REPORTS OF SOCIETY MEETINGS

CONSTRUCTING THE UNDERGROUND

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A report of the LURS meeting at All Souls Club House on Tuesday 8 December 2015

The meeting started with a clear distinction between the three types of underground 'tunnel'. A traditional tunnel is excavated from each end (and sometimes from mid-points, via shafts), using techniques originally adapted from mining. A covered way is built by excavating an open trench, building the tunnel within, and then back filling. More modern covered ways are often built, to minimize disturbance, by constructing the side walls in narrow trenches with less disruption, then laying the roof slab, and only then excavating beneath. Finally, tube tunnels are made through the use of a cylindrical tunnelling shield.

An illustration showed the first tunnelling shield which was invented by Marc Brunel to excavate the first under-river tunnel, opened in 1843 between Wapping and Rotherhithe. A cast iron shield protected 36 workmen inside separate frames, who removed the poling boards across the front of the shield one by one to excavate 4.5 inches of soil. The shield was then jacked forward and the gap behind bricked up. The engineer's son Isambard was resident engineer for much of the time during great difficulties, due to the damaged river bed caused by anchors, and subsequent leakage of polluted river water into the workings.

The Metropolitan Railway was constructed using the cut and cover method, which involved more than just digging up the street because there were utilities below even in Victorian times. Disruption was massive because of the need to excavate three trenches, two at the sides for replacement sewers, and then one for the railway along the mid-line. No invert was constructed originally, which caused problems at Gower Street, requiring reconstruction a decade later. There was already a tunnel under Euston Road at Park Crescent, the Nursemaids' Tunnel. The railway line had to dip down to avoid disturbance, but the crown of its tunnel still cut through the bottom of the original tunnel, and cheek plates were installed at the intersection as can be seen today. The route passed beneath houses at the east end of Park Crescent, and the solution was to buy and demolish them and later rebuild them above the new tunnel.

Baker Street was a typical cut and cover station. An illustration showed the west end with the original stair access to the platforms, which remains as a footbridge and emergency exit. Regular shafts above the platforms originally let in light from the surface, with white tiling to maximize reflection. Glazing in these shafts was soon removed to allow smoke to escape and so improve ventilation. When the current District Line tunnel was being excavated, its route was more difficult. The area around Blackfriars station was shown, where the new railway passes through the mainline railway viaduct after crossing the Fleet sewer and the Blackfriars bridge abutments. The line had to pass over two existing tunnels linking the former gasworks on the Unilever House corner site with coal wharves on the river, and also pass beneath public subways but over a low-level sewer. Minimum clearance was obtained by diverting and widening the Fleet sewer to ensure that it continued to drain to the Thames but could accommodate floodwaters.

This area was later crossed by the Waterloo & City Line, but by then tube railway technology enabled it to pass deep below these obstacles. The City & South London Railway (C&SLR) was the first to use a tunnelling shield designed by James Greathead, the line's engineer. It was quite short at 5ft 11ins, and made 10ft 2ins diameter tunnels. Clay was excavated by hand through a rectangular opening, and was removed in pony-hauled spoil wagons. Manually pumped hydraulic rams then pushed the shield forward, with the cutting edge trimming remaining clay.

Tunnel segments were 1 inch thick and about 18 inches long, six pieces plus key forming a complete ring. They were painted with pitch and tar to protect against corrosion. Grout was then injected through holes in the segments, using compressed air, to fill the space between them and the clay.

An under-river cross-section showed that construction commenced from a shaft near the north bank of the Thames, enabling spoil to be removed by barge. Brickwork at the base of the shaft had four openings for tunnel construction, both to the north and south with the up line above the down line to pass beneath a narrow street on the north bank. The only building under which tunnels passed was at Hibernia Wharf on the south bank of the Thames, by arrangement with the owners. Some damage was caused due to settlement.

Further shafts were sunk at station sites south of the Thames once the under-river works were successful. Iron segments were assembled on the cutting edge and then the ground was excavated from within so that the shaft sank and new segments were added at the top edge. A contemporary sketch illustrated a navvy descending a shaft by standing on a spoil bucket and casually holding the connecting cable. Journalists visited the workings in the same way, and the ponies were lowered in the same bucket.

Greathead was concerned about construction of large tunnels in cast iron, so at stations the cast iron running tunnel segments were unbolted in 5 to 7 feet lengths and replaced with a lining of stock bricks after enlargement. The flattened tunnel base reduced the amount of excavation, but this reconstruction caused extensive settlement in the streets above, up to 8 inches.

A diagram illustrated the transfer of surface measurements to the tunnel alignments. The surface route was marked overnight on the roads above by hammering in metal plugs. These were carefully measured using brass tapes, and theodolites used to measure angles. Where a nearby shaft allowed dimensions to be transferred to tunnel level a frame was constructed at right angles to the route above and two plumb wires hung from either side down the shaft. These were stabilised with a weight beneath within a bucket of fluid. A theodolite was then used to sight the two wires and ensure a cross-tunnel was constructed at the same angle. The distance of the wires from the metal plugs on the surface was carefully measured and the same distances marked in the cross-tunnel. This gave the centre point for the running tunnels at right angles to the cross-tunnel. The tunnelling shield would continue on this alignment for the same distance as the surface measurements had shown. When a curvature was required the shield jacks would be advanced further on the outside of the curve than on the inside, either vertically or horizontally. Rulers scaled to the curve required ensured a smooth transition.

The second tube railway constructed was the Waterloo & City Railway, which again used a shaft in the Thames, this time near the south bank. With a modified process developed by Harley Hugh Dalrymple-Hay for tunnelling through waterlogged ground, additional plates extending forward by 2 feet were fitted to the top front edge of the shield forming a ‘hood’. Small holes were excavated in gravelly/marshy soil a further 23 inches forward of the hood, then backfilled with clay to form a thin layer around the top of the tunnel. This reduced water ingress and helped prevent loss of compressed air. Seven manually pumped hydraulic rams helped steer the shield. An original shield remains in situ in the passenger subway at Bank station leading from the platform towards the Northern line. The use of a couple of small Siemens locos with overhead power wire allowed the line to be built without the use of ponies.

Construction next commenced on the Central London Railway (CLR). A photo showed a shaft being sunk at Bond Street. Shafts were sunk under their own weight as far as the clay, then manually excavated downwards with shaft rings being added at the bottom. Compressed air working was used in waterlogged ground near Shepherd’s Bush, and beneath the Fleet River, but also at Bank because of concerns about the stability of the Mansion House, the Bank of England, and the Royal Exchange.

An innovation seen here was an hydraulic segment erector used in the large shield for station platforms. This lifted segments into position and held them whilst they were bolted, with hydraulic power supplied from London's hydraulic mains. Tarred rope was pressed between adjacent tunnel segments to waterproof the joints, and hardwood packing was used between tunnel rings to form curves, even for the platforms at Bank.

A diagram showed that to get started a temporary headings was excavated from the base of a station lift shaft across the line of the running tunnels. A chamber was then hand dug within the site of the later platform tunnel for erection of a running tunnel shield. This drove off on the required alignment, and large platform shield chambers were then hand dug to allow these shields to be assembled and the larger diameter tunnels to be driven.

Another innovation in construction was the Thomson excavator used between west of Tottenham Court Road and east of Holborn, where hard beds of limestone were found in the clay. It was invented by an engineer working for the tunnelling contractor, and worked along the principle of a dredger, with 37 metal buckets fitted with chisel teeth, and moved on a continuous chain. It projected through the opening in the shield; with gearing allowing it to automatically excavate much of the material at the tunnel face. It promised productivity improvements but in practice its poor reliability nullified these.

The CLR is noted for its saw-tooth gradient profile, which results in trains climbing into platforms but dropping away when leaving them. This is commonly known to assist train acceleration and braking which saves power and brake block wear. However, it also reduced costs of station construction since they were shallower and there was less spoil to remove from shafts. The resultant reduced depth of lift and stair shafts meant less time to reach platforms and less electricity consumed by lifts.

Siding tunnels at Queen's Road and British Museum were built level, to avoid trains accelerating into them, or departing uphill. Emergency access at the far end of these sidings required stairs down to the running tunnels via a cross-passage. Bank siding was not level as it was intended to be the start of a proposed Liverpool Street extension.

The Baker Street &Waterloo Railway was also dug from a shaft in the Thames, on the north side near Charing Cross railway bridge. There were problems beneath the river, with a large gravel-filled depression to be tunnelled through, likely a trench dug for the abortive Whitehall & Waterloo Railway. Compressed air working was required for this section, and the tunnelling shield was equipped with a 'fountain' trap to prevent water from pouring back in the event of a breach. This could be screwed shut if necessary, and was so on four occasions. This trap was removed once the shield cleared the-river.

There was a high standard of staff welfare. A change of dry clothes was provided to workers coming off shift, and a supply of hot coffee. A decompression chamber on the river staging, with doctors to treat those with decompression sickness, the 'bends', reduced that problem. Air pressure in the workings had to be varied with the tide to match the weight of water above. It was difficult to keep the two balanced, and waterspouts in the Thames were not infrequent.

The Great Northern, Piccadilly & Brompton Railway employed a rotary excavator tunnelling shield. This idea had been trialled on the CLR, but the central axle drive made steering difficult. This new design used a circumferential drive, which meant that the cutting head stayed parallel to the shield, and not to the tunnel face. The same shield was used for the Charing Cross, Euston & Hampstead Railway, although the weight of clay above the Hampstead area required the use of a conventional Greathead shield there. Greathead shields were also used for large diameter tunnels since it was not worth building large rotary excavators for the short runs. A photo of such work with men operating on three levels was believed to show the Aldwych branch crossover tunnel.

We now came to the first line extensions. Borough junction was shown, with the original running tunnel to King William Street on the left and the new route to Moorgate on the right. Until this time all junction tunnels had been constructed as large cylinders, but here a conical step-plate junction was created around the existing running tunnel. It was excavated by sinking a shaft down and removing clay around the existing tunnel whilst trains continued to run through until the switch-over, with old tunnel segments supported from the outside through the new junction. Another photo showed the view through the tunnelling shield from Liverpool Street into the end of the CLR overrun/siding tunnel at Bank. The angle of the shield clearly demonstrated tunnel 'roll' which was overcome by the fitting of a 'plough' to one side of the shield until it straightened up.

Enlargement of the C&SLR tunnels to standard size was planned soon after takeover by the Underground Electric Railways of London group, although it had to await the end of the First World War. A diagram showed how much more space became available. A special shield was designed through which trains could continue to run by day, whilst at night the track would be lifted, cables disconnected, and the shield moved forward ring-by-ring. Spoil was removed and rings dismantled, with new segments installed together with the original segments to effect enlargement to an irregular new cross-section.

Difficulties were encountered at Newington Causeway, where the tunnel was being enlarged through wet ground that had given problems during the original construction. Consequently the tunnel crown was being left in position, and the invert lowered with additional side segments installed. Old segments were being removed two at a time, including at the crown, although there was no excavation behind. Wooden boards were inserted into the gap to protect the location during the day. On 27 November 1923 a train passing through this area was covered in gravel and water, and just made it through before the tunnel was filled. The road above collapsed; the gas mains broke and ignited, and were then doused by the broken water mains. Investigation showed that a dip in the surface of clay meant that gravel was probably less than a foot above the tunnel here. The thin layer of clay had dried due to warmth from the tunnel, so losing strength. Vibration of the tunnel caused by passing trains dislodged the boards, and the clay collapsed followed by the gravel. The line was immediately closed until enlargement works were completed.

The Morden extension got into difficult ground around Tooting Broadway, where gravel and sands required compressed air working. Additional shafts were sunk into clay at Trevelyan Road to allow conventional tunnelling southward to be constructed to time. Tooting Broadway escalator shaft was originally excavated 10ft 6ins diameter, using segments removed from the original C&SLR tunnels during enlargement. It extended into the ticket hall area to allow a horizontal airlock to be formed. It was subsequently enlarged to 22ft 4ins diameter from the bottom up. Special elliptical tunnel rings were used, forming vertical slices across the shaft, instead of the more usual circular rings inclined at the angle of the shaft. This may be history, but the problem has again arisen in connection with Crossrail 2 plans, and a proposed Tooting Broadway station may be dropped in favour of one sited in London clay at Balham to ease construction.

A photo showed the Arnos Park viaduct under construction on the Cockfosters extension. This has been falsely claimed to be the last brick-built viaduct in Britain. Built on sloping ground, it is difficult to get a figure for its height. With forty arches in two sections, it used three million bricks. At the same time new platforms were built on the CLR at Holborn to provide a Piccadilly Line interchange in replacement for British Museum station. The new platforms were excavated around the running tunnels whilst in use; and trains continued to run even as the old tunnels were dismantled. A photo showed a 1903-era CLR train passing through whilst wooden props held tunnel segments in place as the rings were unbolted.

Many central London stations had their lifts replaced by escalators. A diagram of Tottenham Court Road station showed a new triple-escalator shaft led to the former CLR lower lift landings, and these circular structures can still be seen today. A second escalator shaft leads down to the Northern line platforms. At the time of this meeting the recently enlarged station had only been open for a week.

The CLR tunnels had to be realigned to fit standard rolling stock, and platforms were lengthened. At Liverpool Street the passageways to the Broad Street lifts prevented any platform extension, whilst at the east end the crossover tunnel to the sidings commenced immediately at the platform end. The solution required construction of a new step-plate junction further east to connect with the sidings, which were also lengthened to their east. This allowed the platforms to be lengthened eastward on the site of the original siding connections.

We now came to the Victoria Line, where new drum digger machines were trialled in the early 1960s. Invented by Arthur Foster Constructional Engineers Ltd. and Kinnear Moodie, they featured a rotating steel cylinder with cutting teeth within the skin of the shield, and were rotated by hydraulic motors. Spoil was transferred back through the rotating cylinder onto conveyor belts, from where works trains transported spoil to vertical conveyors at shafts.

An experimental section of tunnels was constructed north of Finsbury Park as far as Netherton Road. New linings were also trialled. Expanded cast iron linings had shallower flanges than traditional, using six segments per ring, with curved knuckle joints between. Two invert segments were laid, followed by two side segments. The two crown segments were inserted, then forced against the clay using hydraulic rams. Two key pieces were inserted between the invert and the side segments under pressure, expanding the lining outwards to form a tight seal against the clay without the need for grout.

Concrete linings had originally been tried on the CLR, by pressing green (semi-hardened) concrete against the end of the new tunnels using rams on the shield, but this was unsuccessful because of problems getting it to adhere at the crown. They were used again in the late 1930s for the CLR eastern extensions, due to steel being in short supply. Two different types of concrete lining were tried for the Victoria line, designed by different engineering firms. As with cast iron, concrete linings were expanded against the clay using jacks. They were recently found to be difficult to dismantle, when repairing acid-damaged Jubilee line tunnels north of Bond Street.

Wet ground conditions at Tottenham Hale, and later at Pimlico and Vauxhall, were dealt with by freezing the ground before driving escalator shafts. Liquid nitrogen was used for solidifying the ground at Tottenham Hale before it was replaced by chilled brine to maintain the solidity. Brine cooled by ammonia was used on the Brixton extension stations. This method was not new, having been used at St Michel on the Paris Métro around 1904.

The Heathrow Central extension was constructed using Greathead shields fitted with roadheaders, as used in coal-mining. It was not worth building drum diggers for the short lengths of tunnel between Heathrow and Hatton Cross, from where cut and cover tunnelling was used. Each running tunnel used a different make of equipment, and the Anderson Mavor roadheader was reported as “superb” since it cut through large stones found in the clay.

Drum diggers evolved in the 1980s into Tunnel Boring Machines (TBM) which were trialled down at New Cross and first used on the Underground to build the Jubilee line extension in the 1990s. They are effectively mobile tunnelling factories, being entirely self-contained. A photo showed the first TBM being lowered in sections into the station box at North Greenwich. The latest TBM design was shown in a diagram from Herrenknecht, the manufacturer of all eight Crossrail TBMs. It is an Earth Pressure Balance Machine weighing 980 tonnes, and being 148 metres long. The closed chamber at the front behind the cutting head enables pressure to be maintained on the clay face, preventing collapses. A screw conveyor removes spoil after the crusher unit breaks up lumps. Hydraulic rams behind this drive the shield forward. The tunnel lining is assembled using hydraulic systems, lifting segments using vacuum. Segments are stored in a magazine, supplied by works trains. A trailer, pulled behind the TBM, contains the control room, toilets, kitchen, spoil conveyors, transformers, and hydraulic systems. Cables and pipes behind the trailer spool out, but need regular addition of extensions as the TBM progresses. The fastest drive constructed 72 metres of tunnel in a day.

This brings us to the current day but, despite technological advances, the basic tunnelling methodology remains the same as that used on the first C&SLR Greathead shields which were only 5ft 11in long! Much more information will be found in the forthcoming book “Building London’s Underground”.

John Hawkins