head—the rams being drawn back or pushed forward in pairs. The adjacent ends of the grouting ribs were halved so as to make a neat and close joint. The surface of the ribs against the tunnel lining was covered with leather so as to effectually stop the grout from coming out."

The internal diameter of the shield used in driving the 11 feet 8 1/2 inch diameter tunnels was 12 feet 7 inches, being 1 inch larger than the external diameter of the cast-iron lining of the tunnel, the total length from the cutting edge to the end of the tail was 7 feet 1 inch. The maximum speed attained in driving was 46 rings a week. Each ring being 1 foot 8 inches in length, the length driven forward equalled 76 feet 8 inches. In driving certain lengths of this section tunnel, the shields were improved by the addition of an electrically driven rotary excavator of the pattern introduced by Messrs. Price and Reeves, which was fixed to the front of the shield; a conveyor fitted with a travelling belt for loading the clay into the skips being attached to the rear. This machine is illustrated and described in a paper read before the Institution of Civil Engineers by Mr. Edward Henry Tabor, M. Inst. C.E., on the Rotherhithe Tunnel and printed in the Minutes of Proceedings, Institution of Civil Engineers, Vol. CIXXXV. It proved so successful that the rate of driving was increased to a maximum of 95 rings a week equal to 158 feet 4 inches forward. Great care was necessary in driving this type of shield to keep it true to line and level.

The internal diameter of the station tunnel shields was 22 feet 8 1/2 inches, being 2 1/2 inches greater than the external diameter of the cast-iron lining of the tunnel and its length 8 feet 10 inches over all. The face is excavated using neither piles nor heading for a length of about 2 feet in front of the cutting edge, the shield pushed forward and the "iron"
built, the rate of driving was about 20 rings a week. Each ring being 1 foot 6 inches in length the length driven forward equalled 30 feet, a week being eleven twelve-hour shifts.

In the shields in the older tube tunnels the rams were actuated by hand pumps, but in the work under description they were supplied with pressure by hydraulic pumps up to a maximum of 3,000 pounds per square inch, or sufficient to advance the shields. These pumps were driven by compressed air from the service pipes at a pressure of 60 pounds per square inch and were supplied with water from accumulators in the tunnels at a pressure of 1,100 pounds per square inch, the accumulators being fed by the hydraulic pumps at the surface. Each ram in the shield was provided with a valve which allowed for independent action when necessary, this provision giving means of guiding the shields to correct line and gradient.

CAST-IRON LINING TO TUNNELS, PASSAGES AND PLATFORMS

Sections of the cast-iron lining of the 11 feet 8½ inch and the 21 feet 2½ inch diameter tunnels are shown in Fig. 8. It will be noticed that the crown segments or "Keys" are considerably shorter than those forming the sides and bottom of the rings. The abutting edges are provided with flanges to take the connecting bolts. Between the rings are placed thin creosoted fir packings to make the joints watertight and which can be varied in thickness to provide means of keeping the iron square to the centre line and to the correct gradient.

When the minimum radius occurred in a length of running tunnel, the required clearance for the carriages could not be obtained in the 11 feet 8½ inch diameter section tunnel and it was increased to 12 feet 7 inches in diameter. On certain lengths of the Railway where the minimum radius occurred the tunnel from the position of the shield chamber near the shaft was driven on the 12 feet 7 inch section as it was found more economical to drive the whole length on the larger diameter,
the extra cost being more than met by the saving in time and in building one shield with its chamber instead of two.

At intervals of about 300 feet, cross passages for platelayers were provided between the tunnels. Passages were also built between the station tunnels. Opposite the passages the rings were turned to bring the short crown segments into such a position that they could be removed and replaced by heavy rolled steel joists, which were carried at the ends by special heavy jamb castings.

In certain station tunnels the floor level of the passages passes through the crown of the tunnels and where this occurs the footway is carried on a bridge of rolled steel joists and tough flooring. The station tunnels are lined with concrete to carry the tiling. The platform walls are of brickwork and the platforms of rolled steel joists and concrete. At the junctions of tunnels of different diameters headwalls were built either in brickwork or concrete.

For dealing with the transport of materials and the spoil between the shafts and the tunnel faces a double line of contractors' skip road was laid over temporary clay filling to the invert, the skips being drawn by ponies.

**Work Under Compressed Air**

Between Euston and Goodge Street stations a formation known as the Woolwich and Reading Beds was encountered and a layer of sand containing water under a hydrostatic head was pierced, the tunnel being flooded as the first shield entered it. To ascertain how far this extended bore holes were sunk at intervals along the Tottenham Court Road. It was found that the tunnels could be taken over this stratum, after traversing it for some distance by altering the gradients. It was impossible, however, to drive the shields through it without providing means of keeping the water out of the tunnels and the contractors therefore took steps to carry on the work under compressed air.
The necessary plant was installed at Euston site: an air lock of the usual boiler type was built into a 6 feet thick bulkhead wall in the tunnel and the work recommenced. It was found after trial that an air pressure of 15 to 25 pounds per square inch above atmospheric pressure was required to keep the tunnels dry and this was maintained while the work through the sand was in progress. As the sand would not stand of itself, after a length was excavated it had to be timbered and struttued before the shield was pushed forward as shown in Fig. 9 and this reduced the rate of progress considerably. After the tunnels were completed through the sand, the lining was caulked at the joints with the usual mixture of cast-iron borings, sulphur and sal-ammoniac, the bolts fitted with soft lead washers, or grummetts, and the air pressure lowered. It was found impossible, however, to make the tunnel quite watertight and to avoid pumping the Chief Engineer of the Underground Electric Railways Company decided to drain the water into the chalk which lies at a level of about 300 feet below the surface. A passage was driven from the tunnel and a chamber constructed from which a 10 inch diameter bore hole was sunk, which proved successful in dealing with the drainage.

Between the Leicester Square and Strand stations, as the tunnels had to be driven under heavy buildings of which St. Martin's Church, designed by Wren, was one, the local authorities insisted on the work being carried on under compressed air. The available space at the Leicester Square site being too small to allow room for the plant, electrically driven air compressors were placed in the tunnels below, a bulkhead and airlock built and as a precautionary measure a pressure of 5 pounds per square inch above atmospheric pressure maintained. As far as the buildings above ground extended the clay proved sound and it was considered unnecessary to increase this pressure.

The work under compressed air was carried on in three shifts of 8 hours instead of the
usual two shifts during the 24 hours. A few cases of caisson disease or "bends" occurred amongst the workmen at Euston and these were first treated by placing the patient in a medical air lock at the surface, in which the pressure was first raised to that under which he had been working and then very gradually lowered.

**Method of Setting out the Tunnels**

Before any actual construction work was commenced, a traverse survey of the streets above the position of the tunnels was made, the survey lines being permanently fixed by cementing small circular iron discs into the pavements, the intersections being shown by a punch mark. After a shaft was sunk, the shaft line was turned off the traverse line and being transferred to the bottom of the shaft was used as a base line for the underground work, the length obtained being about 22 feet. Fig. 10 shows a plan of Leicester Square station with the traverse line, shaft line and the lines used for construction purposes. All permanent observations above and below ground were taken with a 7 inch Troughton and Simms transit theodolite of the latest pattern with two micrometers reading to 10 seconds of arc in azimuth. For carrying forward temporary lines in driving the tunnels a similar 6 inch instrument was used, a 14 inch Engineer's Dumpy level being used for levelling. All these instruments could be set up on a wall without the use of the stand.

When transferring the shaft line to the bottom, heavy plumb-bobs are hung down the shafts on piano wires over small drums fixed to timbers for the purpose of adjusting their position, the bobs being steadied in buckets of a heavy oil. Their position on the shaft line being carefully adjusted, the theodolite is set up at the intersection of the shaft line and the centre line of the tunnel and the angle turned. For the underground work a white ground-glass screen is fixed behind the plumb line being sighted, the screen being lighted by an electric lamp. When an "Intersection
Point comes in the centre of a tunnel, as on the straight, the actual point consists of a punch mark on an iron disc built into a concrete block in the invert. If an "Intersection Point" comes at the side of a tunnel, as on a curve, the point is filed on a timber dog driven into the joints of the lining, the theodolite being set up on a table bolted to the side of the tunnel. Each angle is turned a number of times, the readings on both verniers being recorded and an average taken to eliminate possible errors.

Taping is done with a steel band tape to which a spring balance is fixed, a pull of about 30 pounds being sufficient to take out the sag. When fixing permanent intersection points, the taping is done over pegs driven into the temporary filling in the invert of the tunnel, levels taken along the line of pegs and the horizontal length calculated. Each tape is tested from time to time over the standard length in Trafalgar Square to ascertain the temperature at which it is correct and when used in the tunnels the necessary adjustment for the difference in temperature is made.

However careful an engineer may be in "Setting out" he has a feeling of uncertainty until the junction in a tunnel driven from two different points is made. The results on this work were satisfactory, the errors as a rule being no more than 1/4 inch for both line and level. The worst recorded between Euston and Charing Cross, was an error of 1 inch in line, which was due to the difficulty of obtaining reliable long sights through the tunnels under compressed air, owing to condensation due to slight variations in the air pressure. An appendix to this paper is given showing the method used in adjusting the position of an "Intersection Point" in the tunnels which may be of interest.

To guide the shields, points on the centre line or tangent lines are filed on timber dogs driven into the joints at the crown of the tunnel near the face from which plumb-bobs are hung and the line sighted on to a horizontal
wooden bar, called a "fiddle," which fits into brackets across the back of the shield. On this bar the centre of the shield is marked. A small board provided with a slit, behind which a light is held, is sighted into position on the "fiddle." If the tunnel is on the straight, the difference is the amount the shield is off the centre line. On a curve allowance is made for the offsets which are calculated radial to the curve.

Boning rods for giving level are bolted to the flanges of the crown of the tunnel lining, the cross pieces being at the bottom. On these, hangers are placed over which a sight is taken to a mark on the shield.

On either side of the shield an eye bolt is screwed into the castings to take hooks to which rods called "Square Line Rods" are attached which are drawn behind the shield in brackets. These rods are sub-divided to read feet and inches. A square line to the centre line is marked on boards fastened to the side of the tunnel, which are moved forward as required and a reading can be made on each rod indicating the position of the shield in relation to the square line. In going round curves the divisions on the outer rod, although reading feet and inches, are larger to allow for the greater radius.

It will be realised that great care had to be exercised in driving the shields, as the construction gauge through the 11 feet 8½ inch diameter tunnels, the section to which most of the tunnelling was driven, was a circle of 11 feet 6 inches diameter, which allowed a maximum error of 1½ inches for line or level.

Permanent observations which include the transferring of shaft lines underground and the checking or replacing the lines put in by the Assistant Engineers immediately in charge of the tunnels, were carried out during Saturday nights and on Sundays, more accurate work being possible when the construction was suspended and the atmosphere in the tunnels clear.
DRAINAGE OF TUNNELS

The tunnels are drained by means of earthenware pipes embedded in the concrete invert carrying the permanent way, which discharge into sumps built in concrete and brickwork, the concrete invert being shaped at intervals between the sleepers to allow an opening for drainage to the pipes.

WORK AT TOTTENHAM COURT ROAD UNDERGROUND STATION

The Tottenham Court Road station which is underground, is situated at the junction of this road with Oxford Street, New Oxford Street, High Street and Charing Cross Road. Fig. 11 is a plan of the work showing booking and waiting chambers, subway and staircases, the latter being conveniently situated at the corners of the streets. The levels vary from 2 to 30 feet below the surface of the roadway, a portion from 10 to 21 feet below being in the sand and gravel overlying the clay at this spot, which although it contained little water was wet enough to necessitate some pumping. The roofing which consists of rolled steel joists and concrete is carried on heavy girders which rest on walls and steel stanchions. The outside walls which are 6 feet thick are formed of concrete of 6 parts Thames ballast to 2 parts sand and one of cement. The inner walls and piers are of brickwork in cement mortar on concrete footings. Sections of the work illustrating the roofing, walls and passages are shown in Fig. 12.

Owing to the site of the station being at one of the busiest street crossings in London, it was not possible to open up the ground except over a comparatively small portion of the area. In Fig. 11 the thick dotted line shows the space allowed the contractors for working, which was enclosed by a hoarding and this area had to contain the crane road, plant and all materials put down from time to time, so that the actual portion opened up was only just enough to allow for sinking the two lift shafts. The disadvantage of the small working space available, which necessitated
underground working and the presence of wet sand and gravel contributed to the difficulties of the undertaking.

As there was little water it was possible to sink the two 23 feet diameter lift shafts by the ordinary underpinning method. After these were completed a heading was driven through an old wall of an underground lavatory which was to be removed, this heading forming the adit from which were driven headings along the positions of the walls and girders. The method of timbering adopted in excavating for the walls is shown in Fig. 13. The top heading was first driven, the bottom trench afterwards excavated in 10 feet lengths at intervals, the walls built up to the level of the underside of the girders or roof joists and the gaps between these lengths filled in. Owing to the loose nature of the ground through which the headings were driven and the presence of wet sand and gravel through the levels where the trenches were sunk the ordinary method of timbering could not be used. The poling boards were driven as piles over the head trees and behind the side trees of the top heading and down behind the wailings in the trenches, the wailings being supported on props as shown in the drawing.

As the road above the 16 feet diameter staircase shaft could not be opened up it was sunk under cover, the chamber above it being first constructed. Fig. 14 shows the method of timbering adopted in excavating the ground for the construction of the chamber. A heading was driven from the adjacent shaft and two of the permanent rolled steel joists of the roof placed in position on props. The heading was then widened out and the floor lowered, the other joists placed and the brick walls forming the chamber built as shown in the drawing, after which the shaft was sunk.

A 3-inch asphalte course encloses the whole of the work above the level of the top of the clay, making it watertight. This course is taken over the rolled steel joists forming the roof, down through the walls 4 feet from the
face, through their footings and through the concrete flooring to the booking and waiting chambers.

During the progress of the work a great number of pipes, comprising gas, water and other mains were uncovered and these had to be slung on chains carried by timbers which were inserted above the pipes and which were removed on the completion of the work. The pipes were carefully packed up before the supports were removed.

**Work at the Strand Underground Station**

The Strand station is situated under the Courtyard of the South Eastern and Chatham Railway Company's terminus "Charing Cross Station" which faces the Strand. There are three lift shafts 23 feet in diameter, one staircase shaft 18 feet in diameter, booking hall and passages to the above Railway Company's station, Villiers Street and the Strand. The roofing, which consists of girders and rolled steel joists covered with concrete, is carried on brick walls with concrete footings founded on the clay at a level of about 35 feet below the surface and is made watertight by a layer of Callenders Bitumen Sheet which was laid and embedded in the concrete covering.

It was expected that this work would have to be constructed under similar conditions to those at Tottenham Court Road, but owing to the accident to the roof of the South Eastern and Chatham Railway Company's terminus which occurred early in 1906, all traffic there was stopped and advantage was taken of this to open up the area of the courtyard above the Tube station. Before this roof was rebuilt and traffic again opened it was possible to sink the shafts, to build the walls to varying depths below the surface and to fix and cover in the girders and roof joists, the walls where not completed being afterwards taken down to their finished level by underpinning them.

The first few feet of depth consisted of made ground above, the London clay and as it held
no water, the timbering in sinking the trenches for the walls and for the underpinning was of the ordinary type.

The work at this station was carried out by the contractors, Messrs. Price and Reeves, but was not included in the original contract. The Chief Engineer for the Underground Electric Railways Company designed and supervised the work, the author being in charge for the contractors.

PERMANENT WAY

The Permanent Way, which was not included in the contract, consisted of the usual bull-head rails, 90 pounds to the yard, laid in cast-iron chairs which were fastened with coach screws to cross sleepers. Between the concrete invert and the sleepers a layer of $1\frac{1}{2}$ inches of fine ballast was placed, which was carried up and round the ends of the sleepers. The super-elevation of the outer rail on curves was obtained by sloping the surface of the concrete invert. A survey of the tunnel rings was carried out to enable small adjustments to be made to line and level when placing the concrete invert and when laying the permanent way.

VENTILATION

While under construction the tunnels were cleared of foul air by opening the valves in the service compressed air pipes near the different faces. For the permanent ventilation air ducts were constructed at the bottom of certain of the shafts where large electric fans were afterwards fixed.

LIGHTING

During construction current was taken from the local mains and the tunnels lighted by electricity.

A general plan to scale and a longitudinal section of the railway are not available and the author has endeavoured to cover this omission by description at the beginning of the paper. With the exception of those illustrating the
shields the drawings were prepared from records and notes kept at the time of construction.

The author desires to record his indebtedness for much of the information contained in this paper to the firms of Consulting Engineers, the Chief Engineer of the Underground Electric Railways Company of London, Limited, and the Contractors to whom reference has been made.
APPENDIX

Adjustment of the Position of an "Intersection Point!"

Assume that the angle off the "Shaft Line" at B shown in sketch plan has been previously turned, points put in at the time intermediate between B and C and the line afterwards prolonged to C while the tunnel was driven.

It is now proposed to adjust the position of the "Intersection Point" C, and to do this it is necessary to check the length BC and the angle ABC.

Correction for Level.

The first operation is to check the length BC which is given as 290.94 feet.

The theodolite is set up at B, the telescope sighted on to C and clamped. Pegs are then driven into the filling in the invert along this line. The tops of the pegs are chalked and centre marked with pencil lines. The lengths between the pegs are then taped and the differences in level between the tops of the pegs found by Dumpy Level.

Taking each taped length between the pegs as the hypotenuse and the difference in level as the height of a right-angled triangle, we have to calculate the length of the base. The sum of these will be the horizontal distance between the actual points B and C.
The horizontal measurement of the distance between the actual points B and C is found to be 290.93 feet and to correct the length BC for level, the point C must be moved forward from B along the line BC by the difference between this and the true length, this difference being 0.01 feet.

**Correction for Temperature.**

Assume that by testing the tape over the standard length in Trafalgar Square it has been found correct at 62° Fah. and that the temperature read by thermometer in the tunnels is 78° Fah.

The coefficient of expansion for steel is 0.0000068 per foot per 1° Fah. and as the temperature in the tunnel is higher than that at which the tape is correct, the measurements read on the tape are short and the length taped actually greater by the following amount:

\[ 290.94 \text{ feet} \times 0.0000068 \times 16 = 0.032 \text{ foot} \]

and to correct for temperature the point C must be moved back 0.032 foot towards B along the line BC.

The total correction for both level and temperature is then:

\[ 0.032 \text{ foot} - 0.01 \text{ foot} = 0.022 \frac{1}{4} \text{ inch} \]

(full) and the point C must be moved back towards B along the line BC by this amount.

**Adjustment for Bearing.**

The next operation is to check the angle ABC. We have already set up the theodolite at B. Set the vernier "A" at zero, sight on to point A and turn on to point C, reading both verniers "A" and "B". The angle is turned a number of times and an average taken to eliminate errors. Readings can be made on the micrometer to 10 seconds but the divisions are large enough to enable an estimate to be made.
to the nearest second. We will assume the reading to be as below:

<table>
<thead>
<tr>
<th>Vernier “A”</th>
<th>Angle</th>
<th>Vernier “B”</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>360° 00’ 00”</td>
<td>179° 59’ 48”</td>
<td>80° 45’ 15”</td>
<td>260° 45’ 15”</td>
</tr>
<tr>
<td>80° 45’ 15”</td>
<td>260° 45’ 15”</td>
<td>80° 45’ 27”</td>
<td>80° 45’ 31”</td>
</tr>
<tr>
<td>161° 30’ 35”</td>
<td>341° 30’ 46”</td>
<td>80° 45’ 11”</td>
<td>62° 16’ 10”</td>
</tr>
<tr>
<td>242° 15’ 46”</td>
<td>324° 10’ 43”</td>
<td>80° 45’ 22”</td>
<td>80° 45’ 24”</td>
</tr>
<tr>
<td>323° 01’ 08”</td>
<td>303° 41’ 43”</td>
<td>80° 45’ 22”</td>
<td>80° 45’ 33”</td>
</tr>
<tr>
<td>43° 46’ 23”</td>
<td>223° 47’ 11”</td>
<td>80° 45’ 15”</td>
<td>80° 45’ 28”</td>
</tr>
<tr>
<td>124° 31’ 45”</td>
<td>304° 32’ 44”</td>
<td>80° 45’ 22”</td>
<td>80° 45’ 33”</td>
</tr>
</tbody>
</table>

\[
\text{Mean angle} = 969° 04' 41' + 12 = 900° 45' 23'
\]

\[
\text{Angle ABC} = 80° 45' 34'
\]

\[
\text{Difference} = 0° 0' 11'
\]

The length of the circular arc subtended by an angle of 1 second, the radius being 1 foot is 0.00000048 foot.

Therefore the correction for bearing

\[
= 200.94 \text{ feet} \times 0.00000048 \times 11
\]

\[
= 0.0152 \text{ foot}
\]

\[
= \frac{1}{64} \text{ inch (bare)}
\]

The angle contained by the lines AB and BC has been found small and to correct it the point C must be moved to the right by this amount.
CHARING CROSS, EUSTON & HAMPSTEAD RAILWAY.
GOODGE STREET SITE, SHAFT NO.1.
METHOD OF TIMBERING IN RINGS NO. 6 & 7.

SCALE
1:100
CHARING CROSS, EUSTON & HAMPSTEAD RAILWAY.
PLAN SHEWING SHAFT NO. 2 JAN. 11TH-04 BEING SUNK
WITH WEIGHS & CUTTING EDGE.
GOODGE STREET SITE.

SCALE

NOTE: TOP RING BUILT TO CARRY
WEIGHTS & TAKEN DOWN AFTER
SHAFT WAS SUNK.

LINE BAGS FILLED WITH BALLAST FROM SHAFT.

NOTE 1: TOTAL WEIGHT INCLUDING
SHAFT ABOUT 450 TONS.

SECTIONAL VIEW THROUGH SHAFT

PLAN AT A A

HOLES FOR LOWERING IRON
ETC.
WATERLOO & CITY RAILWAY

SHIELD FOR DRIVING SMALL TUNNELS

H. H. Dalrymple-Hay on the Waterloo and City Railway
Reproduced from Fig. 7, Plate 2.
Minutes of Proceedings of the Institution of Civil Engineers,
Vol. CXVIII Session 1899-1900 Part 1.
WATERLOO & CITY RAILWAY

SHIELD FOR DRIVING LARGE TUNNELS

H. H. Dalrymple-Hay on the Waterloo and City Railway
Reproduced from Fig. 14, Plate 3.
Minutes of Proceedings of the Institution of Civil Engineers,
CHARING CROSS EUSTON & HAMPSTEAD RAILWAY

DRAWING SHOWING TIMBERING IN TUNNEL THROUGH SAND & WATER

Fig: 9.

CROSS SECTION AT FACE

LONGITUDINAL SECTION

CROSS SECTION AT A.B. SHOWING CAVITIES LEFT IN SAND

CHARING CROSS, EUSTON & HAMPSTEAD RAILWAY

LEICESTER SQUARE

PLAN SHOWING TRAVERSE LINE, SHAFT LINE ETC

USED IN CONSTRUCTING TUNNELS AND PASSAGES.

SCALE

TRAVERSE LINE

WEST STATION TUNNEL

EAST STATION TUNNEL

SECTION A-A
CHARING CROSS EUSTON & HAMPSTEAD RAILWAY
UNDERGROUND STATION AT TOTTENHAM COURT ROAD

DRAWING SHOWING DETAILS OF TIMBERING IN HEADING AND TRENCHES FOR WALLS

SECTION SHOWING METHOD OF TIMBERING IN HEADING & TRENCH.

LONGITUDINAL SECTION A.A.
Fig: 14.

CHARING CROSS, EUSTON & HAMPSTEAD RAILWAY
TOTTENHAM COURT ROAD STATION
DETAILS OF TIMBERING IN CHAMBER OVER 16'-0" SHAFT

SCALE

SECTION AA

SECTION BB

SECTION DD

METHOD OF SIDE FILLING

SECTION CC

16'-0" DIA. SHAFT.
DISCUSSION

The President.—I think it will be admitted that the tube system of railways described is an expensive form of meeting the transport difficulties of a town, except where, like London, the cost of widening streets for the provision of surface tramways and road traffic generally is prohibitive. Further, not all our big cities are so fortunate as to have been built over a bed of clay such as we have in the London area, which made it possible to construct underground lines of communication in an almost perfect medium in any area or to any depth up to 300 or 400 feet without affecting the stability of its many valuable buildings on the surface. We owe this to a period when the surrounding lands, near what is now London, were probably basking under the sun of a tropical climate—for the organic remains found in the clay and adjacent beds indicate that these were the conditions and we are told that the clay, in some places 500 feet thick, was probably laid down in a sea beyond the mouth of a large estuary.

The question of transport in cities is now a much discussed question everywhere and I am glad to see the local authorities are tackling the question of their lines of connection in the City in which we live before it becomes too difficult to deal with it effectively.

Although I am a Railway man I would rather see the traffic facilities of a town promoted by the widening of streets and improvements of surface connections. Railways are unsuitable as a surface means of transport in towns for very obvious reasons and when built underground do not cater in the same way as electric trams and other street motor vehicles for the short distance traffic of a crowded city.

I noticed in the discussion on a paper presented to the Institute of Civil Engineers on “Some aspects of Metropolitan road and rail transit” that one eminent engineer, well known in this country, advises the future promoters of tube railways to build express lines
with stations two or three miles apart. I think this is sound advice for we know that short distance traffic can be better and more quickly dealt with, where it is possible to provide it, by surface means and the express lines recommended can be built much cheaper, for as I gather approximately about two thirds of the cost of our tube railways is spent in building the stations and the approaches from the surface.

I take it that the figure given by Mr. Cooper, viz.:—£1,750,000, which works out at £233,333 per mile of double line, does not include the permanent way, the electric work nor the rolling stock, as I see that the average cost of London tubes work out at about £600,000 per mile of double line, so that there is a considerable difference to be accounted for.

The methods of sinking the shafts as described are simple and require no expensive timbering, which might have been required in a less suitable soil, except in one or two cases where the cylinders were sunk through water bearing strata and where it was necessary to use special timbering until the cylinders entered the clay formation again.

Mr. Cooper gives an interesting account of the shields used in construction of the main tunnels and shows that they were specially designed to avoid any risk of settlement whilst they also gave the greatest protection and confidence to those engaged on the mining operations and the fixing of linings. Here the speed of advance was in the ordinary tunnels about 53 yards a week, which compared with the ordinary speed of hand-driven tunnels in similar strata is, I should say, very fast.

The method of sinking a pipe into the absorbent chalk beds to remove the water met with in the tunnels at Euston is to my mind an extremely interesting and novel way of dealing with what might have been a very expensive item, for if this way out had not
been discovered, a very expensive pumping plant might have been required.

**The Author.**—I should like to express my thanks to the meeting for the kind way in which my paper has been received. In reply to our President, Mr. McMillan, the bed of clay underlying the London area provides an excellent medium for tunnelling and the invention of the Greathead Shield with its later addition, the Rotary Excavator introduced by the contractors, Messrs. Price and Reeves, or as the combination was called, “The Digger Shield” has enabled the Tube Tunnels to be constructed at a great speed within a reasonable cost. Difficulties were however met with, as for instance where the “Woolwich and Reading Beds” have been encountered, necessitating the driving of portions of the tunnels under compressed air and where work has had to be undertaken in the beds of sand and gravel which overlie the clay in places and which as a rule contain water.

With regard to the cost of the work, the figure given in the paper, which is approximate only, does not include the cost of the underground station at the Strand, the cost of the acquisition of the property for the sites of the station buildings, the buildings themselves, permanent way, signalling, power stations, and electrical equipment; lifts, staircases, escalators, rolling stock, etc. In the discussion on the paper read before the Institution of Civil Engineers by Mr. Henry Herman Gordon, B.A., Assoc. M.Inst.C.E., on “Some aspects of Metropolitan Road... and Rail Transit,” the average cost of double line Tube railways fully equipped is given as £600,000 per mile, some more and others less, of which £450,000 is stated to be the approximate cost of the station tunnels, the shafts and passages and the work in connection with the stations, etc., or in other words the cost of the acquisition of property, equipment, and of all work with the exception of the running tunnels, the average cost of the latter being
the difference between the two figures, viz:— £150,000 per mile of double tunnel, so that the cost of the double tunnels, including station tunnels, shafts and passages for the Charing Cross, Euston and Hampstead Railway which was about £230,000 a mile compares favourably with these figures. The cost of constructing the tunnels at the present time would be much higher, as although the price of iron and steel has fallen within the last two years to not much above the pre-war figure, the cost of labour is still more than double what it was in 1913.

With regard to the speed at which the shields were constructed, as stated in the paper, the maximum speed at which the Greathead Shield was driven was about 76 feet a week, while with the "Digger Shield" which was fitted with the electrical-driven rotary excavator the speed attained was much greater, reaching 158 feet a week. In the short lengths of tunnel driven by hand the speed was very much less, seldom being more than 15 to 25 feet a week.