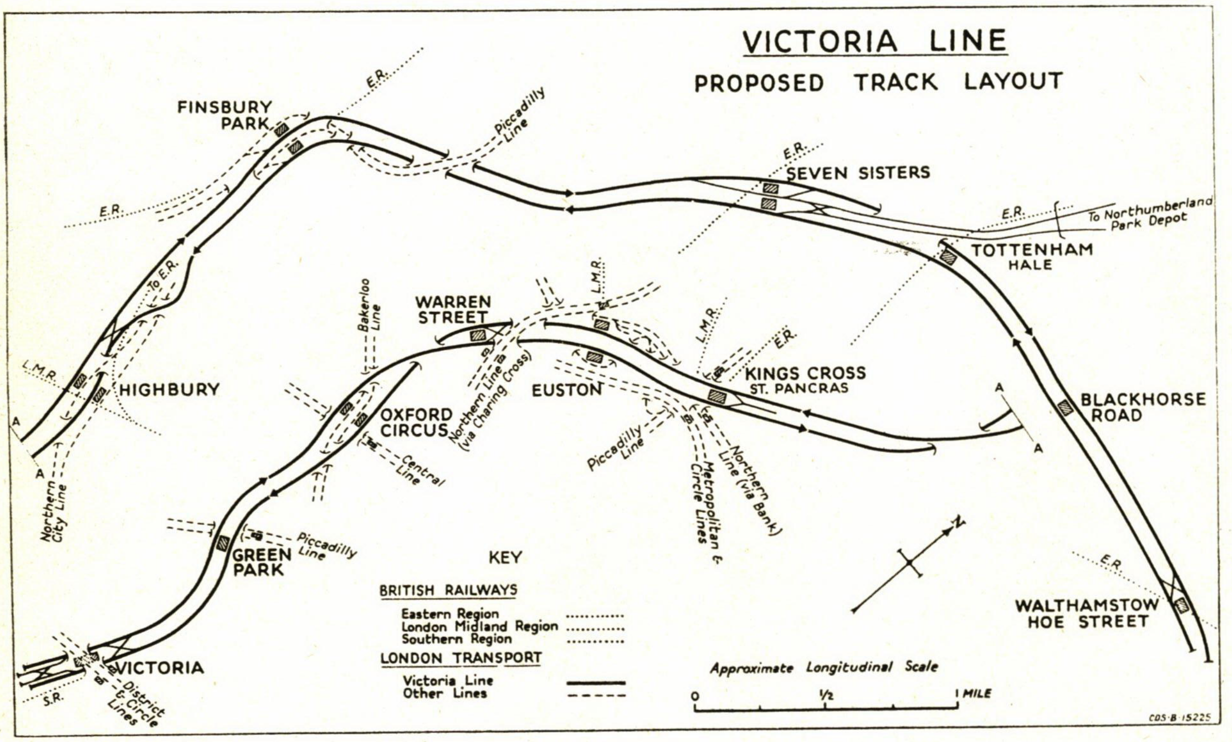
by C. H. S. Tupholme

Excavating for London's New Victoria Line

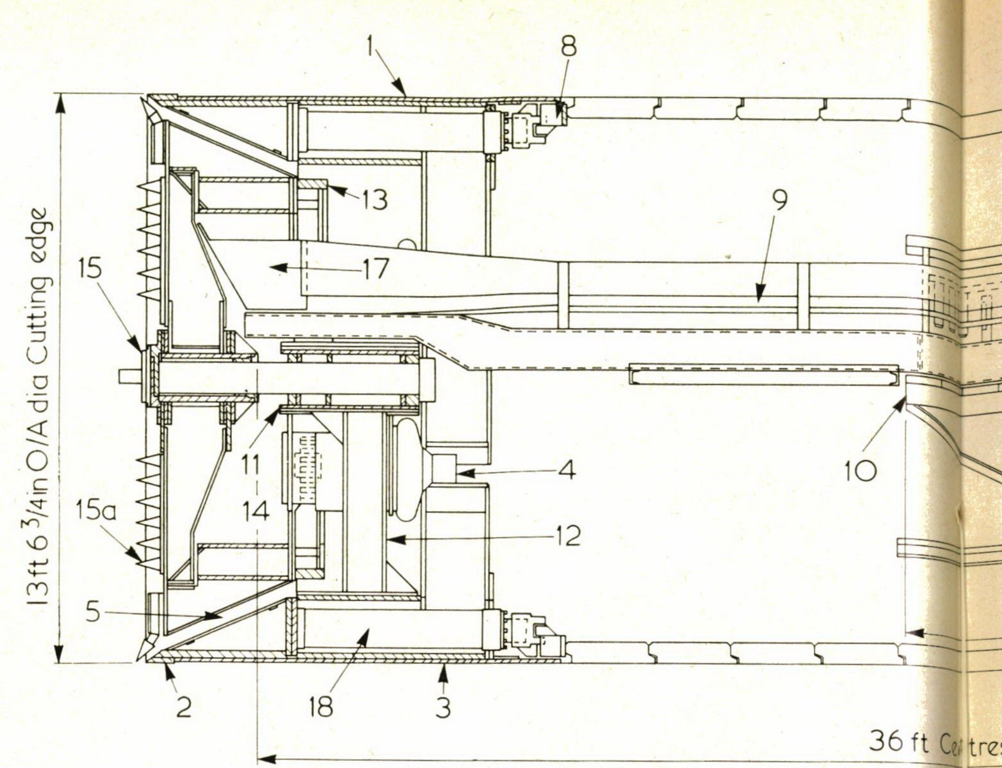


The recently completed Victoria Line is the first deep-level tube railway to be built across the centre of London for 60 years, and runs from Victoria Station for 10½ miles (16.9 km) through London's West End to Walthamstow in the north-eastern suburbs. The average tunnel depth from ground surface to rail level is about 70 ft (21.3 m); the average gradient is between 1:70 and 1:100, and no gradient is steeper than 1:40. Within three years from work starting on the first of the 21 shafts from which the running tunnels were driven, about 500,000 yd^3 (382,280 m^3) of earth was excavated from the 21 miles (33.8 km) of 12 ft (3.66 m) diameter running tunnels alone. In addition, some 300,000 yd^3 (229,360 m^3) of earth has been removed during building of the 12 stations for the new line.

Before work was started on the main section of the line full-scale tests were carried out on the digging equipment and tunnel linings in a 1 mile (1.6 km) length of double tunnel. It was decided that about 1,910 yd (1,747 m) of single tunnel should be built with flexible cast iron lining designed by Mott, Hay & Anderson; and the other 1,612 yd (1,474 m) with pre-cast concrete lining to the design of Sir William Halcrow & Partners. Kinnear Moodie constructed the tunnel in concrete from a site at Finsbury Park; and Edmund Nuttall, Sons & Co., Ltd. the cast-iron lined tunnels driven from the site at Netherton Road. Kinnear Moodie also drove a short cast-iron lined section to link this experimental work with the existing station tunnels at Finsbury Park. It was intended that the experimental tunnels would eventually form part of the new line.

The tunnels were driven with drum digger rotary shields and, using one of these shields, Edmund Nuttall drove a 934-ft (284.7-m) length of tunnel, including excavation and lining, in two weeks. This is equivalent to a speed of 3½ ft (1.07 m) of new tunnel per working hour, a world record for driving and lining a tunnel of this size through clay. It is almost twice the speed considered to be good going with older tunnelling techniques. The drum digger shield was developed by Kinnear Moodie and Arthur Foster Construction Engineers Ltd. It had already been used with success on the Metropolitan Water Board's Thames to Lea Valley water tunnel. Though the shield was smaller in this case than that employed on the Victoria Line, the principle is the same.

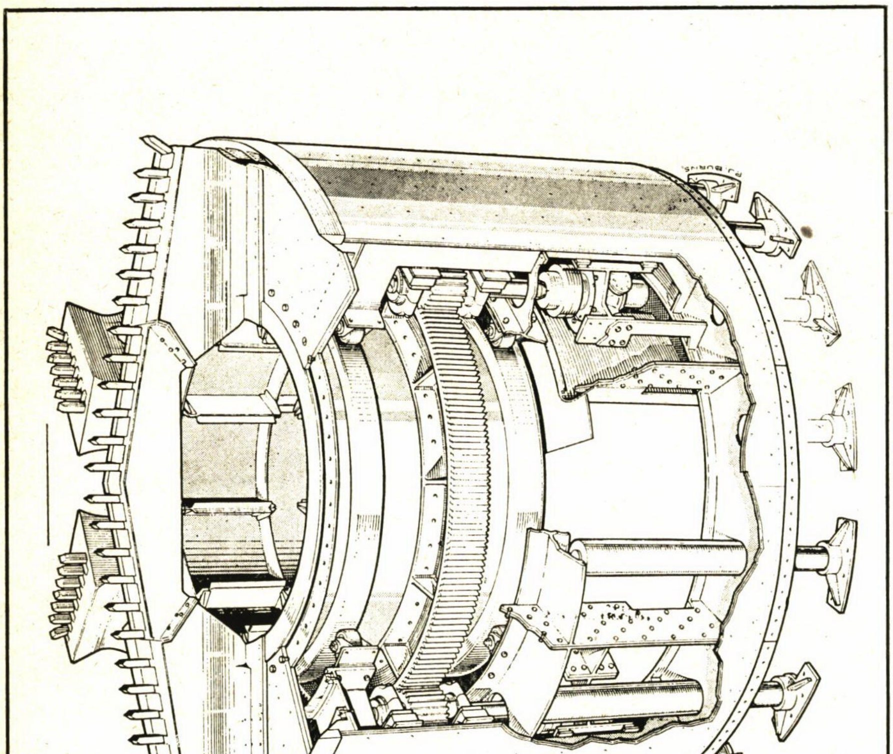
The drum digger used on the concrete-lined tunnels has an external diameter of 14 ft (4.27 m), and that for the cast-iron lined tunnels 13 ft 1 in (3.99 m). The toothed inner drum can be turned at up to 4 r.p.m. by six hydraulic motors driving through gearboxes. The forward movement of the shield is imparted by 14 hydraulic rams spaced equally round the periphery of the shield and pushing against the last completed tunnel ring. These rams are individually controlled by an operator standing within the shield casing but behind the rotating inner drum. These shields proved easier to guide than earlier types and a very high standard of alignment was achieved, i.e., within + / — 1-in (25.4-m) tolerance. The Kinnear Moodie drum digger, which has been described in International Construction (December, 1966), was one of the machine types ordered for digging the running tunnels: the other was the mechanical digging shield developed by Sir Robert McAlpine & Sons Ltd. This has an external diameter of 13 ft 6 in or of 13 ft 1 in (4.11 or 3.99 m) when used with segments erected in contact with the ground behind the shield. The machine, which has a cylindrical body, can have a tail added to enable segments to be erected inside the tail section if required. One of the Victoria Line contractors, using the McAlpine machine, has reported a drive rate averaging 350 ft (106.7 m) of completed tunnel per week.



Nine digging shields were ordered by London Transport, four from Kinnear Moodie and four from McAlpine, the ninth order being placed with Joseph Westwood & Co. Ltd. For excavating the station tunnels, seven Greathead type shields were built by W. Lawrence & Son (London) Ltd. These shields are over 21 ft (6.4 m) diameter, and are not provided with mechanical cutters, the soil being excavated with power-driven hand tools. The shields, however, are also advanced by pressure from hydraulic rams against the rings of the completed tunnel lining.

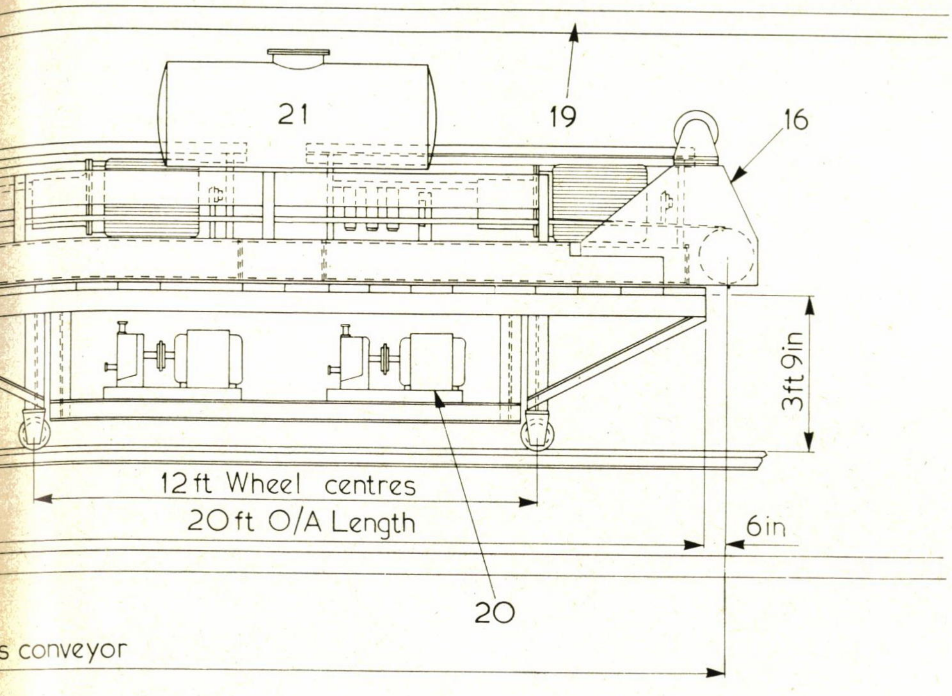
The experimental tunnels also provided a valuable opportunity for testing the tunnel linings. On one section, the lining is of unbolted flexibly jointed cast iron segments. There are six segments, each 1 in (25.4 mm) thick, to every 2-ft (210-mm) tunnel ring. One end of each segment is concave and the other convex, so that the segment ends form knuckle joints, each fitting into the next in sequence. The segments were placed behind the shield when the rams were withdrawn, the two segments forming the invert being laid first, followed by the side segments and then those holding the roof were placed and held by needles at the rear of the shield. The two segments forming the floor of the tunnel were cast with small recesses at their upper ends and, when the segments had all been erected, hydraulic jacks fitted into the recesses expanded the ring segments against the clay outside.

The pre-cast concrete lining is also of a new type. These segments were tested, the thicknesses ranging from $4\frac{1}{2}$ in to 9 in (114.3 to 228.6 mm). The larger size was found to be unduly thick, while the thinner segment might be liable to break during handling. As a result, a thickness of 6 in (152.4 mm) was chosen. The knuckle joints in the concrete lining were subject to inaccuracies in manufacture and erection to the extent that the point of contact could be well off-centre. Mott, Hay & Anderson elected to retain this type of joint, but to reinforce it to eliminate the danger of spalling: Sir William Halcrow & Partners modified the joint to have two concave surfaces to ensure near central contact. Other alterations were made to the concrete lining to produce



Cutaway drawing of the K. M. tunnelling machine, four of which were ordered by London Transport for use on the Victoria Line.

Section through the McAlpine tunnelling machine, showing details of tunnel lining.



a shaped invert, which was considered preferable to two segments 6 in (152.4 mm) thick, and which at the same time enabled a great saving in the amount of in situ concrete to be placed under the track.

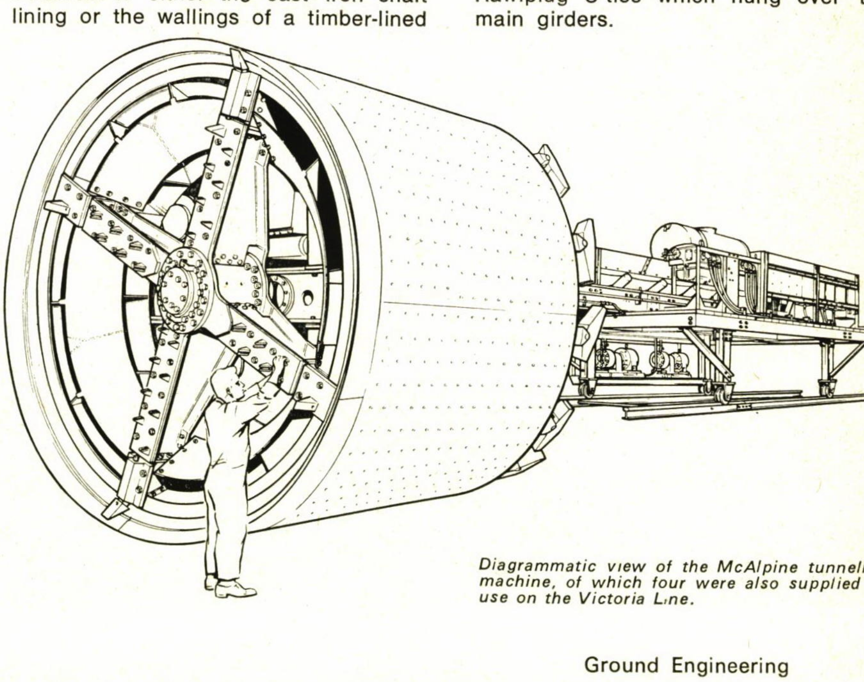
The flexible cast iron lining was recommended by Mott, Hay & Anderson for use on the length of running tunnel between Victoria and Oxford Circus, where the marginal advantage of using this type of lining was considered to warrant the somewhat higher cost compared with a concrete lining. With the above and other improvements, reduced estimates were possible for all running tunnels in good ground, resulting in a total saving overall of some £3 m. London Transport placed a contract worth £5m for cast iron segments with Stanton Staveley, Ltd., one-third of the order being sublet to Head Wrightson Iron Foundries Ltd. A further contract, worth some £104,000, for special type cast iron segments, was placed with Harland & Wolff.

It was obvious that problems would arise in constructing the new Victoria Line in view of the complexities of London's existing underground railway system. Under the Victoria main line station, for example, the 30-ft (9.14-m) diameter cross-over tunnel of the new line had only from 7 ft to 8 ft (2.1 to 2.4 m) of clay above it, and chemical stabilisation of the gravel under the main line station was necessary. A contract for £130,000 was placed with Soil Mechanics, Ltd. for this work. Contracts were also placed with Cementation, Ltd. for similar work, using TDM, one of Cementation's own single-shot chemical grouts. A layer of water-bearing sands and gravels 5 ft (1.5 m) thick and 350 ft (106.7 m) long was also treated with TDM.

For tunnelling the south end of the new line (i.e., at Victoria), which also included the enlargement of the running tunnels for four 21-ft (6.4-m) diameter station tunnels, the tunnels being lined with cast iron segments. Two shafts were sunk to provide access for construction, one at Gillingham Street and the other in the north-east corner of Green Park. Both shafts were sunk with a special hydraulic excavator constructed by John Mowlem, the civil engineering contractors for this end of the line. This excavator was built by adapting the digging equipment of a Massey-Ferguson 220 digger. A hydraulic power pack was incorporated to replace the hydraulic power normally provided by one of the tractors in the MF range. The digger stood on its hydraulically operated stabilising feet and was held in position by a spigot which engaged in a bracket attached to either the cast iron shaft lining or the wallings of a timber-lined shaft. From this position the machine excavated more than half of the shaft areas, loading the spoil into skips removed from the shaft by crane. The digger was then transferred to the opposite side of the shaft to complete the excavation cycle.

The new station at Oxford Circus proved to be something of a jigsaw puzzle in view of the complex already existing. Not only were there two existing underground lines at this point, but also a maze of electric cables, Metropolitan Water Board tunnels and G.P.O. mail delivery tunnels. In addition, the serious lack of surface area at Oxford Circus brought its own problems. This was coped with by building a steel umbrella over the crossing of Oxford and Regent Streets, so that surface traffic could still proceed; and by using nearby Cavendish Square as a base area, which was connected to Oxford Circus by temporary tunnels, built solely for the purpose of access. The new station at this point was part of the £6 m contract given to Kinnear Moodie, and included driving 9,000 ft (2,743 m) of tunnel of 20 different diameters in blue clay, varying from 5 ft (1.52 m) diameter for the smaller sewer diversions to 27 ft (8.23 m) for one of the new station tunnels. The tunnels are lined with some 40,000 cast iron segments, bolted to form 5,400 rings. The consulting engineers for this rather daunting job were Sir William Halcrow & Partners.

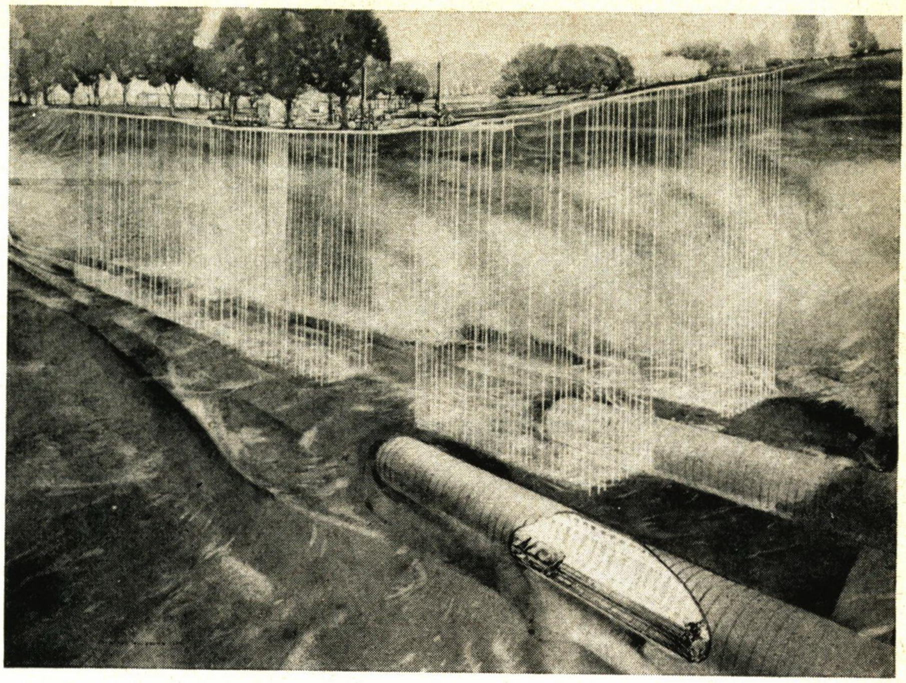
The construction of the new ticket hall at Oxford Circus, being very close to road level, was a complicated job. The concrete finish had to be of a very high order and no bolts could be passed through the soffit concrete because of the risk of leaks. Because of the variation in the excavated ground level, it was impossible to use props for the shuttering, so a shutter scheme which was self-supporting within the bay areas was specially designed by Phoenix Formwork. Standard Wallforms were used in these bay areas, supported by Acrow adjustable joists. All the shutters were supported with Rawlplug U-ties which hung over the main girders.



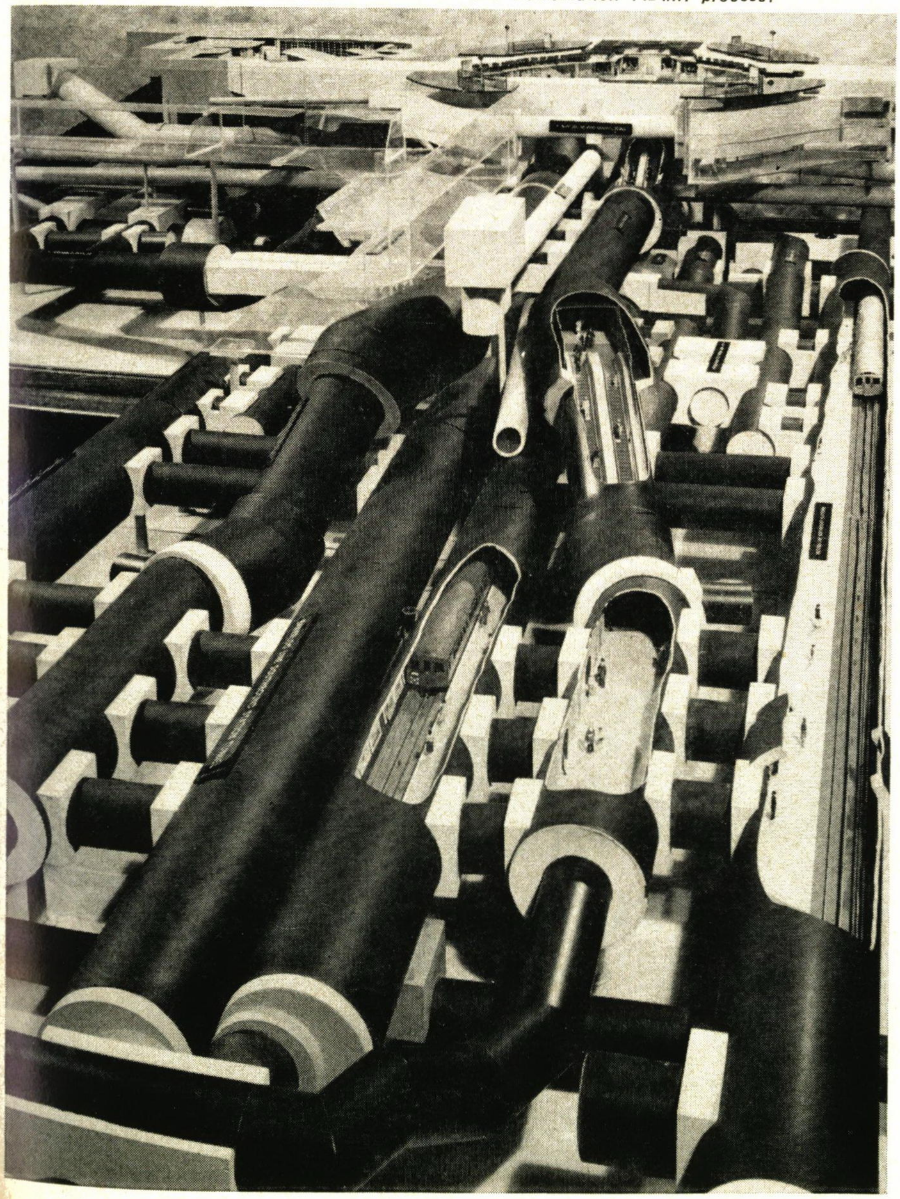
Diagrammatic view of the McAlpine tunnelling machine, of which four were also supplied for use on the Victoria Line.

One corner of Oxford Circus is occupied by a large department store, and the southbound Victoria Line tunnel passes immediately under the massive column foundations of this 5-storey block. To prevent foundation settlement, underpinning had to be done before the tunnel could be driven, and the problem was to distribute the load from the present foundations evenly over the arch of the proposed tunnel. A feature of this task was the small clearance between the roof of the tunnel and the underside of the foundations. So as to develop the necessary strength in the restricted height, the consultants decided to use prestressing techniques; and the underpinning took the form of post-tensioned concrete blocks which act as beams to distribute the column loads over the tunnel arch.

The pilot tunnel was driven parallel to, and slightly below, the column foundations of the 5-storey building. From this tunnel, small rectangular headings were driven to enclose the area to be filled with concrete. Underpinning was then carried out by driving a sequence of narrow headings under the foundations and immediately filling them with concrete so that only a narrow strip of foundation was left without support at any one time. Ducts for the prestressing cables were laid during concreting. This operation called for great precision by the setting-out engineers because each duct had to line up perfectly with its neighbour in the adjoining heading. After all the concrete had been poured, the cables were threaded through ducts, tensioned and grouted.



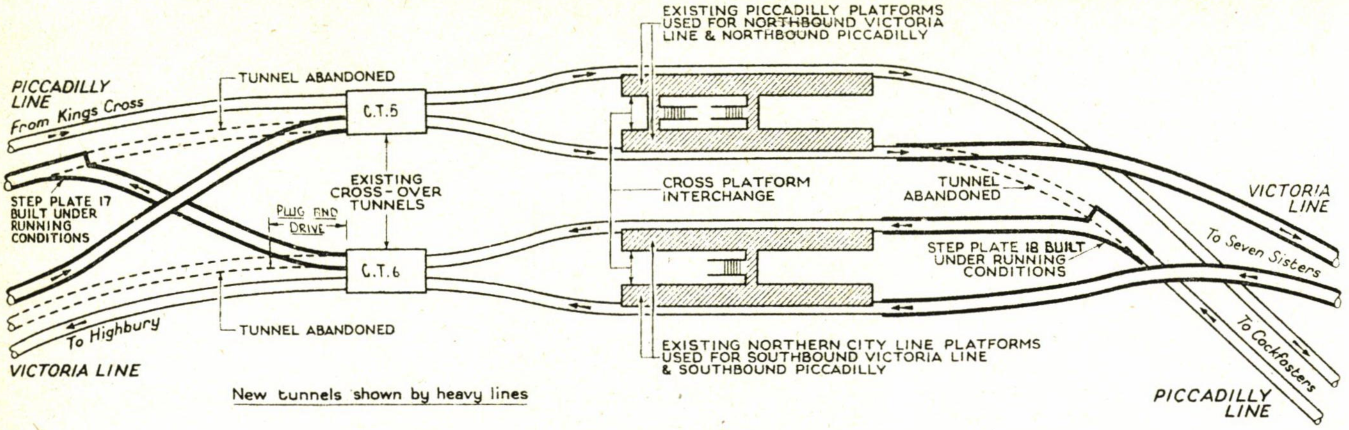
Above: Diagrammatic section showing the consolidation of water-bearing sands and gravels beneath Green Park, carried out by the Cementation T.D.M. process.



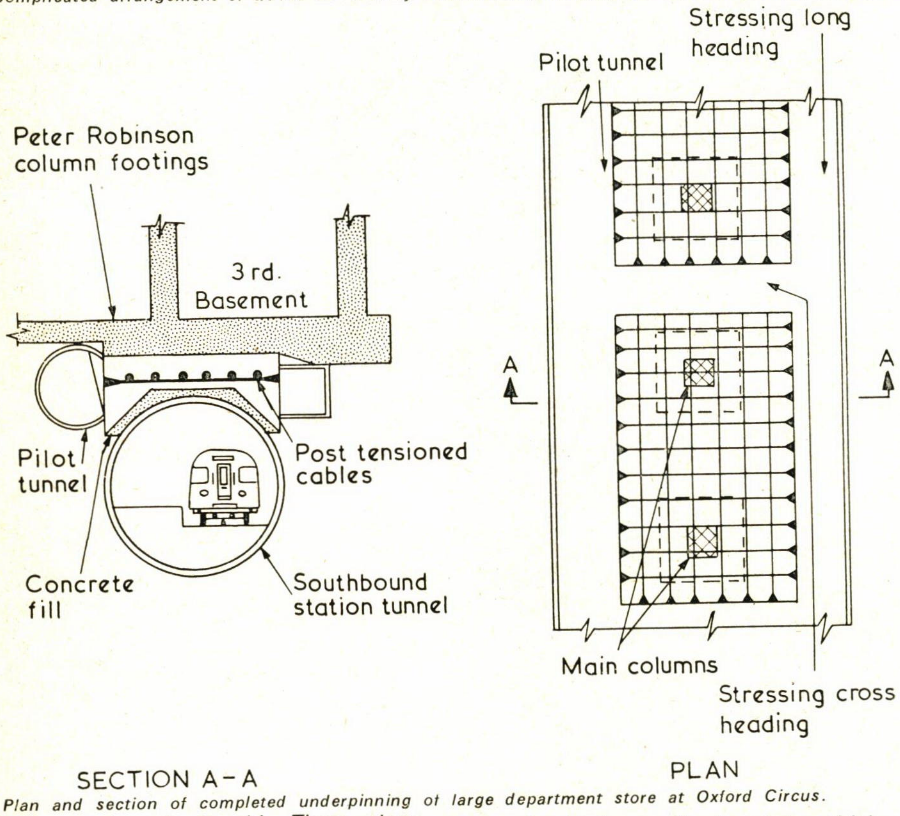
Below: Some of the complexity involved in adding to an existing underground system is shown by this model of the new ticket office and access tunnels at Oxford Circus.

The caulking of the cast iron segments of the northbound station complex at Oxford Circus was done with PC4 cold caulking compound, an asbestos cement material made by Philplug, Ltd. This firm also supplied the grummets for waterproofing tunnel segments on the line. These grummets were of two types: one, of hemp predipped in a mineral gel; and the other, known as the "Oyster", uses low-density polythene. These grummets accommodate themselves to the shape of the bolt holes and will withstand a pressure of 3,000 lb/in^2 (211 kg/cm^2). Damp patches on concrete linings are unsightly and correction is apt to be costly if carried out while the tunnels are in operation. To cope with this problem, Laminor, Ltd., a member of the Drake & Gorham, Scull Group, developed a specification based on grit-blasting adhesion surfaces, filling grooves and cracks with sealing compounds with low-shrinkage characteristics, followed by over-sealing with compatible epoxide-type resins and glass reinforcement. The standard bolts were fully tightened and then sealed with plastic foam, and the clusters of bolts over openings in the tunnel were shrouded with glass fibre mouldings fabricated on site and afterwards filled internally with plastic foam.

One of the more interesting jobs in constructing the new Victoria Line was the building of step-plate junctions to



Complicated arrangement of tracks at Finsbury Park Station, showing the positions of step-plate junctions Nos. 17 & 18.



Plan and section of completed underpinning of large department store at Oxford Circus.

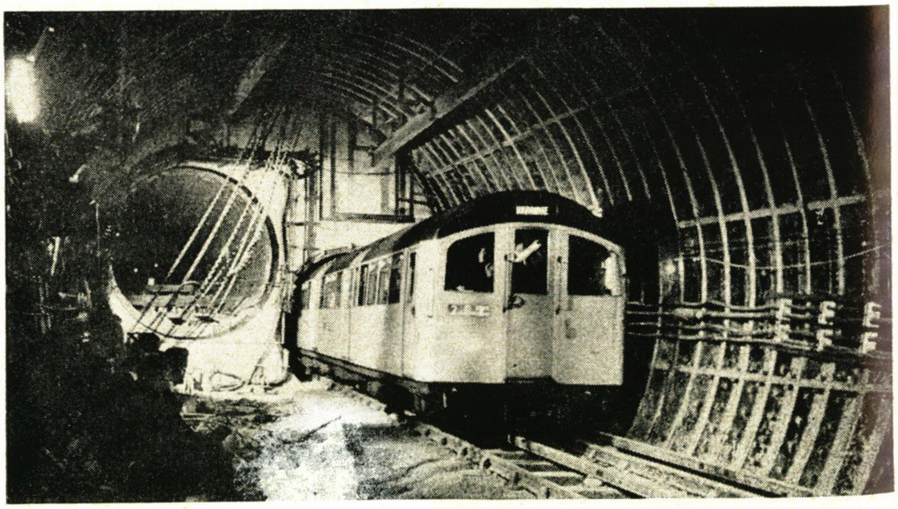
join new tunnels to old. These step-plate junctions are formed by gradually enlarging the size of the tunnel rings from those carrying a single track at one end of the junction to large-diameter rings capable of enclosing two tunnel mouths at the other. This was done by encirclement of the existing tunnels, and diversions through junctions of this type were carried out at Euston, Highbury and Finsbury Park to give easy same-level interchange between the Victoria Line and the Northern Line (City Branch), and the Northern Line and the Piccadilly Line respectively. The work was carried out while the trains continued to run.

A. Waddington & Son carried out the works at Finsbury Park, including the diversion of the Piccadilly Line. The first stage was the construction of two step-plate junctions, which were built by encircling the existing westbound Piccadilly Line tunnel north and south of the station at the ends of the proposed diversion. This was carried out without interrupting the train service.

The site of the north step-plate, which was to taper from 29 ft 6 in to 18 ft 6 in (8.99 to 5.64 m) i.d., was approached from the southbound Victoria Line tunnel by a short adit and a drop shaft. At the base of this shaft a space was formed round the Piccadilly Line tunnel and work started in the 21-ft $2\frac{1}{2}$-in (6.54-m) diameter section of the step-plate, first working southwards to the 29-ft 6-in (8.99-m) diameter headwall, and then northwards to the headwall at the extremity of the 18-ft 6-in (5.64-m) diameter section. Another heading was driven, at the same time as the first, from the southbound tunnel at a point about 100 ft (30.5 m) north of the station to enable the 12-ft 2-in (3.71-m) diameter cast iron lined diversion tunnel to be driven between the station and the step-plate.

At the extremity of the access tunnel a 16-ft 6-in (5.03-m) diameter turning chamber was built, and the 12-ft 2-in (3.71-m) diameter diversion tunnel was driven south to the position of the north headwall of the step-plate junction. From there a 7-ft (2.13-m) diameter pilot tunnel was driven as far as the 21-ft $2\frac{1}{2}$-in (6.46-m) diameter section of the step-plate. Whilst the levels of the existing and future westbound Piccadilly Line within step-plate 18, north of the station, were nearly equal, at step-plate 17 south of the station, the existing westbound line was on a falling gradient of 1:89 and the diversion track was required to rise at 1:90 to meet it, thus producing a difference in rail level of some 5 ft (1.52 m) at the north headwall.

During the construction of step-plate



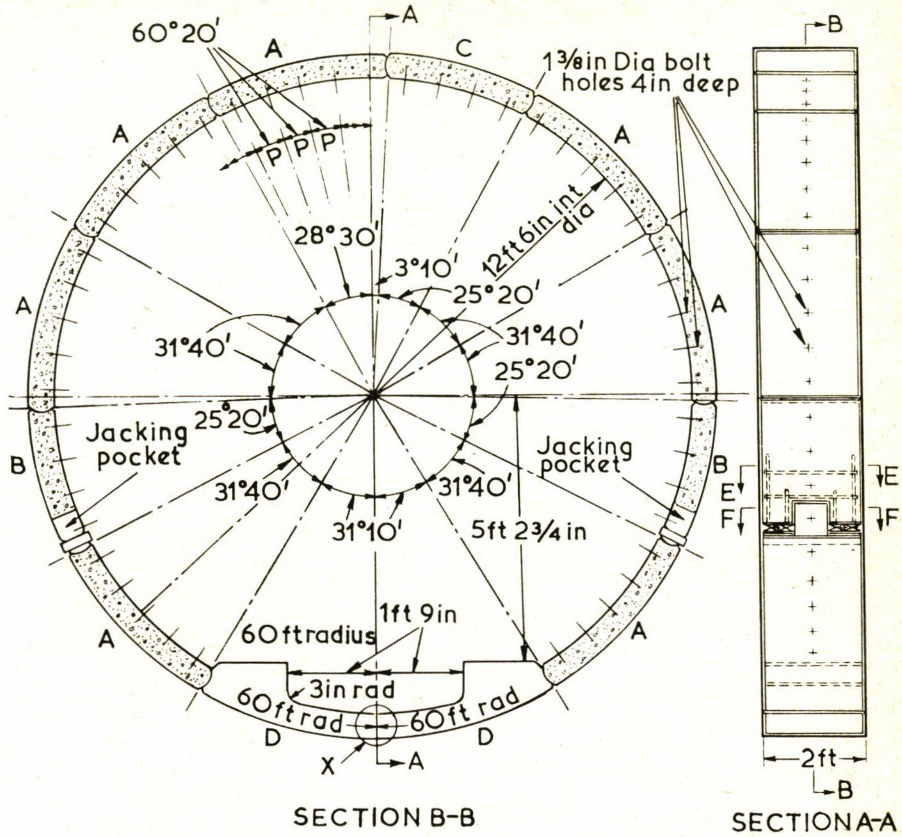
First train emerging from div… …el at the lower level at Step-plate 17.

18 the new invert concrete was placed so as to give support to the existing running tunnel as close to the working face as possible and, using temporary props, the maximum span of the tunnel lining was limited to 5 ft (1.52 m). This procedure could not be used in step-plate 17, where the underside of the existing Piccadilly Line running tunnel was, for most of the length of the step-plate, at a higher elevation than the invert concrete for the future track. During the construction of the encircling tunnels, supports had therefore to be provided which would initially carry the existing tunnel lining and the track after the lining had been dismantled. The supports were designed as steel trestles at 5-ft (1.52-m) spacing, with their legs bearing on the invert of the new lining. A bolted joint was provided at the surface of the invert concrete so that the upper part could be removed, leaving the centre leg and side supports in place.

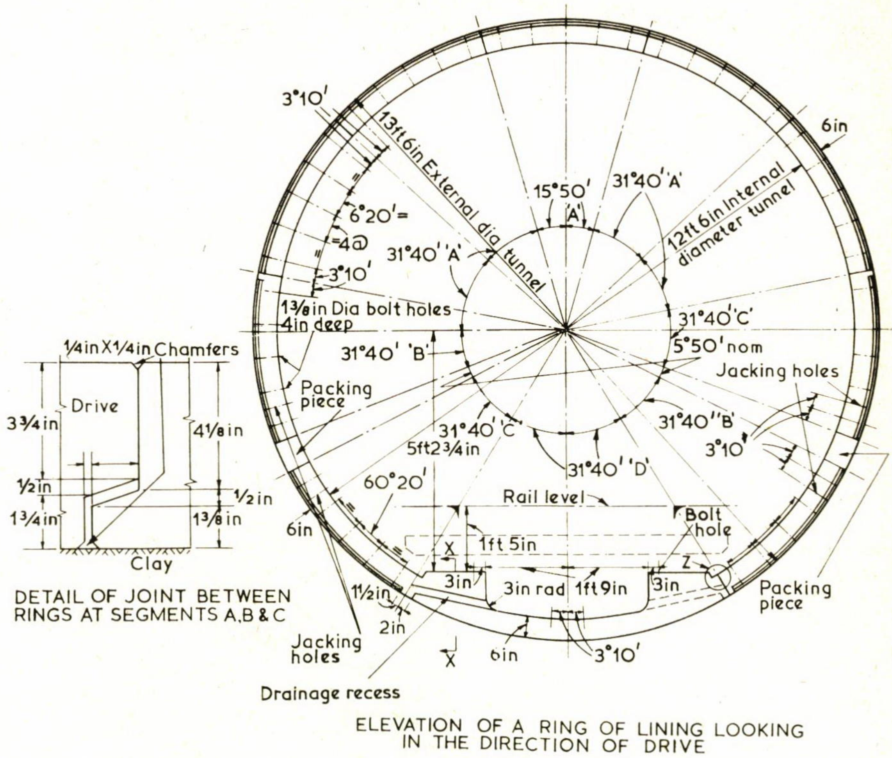
After the segments from the top and one side of the existing tunnel had been dismantled, the track bed concrete was removed from each pair of sleepers. When the invert segments at step-plate 18 had been removed, the track was supported on the new concrete. At step-plate 17 the track was supported on 12 x 12-in (30.5 x 30.5-cm) timber waybeams resting on a timber shaped to give the appropriate superelevation: this in turn was supported on the trestles. Each pair of waybeams with cross ties and struts formed a unit 10 ft (3.05 m) long carried on three trestles.

The 12-ft 2-in (3.71-m) diameter diversion tunnel south of the station was connected in to the 16-ft (4.88-m) diameter existing Northern City Line tunnel. Where the new tunnel would break into the existing one, it was necessary to support the 16-ft (4.88-m) diameter lining by plugging the existing tunnel with weak concrete. To minimise the use and breaking out of concrete, the plug was rough-shuttered to the profile of the extrados of the 12-ft 2-in (3.71-m) diameter lining. A similar procedure was used at the north end of the station where the diversion tunnel intersected the over-run tunnel at an oblique angle.

While the stripping and loading of the waybeams and steelwork at the northern end of step-plate 17 was being carried out, London Transport Permanent Way Department were working at the Arsenal end of the step-plate where 130 ft (39.6 m) of track was slewed to the new alignment and supported on reconditioning jacks. This left a length of 92 ft (28 m) to be reconstructed, supported on reconditioning jacks and joined to the 80-ft (24.4-m) length previously laid, after dismantling the third section of track supports. Conductor rails and signalling equipment was then installed, and the new track was topped and lined. The whole of these elaborate works were completed on time and the track handed back for the resumption of traffic.



Detail of concrete lining, showing jacking pockets.



Detail of cast iron lining, showing jacking holes and packing pieces.