(*Paper No. 3317.*)

“Subaqueous Tunnelling through the Thames Gravel :
Baker Street and Waterloo Railway.”

By ARTHUR HARRY HAIGH, B.Sc., M. Inst. C.E.

By the original Parliamentary Acts of 1893 and 1896 the Baker Street and Waterloo Electric Railway was authorized to be constructed from Dorset Square to Waterloo, in two cast-iron tunnels, forming a double line with a length of 3 miles 1 furlong 1·3 chain. The route is beneath the Baker Street Station of the Metropolitan District Railway, by Regent's Park and Crescent Gardens into Portland Place, through Langham Place and Regent Street to Oxford Circus, where the tubes pass over those of the Central London Railway (the clearance over one of them being only 6 inches), down Regent Street to Piccadilly Circus, along Haymarket and Cockspur Street to Charing Cross, thence down Northumberland Avenue, and under the Thames to College Street, Vine Street, and Waterloo. Foot-passage connections will be provided with the Great Central Railway station at Marylebone Road, with the Metropolitan lines at Baker Street, with the Central London Railway at Oxford Circus, with the District Railway at the Embankment, and with the London and South Western main line and the Waterloo and City line at Waterloo. Access to the line will be afforded by lifts at the stations in the modern way. In addition to the stations at the connections referred to, there will be others at Piccadilly Circus and at the Nelson column at Charing Cross. Most of the permanent shafts for lifts and stairs, and the greater portion of the 6 miles of tunnel, have been constructed. Excepting the river portion, the whole length of the tunnels is through London clay; and what is generally known as the Greathead shield is employed for construction. This Paper, however, is limited to a consideration of the special river portion.

Subsequent Parliamentary Acts authorize the extension of the railway at the south end from Waterloo to the Elephant and Castle, with sidings and an electric generating-station on the present site of the School for Indigent Blind near St. George's Circus; and at the north end from Dorset Square to Bishop's Road, Paddington.

THE GRAVEL.

Between the bottom of Northumberland Avenue on the left bank of the river and the west end of College Street on the right bank, the tunnels pass through a bed of clean gravel and sand, lying in an abrupt depression of the surface of the London clay to at least 45 feet below its general level. This feature necessitated construction under compressed air. The foundations of the Charing Cross Railway Bridge, 250 feet away, gave no indication of this depression, which was found during the boring-operations that were conducted as necessary preliminaries to the final location of the centre-lines of the tunnels, and to the commencement of the temporary works for construction. The profile of the clay surface through this depression, and along the centre line of the tunnel lately constructed, which had been determined from borings not exactly on the adopted centre-line, corresponded closely with the surface actually encountered during construction, where it was capable of being so tested; and the guidance it afforded was sufficiently exact for all practical purposes.

LOCATION OF THE TUNNELS.

The two tunnels, 12 feet in internal diameter, for traffic in the two directions, were located through the gravel bed 23 feet apart from centre to centre in plan, giving a clear space of over 10 feet between their horizontal diameters (Fig. 1, Plate 2). Northward this distance between centres diminishes from 23 feet at the left bank of the river to the normal distance of 17 feet 6 inches in Northumberland Avenue; and southward, from 23 feet, near low-water mark on the right bank, to zero in College Street, where the east tunnel will be vertically over the west tunnel, in order that both may pass within the confines of the narrow street. The gradients of the tunnels over this portion were arranged so that, with a gentle downward slope of the one and a similar upward slope of the other, the relative positions in College Street could be attained without reducing the minimum thickness of clay between them to less than 3 feet 6 inches. These gradients, as will be seen from

the section (Fig. 2, Plate 2), are 1 in 107 down, southward in the west or down tunnel, and 1 in 111 up, southward in the up or east tunnel. In plan (Figs. 1) the centre-lines curve from the river into Northumberland Avenue by 12-chain curves, and into College Street by 15-chain curves.

SHAFTS.

In the preliminary arrangements for construction it had been intended to make a timber stage on piles driven into the river-bed near the right bank, from which temporary shafts might be sunk to the tunnel-levels, and from which a bridge might lead to the shore at the end of College Street—similarly to the method used for the Waterloo and City Railway. The depression in the surface of the clay necessitated a re-consideration of the method of opening out. The Thames Conservancy courteously agreed, without any difficulty, to permit the erection of a stage 150 feet from the left bank of the river, near the wall of the Victoria Embankment; and the South Eastern Railway Company permitted a temporary footbridge from the stage to the shore to be carried on cantilevers attached to the Charing Cross Railway Bridge.

In this position a timber stage 50 feet wide was constructed on piles, extending 370 feet up-stream from the first cylinder-pier of the bridge in the river on the Embankment side. From this stage, shafts of cast iron, 16 feet in internal diameter and 50 feet in depth, were sunk, and brick chambers were constructed below. The stage holds all the necessary shops, stores, buildings and machinery. Along each side crane-roads, of 6-foot and 4-foot 8½-inch gauges, were laid on longitudinals. From these roads travelling steam-cranes, having a horizontal radius of 20 feet, are able to command barges lying alongside, and the middle of the shafts. The boilers, air-compressors, and dynamos are described in the Appendix. Below stage-level are two boiler-shaped air-receivers and a condenser, in a caulked water-tight wooden chamber below high-tide level. Near the shafts are the engine and mixing-pan for the pugged clay so extensively and effectually used at the face. The portion of the stage occupied by the engine-houses, boilers, and offices, is decked with Portland-cement concrete, with lengths of wrought-iron joist and girders built into it. Against short cross joists in the concrete, long raking struts of whole timber are butted, footing against the piles. Eight pairs of these struts form a rigid support, and the simultaneous use

of all the air-compressors does not cause perceptible vibration. The remainder of the stage is decked with two thicknesses of planking.

After boring-operations through the river-bed, occupying more than 3 months, the first pile of this stage was driven on the 20th June, 1898, and the structure was practically completed early in the following November. The stage stands 6 feet above Trinity high-water level, and on the average has 27 feet of water around it at high tide. The two temporary cast-iron cylinders, 16 feet in internal diameter, consist of six rings, each 8 feet in depth, having six segments to a ring. The joints were machined, and the pieces were put together with red lead and hemp-yarn. A 2-foot cutting edge, with bevelled vertical flanges and sharpened edge, was used to sink the cylinder. Six rings and the cutting edge make up the 50-foot length of iron cylinder, reaching about 10 feet into the London clay. Below this the brick chamber extended downwards a further distance of 22 feet. To prepare for sinking the cylinder, a timber platform was erected, somewhat above the level of low water, and on it the cutting edge was put and bolted together. The two succeeding rings were then built above, and the length was slung by chains, and held by union screws from timber barks across the opening in the stage-decking. The platform below was next removed, and the 18 feet of cylinder was lowered through the mud, the grab being used within, until, on its taking a bearing, the screws could be detached, when another two rings were built. Including the weight of the cylinder, a load of 106 tons, equivalent to about $2\frac{1}{2}$ cwt. per square foot of maximum surface exposed to friction, sufficed to sink the remaining 6 feet to the required level for underpinning the cylinder with the brick walls, 23 inches thick, for the enlarged chamber below. In carrying down the brickwork, spaces were left for eyes, in which five-ringed brindled brickwork in 2 to 1 Portland-cement mortar was afterwards built, forming complete circles through which the tunnelling-shields were to be driven, the work above being propped in the meantime. Each leg of succeeding rings of brickwork was built under the junction of two legs of its predecessor. Inverts were made of 15-inch Portland-cement concrete, dished about 6 inches.

From No. 1 shaft, in the "down" or west tunnel, tunnelling northward was begun in February, 1899. The south faces stood until the 22nd March, 1900, when the shield was driven through the eye of the west tunnel.

THE SHIELD.

In bad ground the ordinary shield affords no protection in front of the cutting edge to the men working in the "length." Consequently, its use then involves the driving of a top heading, from which the length is opened by timbering downwards. The shield is then driven through the length and the timber is built in, as was done on parts of the City and South London and Waterloo and City Railways, in passing through gravel south of the river. Not only is much timber thus built in, involving expense and also liability to future settlement of superincumbent soil owing to its decay, but also, while the shield is being driven, considerable disturbance of the material is caused by movement of the timbers, with consequent risk to the stability of the face. The strata to be dealt with in the Baker Street and Waterloo Railway tunnels—very open ballast charged with water directly beneath the river under a head of 70 feet at high tide—did not permit of such a risk being incurred. Apart from the absolute danger of collapse of the face, it would have been extremely difficult to render moderately air-tight such a timbered space, with so large a proportion of top or roof where the escape was most ready; and the large and sudden losses of air which would have resulted would have necessitated extensive plant and involved heavy pumping-expenses, even if the requisite pressure could have been maintained at all. In the actual construction a small area of exposed face involved such a rapid loss of air that every portion had to be thickly plastered with pugged clay as quickly as possible. The adoption of a hood in front of the shield, as used on a portion of the Waterloo and City Railway, obviated the difficulties referred to: the hood is simply a prolongation forward of the cylindrical skin of the shield at the cutting edge, except only at the invert, where the edge is cut away, for affording access to the uncovered ground for working.

It was important to provide for the safety of the men in the event of a "blow," which would be of likely occurrence with such open ballast, and also to prevent flooding of the tunnel. This was effected by attaching, within the circle of the ram-casting, a fountain trap, as applied to the shield used in the construction of the Mersey aqueduct tunnel.¹ In advance of the upper screen of the trap there was just sufficient working-space for the miners; and the screen was so close to the men that they had no difficulty

¹ *Ante*, p. 11.

in escaping under it when a "blow" occurred. But in a shield of this size space was insufficient for the use of shutters at the narrowing vault above the miners' heads; and a pair which were tried at the top were forthwith abandoned. Both were badly bent at their narrowing ends, evidently from the attempt to screw them forward without having effectually cleared away the ballast in front of these ends. In this respect the circumstances were essentially different from those of the Blackwall Tunnel, where the size of the shield for a 27-foot tunnel permitted access to the shutters for removing the material with facility. It was originally intended to use shutters down the whole face; but the top pair having been abandoned, it was found more convenient to continue the timbering downwards as a homogeneous system than to apply shutters below with timber above.

Figs. 3, Plate 2, show the shield, weighing $29\frac{1}{2}$ tons, made by the Widnes Foundry Company from drawings sent out by the contractors, Messrs. Perry & Co., after consultation with the engineers. Its outer casing consists of a steel cylinder 13 feet in external diameter, having the lower part in front cut away, in a curved form, from a maximum height of 3 feet at the cutting edge, thus leaving a hood or cover above an open invert. The middle portion of the shield's length covers the rams, and the back part forms the tail space for erecting the iron tunnel-rings. The edges of the plates at the front of the hood are bevelled at an angle of 45° to form a cutting edge. The circular box-girder, 10 feet 1 inch in internal diameter, and the middle vertical girder within it, form the main frame or rib of the shield. The several thicknesses of steel skin at the hood are connected by nine circular rows of 1-inch rivets with 6-inch pitch, and one row of 3-inch pitch close to the bevel of the cutting edge; all have their outside heads countersunk. The segments of the several layers of the skin break joint; and cover-strips run the whole length of the shield over the outermost six longitudinal joints. Nine gussets connect the side plate of the box with the skin of the shield. The whole length of the shield is 9 feet $8\frac{1}{2}$ inches; which may be divided into, main body 5 feet, tail 2 feet 6 inches, hood 2 feet $2\frac{1}{2}$ inches. Within the main body, behind the circular girder, is the cast-steel ring bearing the fourteen hydraulic rams, each 6 inches in diameter, eight clustered at the lower parts and six set in pairs laterally (Figs. 4 and 5, Plate 2). Ordinarily the lowest four were not brought into use; and six or more of the remaining ten were suitable and sufficient for driving the shield. Each ram is capable of being actuated independently. The ram-cylinders, of cast steel, are $1\frac{1}{2}$ inch thick, and have a stroke of

20 inches. All the cylinders, pipes, valves and connections are adapted to stand a hydraulic pressure of 2,400 lbs. and were tested to 3,500 lbs. per square inch. Working-pressure is supplied to the rams by an intensifier, having a cylinder 7 inches in diameter, fed by the London Hydraulic Power Company's water from their mains in the Embankment, at about 800 lbs. per square inch; and the pressure on the piston of the intensifier is transmitted by two plungers 3 inches in diameter to the water in communication with the rams. The calculated multiplication is $4\frac{2}{3}$, and an effective result of 3 is allowed. The usual average pressure on the rams when in action is about 1,300 lbs. per square inch.

The safety-appliance, which may be described as a fountain trap, was formed by closing in the lower half of the shield, 3 feet behind the box-girder, by a vertical steel plate reaching upward above the centre of the shield; and similarly closing in the upper half by a plate against the box-girder, and therefore 3 feet ahead of the back plate, and reaching downward $6\frac{1}{2}$ inches below the lip of the back plate. A bird's drinking-fountain illustrates the principle of action of the shield trap: the domed reservoir holds a supply of water, which would flow away through the supply opening at the bottom, were it not that, the air-pressure being superior to the hydraulic head, flow from the reservoir ceases as soon as the supply opening is immersed. The apparatus effected automatically, in case of emergency, the change of a face ordinarily vertical to one horizontal, forming, in case of a blow, a seal by the action on the horizontal surface of water in the trap of an air-pressure superior to the hydraulic head beyond the diaphragm. This arrangement acted quite satisfactorily, the occurrence of a few blows from time to time showing that the four men at work between the diaphragm and the face had time to escape through the trap, and that, on filling, the trap sealed automatically, maintaining an unstable equilibrium, until the sand, which followed from the face, filled the trap, and extended with a sloping surface from the lip of the diaphragm to the face at the cutting-edge soffit. It was possible to remove this sand subsequently, by opening carefully under the edge of the diaphragm, until a miner could gain access to the face, and set protecting timber. The top of the trap was provided with a plate with a manhole through it, and a covering lid which could be screwed down in case of need. Round iron foot- and hand-bars were fixed up the curved sides of the trap and inside the circular girder. The semicircular diaphragm-plate and the back vertical plate of the trap were pierced, each with two holes, for the four hollow round steel struts, for holding the face timbers independently

of the shield. When in position, these struts passed through leather sleeves, 18 inches long, attached to the steel plates on the pressure side by angle-bar rings and bolts (Figs. 11, Plate 3).

IRON LINING (Figs. 6-9, Plate 2).

The special tunnel-rings of cast iron for the length in river-gravel consist of seven segments, four of one pattern having longitudinal radial joint-flanges, and two having a radial flange at one end, and at the other a flange set at an angle to meet the tapered flanges of the short key-segment, which is 10 inches wide outside and $10\frac{1}{4}$ inches inside. These seven segments form a ring 18 inches long, 12 feet in internal and 12 feet $9\frac{3}{4}$ inches in external diameter, and weighing 1 ton 15 cwt. 1 qr. 16 lbs. The metal skin is 1 inch thick, and there are 53 bolts at each circumferential joint. The joint between two segments bisects the pitch-distance between two bolt-holes. The rings are placed joint opposite joint, forming a tunnel with continuous longitudinal joints. Circumferential joints were caulked with iron-rust cement. When the use of the special rings was begun, both circumferential and longitudinal joints were machined; but for the bulk of the work the circumferential joints were left rough, and put together with creosoted pine-wood packing. Machined joints were painted with a mixture of red lead and Stockholm tar, before being put into the tunnel. Numerous grommets were put around bolts to ensure water-tightness. The grout-holes provided in the key-segment and the two segments next to it were tapped, and were stopped with steel screw-plugs after grouting. The grouting-mixture used throughout was 3 of blue lias lime with 1 of clean sharp sand. The grouting-machine is shown in Fig. 10, Plate 2. The ordinary cast-iron ring used in London clay is 20 inches long.

TUNNELLING.

The shield for the west or down tunnel was built in the chamber at the bottom of the shaft during January, February, and March, 1900, and tunnelling was begun on the 19th March. For guiding the shield the usual method of plumb-bob lines and boning-rods was used. Side rods, graduated in feet and inches and passing over fixed index-marks set square to the centre-line, were drawn along by the shield to gauge the equality of its lateral advance; and a suspended bob-line on the shield itself indicated its position for maintaining the advance on the requisite gradient,

or for correcting any want of exactness in position as regards level. When travelling on the curve, one of the side rods bore a shrunk scale to correspond. The centre-line below was taken from a 15-foot 6-inch base, transferred down the shaft by wires set in position from the embankment-wall 180 feet away.

On leaving the shaft the shield had a cover of clay 17 feet thick, and was 24 feet below the river-bed. Driving under ordinary atmospheric conditions was continued until the 2nd April, when the advance was suspended in order to build the bulkhead wall with air-locks behind the shield. At that time there was still 15 feet of clay above the crown of the tunnel. A wall, 8 feet thick, of wire-cut gault bricks and Portland-cement mortar, grouted with neat cement by air-pressure through iron pipes built in for the purpose, formed the air-tight diaphragm. Besides the working-lock 5 feet 9 inches in diameter and 13 feet 6 inches long, and an emergency-lock above it 3 feet 9 inches in diameter, all the necessary pipes and electric wires were built in as the brickwork rose.

The shield was re-started on the 2nd May after one month's interval. On the 21st, when the clay showed a change in quality, the shield was stopped, and the fountain trap at the back was attached. The cover of clay at the cutting edge was then 5 feet, and the depth below the river-bed 18 feet. Hitherto a box heading, with 6-foot timbers for head and side trees resting on sills, had been worked in advance of the shield to a distance of about 7 feet. This was now stopped. Auger-borings were being made in the length each time the shield was driven forward, extending to 5 feet above and in advance of the cutting edge; they were also made in advance of the box heading. On the 23rd May the lock-doors were closed, and an air-pressure of 10 lbs. per square inch was maintained. After building-in the locks and re-starting the shield, one engine had been running and blowing air into the tunnel in readiness for closing the doors at any time.

On beginning compressed-air work the labour-shifts were altered from two 12-hour to three 8-hour gangs. On the 6th June the cutting edge entered the gravel at the soffit. For about 3 days previously there had been practically no thickness of clay cover; and the vertical face at its upper part was poled up and down, middled by a waling, and the top of the length was guarded by a few boards. When ready for driving, the short stretchers against the shield were struck, after substituting a waling low enough to be held by the hollow steel struts which passed through the diaphragm-plate, and were blocked against a transom 9 inches by 8½ inches, secured in the flanges of the last-built ring of tunnel

(Figs. 12, Plate 3). Two pairs of these hollow struts were provided. Each was $5\frac{1}{2}$ inches in diameter, closed at the forward end by a screw plug, which was shouldered flush with the outer cylindrical surface of the strut, so as to form a solid butt against the face timbers; while at the back or tunnel end was a similar plug, but tapped with internal screw-thread, through which worked the screw bearing the round ram-head and perforated with holes for lever-bars, for tightening against the transom. Each pair of struts passed through the holes in the diaphragm-plates of the fountain trap. As soon as the thickness of the clay cover above the cutting edge had diminished to only 2 or 3 inches, hand holes or pockets were opened, in advance of the face and in front of the cutting edge, reaching a few inches above it, and rather more than one length in advance, into which well-tempered clay was put, precisely in the manner described by Mr. H. H. Dalrymple-Hay in his Paper¹ on the "Waterloo and City Railway," as used there with the hooded shield; a series of such pockets formed finally a continuous portion of an annular bed of soft clay, into which the cutting edge could easily enter. The circumferential length of this annular bed grew as the amount of ballast face increased, until it extended round the whole hood; thus forming, as the shield advanced, an air-seal at its tail where the last tunnel-ring had been built, and affording a clear space for the grout to enter around the tunnel. As the ballast face grew downward a second row of poling-boards was introduced below, with a middle waling 9 inches by 4 inches; the two walings were held by soldiers 11 inches by 6 inches, and by the upper pair of steel struts, when the shield was being driven (Figs. 13, Plate 3).

On the 16th June the special 18-inch lining-rings were first employed. There was then 15 inches of ballast at the face, and a cover of 22 feet to the bed of the river. When the ballast extended down 3 feet 6 inches, which was the length of the upper polings, it was found desirable to substitute horizontal planks for the vertical upper polings, which exposed too high a portion of the face on removal; two sets of vertical polings continued to be used against the clay below. Each of the three uppermost widths under the hood consisted of two pieces, while a few below them were long planks across the whole face (Figs. 14, Plate 3).

From the 21st to the 27th June the top pair of iron shutters was used. In addition to the difficulty of limited space for

¹ Minutes of Proceedings Inst. C.E., vol. cxxxix. p. 25.

using them, the range of movement was so small that setting forward the face for one tunnel-ring required double labour, that is, setting forward twice. Suitable progress under such circumstances was not possible; and the crippling of the top pair of shutters soon proved that the miners' patience was unequal to the task. Horizontal timber members, in two parts across the face, were therefore substituted. When the face-planking came into use as far down as the lower pair of steel struts, the planks were held by soldiers and walings against the steel struts. Figs. 12-19, Plate 3, show the face-timbering used at various stages, at the dates noted thereon. The face was set forward to a position varying between 2 feet 2 inches and 2 feet 6 inches beyond the front edge of the vertical girder. The whole of the gravel portion of the face was thickly plastered with pugged clay, against which the planks were set.

On the 15th July there was a full face of ballast. On the 21st a run of water filled the fountain trap. On the 20th and 21st August blows occurred, filling the trap with water, followed by ballast which choked itself in the shield. The four men at the face escaped safely under the diaphragm-plate, and were able subsequently to attack the face again by getting into one half-section of it at a time, the vertical girder forming a divisional guard exactly adapted to the circumstances. On both the latter occasions it was the uppermost planks which were blown in. It is probable that on the 20th August more timber than a single width of board was removed simultaneously for setting forward; the rule was one width only. After the second of these two blows the space of the five uppermost planks was found exposed, the blow occurring when the lower portion of the face, at about floor-level, was being set forward. Possibly, therefore, there was lack of vertical support, through insufficient inclination of the temporary props to the face-planks; thereby allowing a slight downward movement of the boards, and a consequent loosening which permitted the uppermost planks to blow in. Or else the pugged-clay stopping at the cutting edge was insecurely held at some place, allowing an escape of air and a loosening of a mass of pugged clay, by the oscillation of hissing air and the opposing water pressure outside; and such a mass, dropping out of its place, involved a sudden loss of air-pressure, and a rush of water, scouring the face and freeing the planks.

On the 14th September the last blow occurred, which filled the fountain trap with ballast. This also was successfully dealt with, but involved delay.

On the 21st September a good deal of water was let into the tunnel from deficiency of air-pressure; but only near the face was the rail-road awash. From this time until getting completely into the clay the ballast was coarse and open; and the air escaped so readily through it that difficulty was experienced in keeping up the requisite pressure. The blow-off valve of the air-receiver was regulated automatically by a float on the river, which carried a vertical board having an inclined channel-bar groove attached to it. The groove constrained a roller, which moved horizontally as the board rose and fell with the tide, and varied by its movement the position of the fulcrum of the loaded valve-lever, thus varying the pressure according to the hydraulic head.

The specific gravity of the ballast was found to vary between 1.42 and 1.60; the average weight was 96 lbs. per cubic foot, or 1.55 specific gravity. A mass of the ballast became fully charged with water by the addition of between one-fourth and one-third of its volume; the specific gravity of the mixture varied between 1.75 and 1.85, and the average weight was 112 lbs. per cubic foot, or a specific gravity of 1.80. The specific gravity of the solid flinty constituents was 2.13, or 133 lbs. per cubic foot. As the iron tunnel weighs about 2,620 lbs. per lineal foot, the buoyancy of the tunnel, 12 feet 9 $\frac{3}{4}$ inches diameter, in water, is 8,114 lbs. — 2,620 lbs. = 5,494 lbs. per lineal foot. The counter-balancing downward pressure of the weight of 1 foot thickness of ballast above the tunnel is $62.42 \times (1.8 - 1)$ lbs. per foot of diameter, equal to 640 lbs. over the tunnel diameter. The cover of ballast therefore necessary for a balance of buoyancy and super-incumbent weight is $5,494 \div 640 = 8\frac{1}{2}$ feet about; say, allowing for the slope of the haunches, 8 feet. Under that depth of ballast in the water the weight of the tunnel and the load above would be just supported by the fluid pressure.

On the 27th September the tunnel re-entered the London clay at the invert, and on the 6th October a full face of clay was again obtained. During straightforward work, normal progress with a ballast face was three 18-inch rings per day of 24 hours.

On the 8th October the use of ordinary 20-inch rings was resumed; and a box heading was again begun, driven as low as possible. On the 24th, at low tide, all the compressed air was let out to test watertightness. There were droppers through bolt-holes and some joints as the tide rose. Air-pressure was then restored, in order to fix grommets on bolts and to recaulk some joints. On the 27th the compressed air was finally dispensed with; and on the 8th November the removal

of the lock-wall was begun by attacking it with drills. The water-spout at the river-surface over the tunnel-face, which for some months had been a feature visible from either bank, had now ceased to rise. It had sometimes risen to about 2 feet 6 inches above the surface, forming a picturesque cap to the invisible column of air ascending through the ballast and water from the working-face. The column was usually deflected from the vertical by the tide. At some positions a deviation occurred due to other causes—probably to the different degrees of openness of the material through which the air ascended. It was found during tunnelling that at some places the beds of different materials alternated rapidly. Sometimes two air-spouts were delivered, a considerable distance apart. In addition to forming these spouts, the air escaped in innumerable frothy bubbles over a large area above the tunnel-face.

WORK UNDER COMPRESSED AIR.

During the whole period whilst the face or any portion of it was ballast, the air-pressure maintained in the tunnel was equal to the hydraulic head of the tidal water. The daily range of air-pressure was therefore ordinarily between 24 lbs. and 32 lbs. per square inch above atmospheric pressure. Whenever, by reason of the rapid escape of air, the engines were unable for a time to maintain an air-pressure equal to the hydraulic head at the invert, the depth of water standing in the length at the front of the shield corresponded exactly with the difference of pressure. Often, with a boxed face well pugged, the engines delivered more air than escaped, and at high-water the air-pressure rose to 35 lbs. per square inch. With such deficiency and excess of pressure the range was between 21 lbs. and 35 lbs. per square inch. While the three engines were running at full speed, atmospheric air was being pumped through the tunnel at the rate of 200,000 cubic feet per hour; but with a clay face sometimes only 30,000 cubic feet of air per hour was blown through, with one engine only at work.

From the 23rd May to the 27th October, a period of 157 days, during which compressed air was employed, one hundred and twenty miners and labourers were at work during some portion of the time. As three gangs worked daily, ordinarily in 8-hour shifts of thirteen men each, there were, on the average, three complete sets of the full complement of thirty-nine men. Twenty-eight men worked practically throughout the compressed-air work. Eight—who began somewhat later—had a total record on the time-sheet as

high as several of the former, making with them thirty-six men who worked regularly through the bulk of the compressed-air construction. Thirteen others worked altogether half time of the whole period. One man worked 41 consecutive days, one 40 days, and another 35 days. The last continued at work to the end of the special construction, totalling the highest number of days worked, viz., 129; in addition to which on eight occasions he worked two shifts in one day. Another, almost as pertinacious, totalled 125 days, with 31 days of consecutive labour. Among the whole number thirty-two men worked less than 10 days each. Out of one hundred and seventeen men twenty-eight worked all through, six a large portion of the whole time, thirteen about half time, thirty-six casually, and thirty-two for short periods.

Dr. Frederick Wainwright, the medical officer appointed by the contractors to examine the labourers in the compressed-air work, and to attend to cases of sickness affecting them, reported that, out of the one hundred and twenty men he passed, eighty-eight had previously worked in compressed-air, thirty-two having had no previous experience of it. Forty-seven cases of illness came under his treatment, which occurred among forty different men, two of whom had three attacks, and three of them two. He was of opinion that none escaped a slight twinge of pain at some time or other. Details of his observations and cases are published in the *Lancet*.¹ The pathological effects of compressed air, as manifested during this work, were of two kinds. The minor effects were the direct result of the actual mechanical pressure during the change in the lock; the more serious effects, the real "bends," as they are called, were due to other causes, and appeared some time after egress, and only after a lengthy stay in the compressed atmosphere. The symptoms of the former are chiefly pains in the ears, and slight bleeding from the nose; of the latter, pain, usually in the joints, and often very severe.

Apart from undergoing the condition of changing the pressure in the air-lock, the effect of an atmospheric medium under higher pressure, for living and working in, does not seem as a rule to be deleterious, at any rate up to a pressure of about three atmospheres. It is true there are many individuals for whom it is unsafe to go into compressed air; for, under working-conditions, they must frequently be subjected to variations of air-pressure, and occasionally to more highly dangerous incidental circumstances. There are three factors which appear to govern the occurrence of compressed-air sickness:

¹ 22 December, 1900.

namely, the amount of the pressure, the proportion of carbonic acid present in the atmosphere, and the length of stay in the compressed air. These might be shortly designated as pressure, purity of air, and time. Cases of "bends" appear to occur only after 3 or more hours' stay in the compressed air, and mostly when the purity of the atmosphere is below a certain standard. As a rule in this tunnelling, in view of the difficulty of preventing a large escape of air at the face, the compressed air was delivered immediately at the lock end, and traversed the whole length of tunnel before egress at the face, thus effectually displacing the older and more contaminated atmosphere. As the tunnel and the work at the face were well lighted electrically, the vitiation of air was reduced to a minimum. With a gravel face the carbonic acid was 0·06 to 0·07 per cent. by volume of the compressed atmosphere; while with a clay face 0·08 to 0·10 per cent. was registered. The largest quantity delivered per man per hour, in the purest condition, was equivalent to about 13,000 cubic feet of air, measured at ordinary atmospheric pressure. Under the worst conditions, only between 1,300 cubic feet and 2,000 cubic feet per man per hour was delivered. Between the 23rd May and the 4th October, while the best ventilation prevailed, thirty-four cases of sickness, or eight per month, were treated by the medical officer; while after the latter date, thirteen cases were treated in 12 days.

If carbonic acid is an essential element in causing compressed-air sickness, it would seem that, taken in conjunction with the other contributing causes, a partial explanation of the ailment is afforded by the assumption of a large absorption of the gas by the human system, and a subsequent effect due to that absorption. As carbonic acid gas is readily absorbed by liquids—in water to the extent of about 66 per cent. by volume at atmospheric pressure—the blood under the compressed air may become highly charged with it: so that on reducing the pressure the expanding gas may discharge into joints and tissues and even into the circulation channels, causing painful inflations or mechanical obstruction to the ordinary flow.

The remedies applied by the medical officer were re-compression followed by slow de-compression, the administration of the drug ergot, and sometimes the application of liniments. In almost every case re-compression in the medical lock afforded relief from pain; and slow de-compression usually seemed an effective remedy.

Every provision for the workers in the compressed air was made by the contractors, Messrs. Perry and Co. Hot coffee was served to them on leaving work; dry working-clothes were provided,

and a changing-room for going to work and leaving under suitable healthy conditions. There were no deaths; and although two men were provided for after the compressed-air work in consequence of serious illness, one of them, finding outside work not paying so well as mining, returned to tunnel-work, and is anxious to work again in compressed air, to which, in fact, his illness was not due.

THE EAST TUNNEL.

As the depth of the surface of the clay at the places where the tunnels enter and leave the ballast had been verified by the first tunnelling, and the nature of the ballast had been learned; and as the adaptation of the shield, the machinery and the general appliances had been tested, and the general conditions ascertained; it was a simpler matter to arrange the commencement of the east tunnel with certainty of results than it had been for the west tunnel. After the shield emerged from the ballast, in the construction of the west tunnel, some months were required for it to complete its journey to Waterloo. Small alterations were then effected in it, before re-erecting for the east tunnel. By cutting away the forward flange of the box-girder, and also the front of the vertical girder, and the front ends of the hood gussets, a few inches more working-room was obtained for the miners; so that the work could be brought altogether under cover of the hood. It had been necessary in the west tunnel to set forward the face-timbers some inches beyond the cutting edge of the shield, whereas the alteration obviated this. Figs. 11, Plate 3, show the mode of working adopted in the east tunnel.

The pattern of iron casting was also slightly altered at the joints, with the object of getting spaces that could be more easily caulked and a better body of material for permanent effectiveness. It has been found that the new joints shown in Figs. 9, Plate 2, and the rings put together with wooden packing-slips, tapered from $\frac{5}{8}$ inch at the back of the iron to $\frac{1}{2}$ inch at the interior of the flange, cut widely clear of the bolts, are the most suitable. The interior face of the packings in place is chiselled out to a depth of $\frac{3}{4}$ inch, and the space can then be securely caulked.

The east tunnel was begun from the temporary shaft at the river-stage on the 17th May, 1901. The air-tight diaphragm-wall, with air-locks, pipes, etc., was erected 100 feet from the shaft; and the use of compressed-air was begun on the 24th June with still about 9 feet of clay cover over the shield. The box heading was continued until the ballast was reached on the 27th June with an

auger-boring from the length in front of the shield. The tunnel touched the ballast on the 6th July, and a full face of ballast was encountered on the 1st August. The air-pressure employed was the exact equivalent of the head of water in the river above the invert at the face; on the 1st August it was 27 lbs. per square inch at high water, and 18 lbs. per square inch at low water.

Many of the miners who began this tunnel had had the experience of the one previously constructed. They had learned that to adhere closely to the details of working as directed by the engineers was the surest method of ensuring rapid progress; and that the warnings against blows were not without necessity. Blows, they found, could occur; and piece-work with steady progress paid best. The consequence of this was that, with more careful attention to the clay-pugging process and to the security of the face and retention of the air, the compressed-air work proceeded regularly, expeditiously, and economically with a full face of ballast, which varied from time to time from very open material to fine close sand, often in layers of the same face. The rate of progress was more than 5 lineal feet per working-day of three 8-hour shifts; and the weekly progress has reached 36 feet.

The success of this work has shown incontestably that the method of tunnelling employed, with the use of the clay pocket and the hooded shield, as devised by Mr. Dalrymple-Hay, is admirably adapted to the Thames water-bearing ballast.

The east tunnel again encountered the London clay at the invert on the 26th September; and the shield completed its work through the ballast on the 2nd October, 1901, when a full face of London clay was again obtained. The amount of compressed-air driven into this tunnel has been on the average 100,000 cubic feet per hour, measured at atmospheric pressure, during the full face of ballast.

The Engineers were Sir Benjamin Baker, K.C.M.G., Past-President Inst. C.E., and Messrs. Galbraith and Church, MM. Inst. C.E. Mr. H. H. Dalrymple-Hay, M. Inst. C.E., was Chief Assistant to Messrs. Galbraith and Church. Mr. C. A. Rowell, as Contractors' agent for Messrs. Perry & Co., carried the work through. The Author was Resident Engineer.

The Paper is accompanied by sixteen drawings, from which Plates 2 and 3 have been prepared.

APPENDIX.

PARTICULARS OF MACHINERY.

Boilers—

Two 100-N.HP. marine (Laird).

Three 40-N.HP. locomotive type (Davey, Paxman & Co., and Nicholson & Co.).

One 80-N.HP. semi-marine (Davey, Paxman & Co.).

Air-Compressors—

Three double-acting, for 60 revolutions at 100 lbs. steam-pressure.

Steam-cylinders 18 inches in diameter $\times$ 30 inches stroke.

Air-cylinders 26 inches in diameter $\times$ 30 inches stroke.

Water-jacketed. (Markham & Co., Chesterfield.)

One portable, for grouting-pans (Slee & Co., Earlestown).

Dynamos—

Two (Thomas Parker), worked by Belliss engines on the same frame:—
600 revolutions, 130 amperes at 210 volts; 27 kilowatts; for locomotive traction.

Two similar to above but giving 62 amperes; 13 kilowatts; for electric light.