

Street and Waterloo tunnels will next be described, representing as they do, one of the most recent of the London Tube railways driven through water-bearing strata.

BAKER STREET AND WATERLOO RAILWAY.—This railway is about $3\frac{1}{8}$ miles long, consisting of two tubes, lined with cast iron, 12 feet internal diameter. With the exception of the river section, the whole length driven was through London clay.

The first operation in connection with the river section was to construct a stage, from which cast iron cylinders, 16 feet internal diameter, and 50 feet deep were sunk, and brick chambers were constructed below. From these shafts the tunnels were driven under the river by means of shields, work being commenced on the first of these, the west tunnel, in February, 1899. Under the river was a bed of water charged, open ballast, containing but little sand. The shield was of the "hooded" pattern, 13 feet outside diameter, 9 feet $8\frac{1}{2}$ inches long, formed of $\frac{1}{2}$ inch plates, stiffened with a circular box girder. The cutting edge consisted of four $\frac{1}{2}$ inch steel plates. To the circular girder was attached a diaphragm plate, and the base of the box, as referred to below. The lower part of the front of the shield was cut away, thus leaving a hood 2 feet $2\frac{1}{2}$ inches long at top, with an open invert. For operating there were fourteen rams, 6 inches diameter, 20 inches stroke; six of these were sufficient for driving the shield, with a usual average pressure of 1,300 lb. per square inch. It will be readily understood that work in this open strata, under a head of 70 feet of water at high tide, was difficult owing to the escape of compressed air, and dangerous owing to the risk of collapse of the face. As originally designed, there were to be a number of sliding shutters for holding up the ballast at the face, as had been done previously in the Hudson River and Blackwall shields, but these were subsequently abandoned for a system of timbering supported by $5\frac{1}{2}$ inches steel tube raking struts, which worked through leather sleeves and could be tightened by screws at the rear end. This arrangement made it possible to support the timbering and at the same time take advantage of the shield as a protection at the face. A feature of this shield is the use of a safety appliance in the form of a fountain trap formed by a box, of which the back plate extended above the centre of the shield, while the front plate reached $6\frac{1}{2}$ inches downward below the top of the back plate. This contrivance, which was first used in the Vyrnwy Aqueduct Tunnel under the Mersey, proved efficacious on several occasions in allowing men to escape through a manhole in the top of the box in the case of "blows" at the face. The pressure of the air on the horizontal surface of the water in the trap being superior to the hydraulic pressure beyond the diaphragm, flow ceased as soon as the trap was sealed.

When the shield was working in ballast over the whole face, hand holes were opened, in advance of the cutting edge, reaching continuously round the circumference of the shield, and slightly beyond it all round. These hand holes or pockets were filled with soft clay for a distance in front of the shield of slightly more than the length of the cast iron lining segments, and in consequence, when the shield was forced forward, the clay formed a seal for the compressed air at its tail, or adjoining the last ring of the lining. The whole of the ballast face was also plastered over with clay.

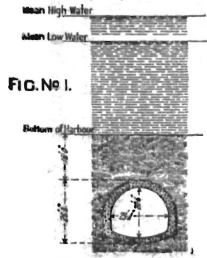
In setting forward, only one plank at a time was removed. This method is similar to that employed in the "Waterloo and City Railway." The length of the cast iron lining was reduced from 20 inches to 18 inches throughout the water-bearing strata, and where the work was straightforward, the rate of progress with a ballast face was three 18 inch rings in 24 hours. The maximum air pressure was 35 lb. per square inch.

The above have been referred to as interesting examples of small tunnels driven with a shield for tube railway purposes.

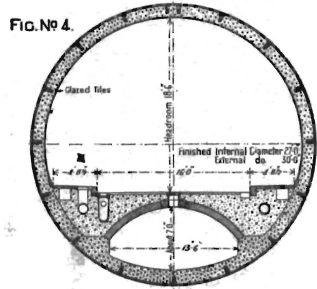
The Waterloo and City Railway Tubes, 12 feet $1\frac{3}{4}$ inches diameter, which also cross under the Thames, were constructed at a date intermediate between the two, but space will not admit of a description of the methods there employed, nor of other British subaqueous tunnels, which include that under the Mersey, 9 feet internal diameter, for the Liverpool Water Supply; the Glasgow Harbour Tunnels, 16 feet diameter, two for vehicular, and one for foot passenger traffic; the Glasgow District Subway, two tunnels 11 feet diameter, for railway purposes; the London Water Supply tunnels, 8 feet 4 inches diameter, under the Thames at Kingston and Chelsea; the Blackwall Tunnel under the Thames, 24 feet 8 inches diameter, for vehicular and foot passenger traffic; the Greenwich Footway Tunnel, 11 feet 9 inches diameter, under the Thames; the Lea River Tunnel, 11 feet 6 inches diameter, for sewerage; nor that under the Dee at Aberdeen, 7 feet 8 inches diameter, also for sewerage. Some particulars of these are given in Appendix 1.

ROTHERHITHE TUNNEL.—The Rotherhithe Tunnel, Plate 2, Fig. 4, under the Thames, is of larger diameter than any shield driven tunnel yet constructed. The external diameter is 30 feet, and the internal diameter inside lining 27 feet, giving a roadway of 16 feet wide, with two footways, each 4 feet $8\frac{1}{2}$ inches wide at kerb level. The subaqueous portion is 1,535 feet long, and there are also considerable lengths of shield driven tunnel on either side, which, with the four shafts, and cut and cover and open approaches, make up a total length of 6,883 feet. The contract cost of the works, including a considerable quantity

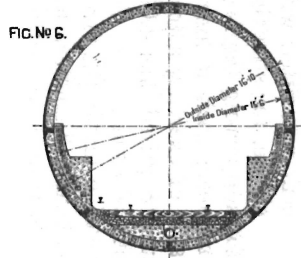
BOSTON HARBOUR TUNNEL



ROTHERHITHE TUNNEL



NEW YORK AND LONG ISLAND R.R. BELMONT TUNNEL



NEW YORK RAPID TRANSIT R.R. UNDER EAST R. BATTERY TUNNEL

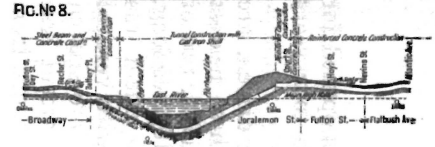
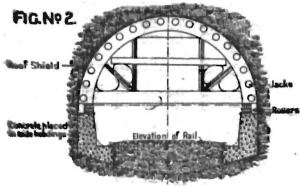
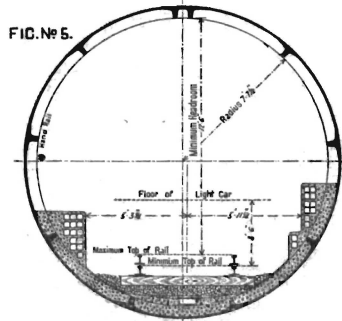


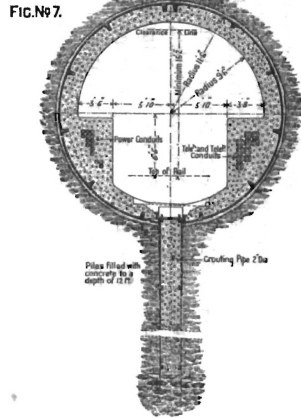
FIG. No 2.



HUDSON AND MANHATTAN R.R.Cs (1908)



PENNSYLVANIA R.R. NORTH RIVER TUNNEL



Reconstruction of Crown and Invert

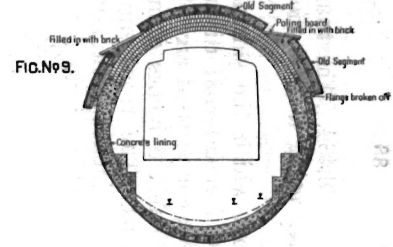
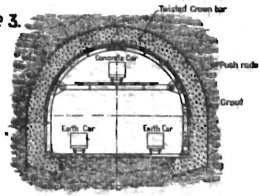
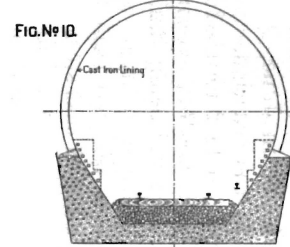


FIG. No 3.



Reconstruction of Invert



of street widenings was £1,088,484. The tunnel was opened for traffic in June, 1908, after being a little more than four years in construction.

The four shafts, from which the shields were driven, are each 60 feet external, 50 feet internal diameter, those nearest the river being sunk under compressed air. The shields, two of which were used, were 30 feet 8 inches diameter, 18 feet long, and weighed each 380 tons. The front end of the shield was built of cast steel segments 3 inches thick, stiffened with vertical and horizontal diaphragms, which divided the face into sixteen compartments for working purposes. Each compartment was constructed with two diaphragms, 3 feet 7 inches apart, one from the roof and one from the floor, which overlapped 4 inches and formed a water seal similar to that described for the Baker Street and Waterloo shield. Each compartment was fitted with two rams 5 inches diameter, 2 feet 6 inches stroke, for strutting the boards, which were at times required for supporting the face.

The main shield rams were 40 in number, each 9 inches diameter, 3 feet 6 inches stroke, and capable of exerting a total pressure of 6,000 tons. The usual pressure required was 4,000 tons, and the minimum pressure used about 600 tons.

In order to test the nature of the formation under the river, a small pilot tunnel, 12 feet 6 inches external diameter, was first driven and lined with cast iron. This tunnel was driven by means of a shield fitted with a Price rotary excavator, which had been used with much success in driving some of the tube tunnels through London clay. This consisted of a framework formed of channel bars, to which were fixed steel knives, rotated by means of a 52 H.P. electric motor enclosed in the shield. The pilot tunnel was successfully driven under an air pressure of from 12 to 21 lb. per square inch, at an average rate of 13 feet 6 inches per day. The material passed through consisted of a bed of limestone rock from 3 feet to 5 feet thick, overlaid by clay and sand, and with a bed of sand and pebbly gravel underneath. When the driving of the pilot tunnel had sufficiently advanced, the main tunnel under the river was commenced. Although there was only a cover of 8 feet over the top of the shield at about midway across the river, the leakage of air was very slight, and it was not found necessary to increase the cover by means of a blanket of clay. A safety bulkhead fitted with air locks was built in the tunnel at 320 feet back from the shield, the portion of the tunnel at the rear of the bulkhead being then left open to the atmosphere. Rapid progress was made, reaching a maximum of 267 feet in one month, and the tunnel was carried through from shaft No. 3 to shaft No. 2 without any extraordinary difficulty. The face stood well, and as a rule needed little support. A length of 2 feet 6 inches, or the length of one ring of lining was usually excavated in

front of the shield over the whole face, with the exception of the edges, which were broken down by the cutting edge. It is satisfactory to note that in taking out the smaller tunnel, which was removed as the larger shield advanced, the grouting which had been put in round the pilot tunnel in the usual way was found to be in excellent condition, and to have filled the voids in the surrounding material.

A small portion of the approach tunnels was partly through ballast. These tunnels were driven on a grade, and between shafts Nos. 3 and 4 round a curve of 800 feet radius.

The cost of the section under the river was £412 per lineal yard, as against £378 at Blackwall, exclusive of the internal lining and roadway in either case.

AMERICAN TUNNELS.—Passing now from Great Britain to the United States we find that in 1869, when Greathead was engaged in driving the Tower Subway, Beach in America was working upon similar lines in connection with the shield which bears his name, and was first used for a pneumatic subway, 8 feet diameter, driven under Broadway, New York, through loose sandy soil, and lined with brickwork in cement.

Since that date, the shield has been used in several important subaqueous tunnels in the United States.

THE FIRST HUDSON RIVER TUNNEL.—This tunnel connects Morton Street, New York, with 15th Street, New Jersey. It was initiated in order to connect the City of New York with the great railways from Washington and the south, which then terminated in Jersey City. The work was commenced in 1879, and is of special interest as being the first large work of this character in which compressed air was used, and also of the long time, 26 years, occupied in the construction. A shield was not used at first, the system adopted being to build out successive incomplete rings of wrought iron plates in advance of the brickwork with which the tunnel was lined. This system ended in disaster, as a large escape of compressed air occurred, and the roof being deprived of the support of the air, collapsed and twenty workmen were drowned, in July, 1880. Work was shortly after resumed under a new method known as Andersen's Pilot Tunnel system, whereby a small central iron tunnel, 6 feet diameter, was driven under compressed air in advance of the iron rings which formed the temporary lining of the full-sized tunnel. After considerable difficulty a distance of 1,540 feet had been driven from the New Jersey end, and 74 feet from the New York end of the northern tunnel; and 600 feet from the New Jersey end of the southern tunnel in 1882 when the Company which was prosecuting the work suspended operations. The mortality up to that date under the compressed air had been

excessive, being at the rate of 25 per cent. of the men employed. After the failure of the Company, work was abandoned until 1889, when it was resumed under English management.

For some time the Pilot Tube system was continued, but after 500 feet additional had been driven in the northern tunnel from the New Jersey end, it was decided to employ a shield and to line the tunnels with cast iron instead of masonry. The shield used was 19 feet 11 inches external diameter, or 5 inches greater than the external diameter of the cast iron lining. Work was carried on for some time, but after a length of 3,895 feet had been driven in the northern tunnel towards New York, operations were again stopped for about ten years, or until 1902, when tenders were invited for the completion of the tunnels. Operations were shortly after resumed by the New York and New Jersey Railroad Co., and carried to a successful completion.

The north tunnel, which is 18 feet 11¼ inches clear inside diameter, was completed in March, 1904, by means of a shield fitted with a movable hood, and driven by sixteen 8-inch rams. The south tunnel, which is 15 feet 3 inches inside diameter, 5,700 feet long between shafts, was completed in September, 1905. About 600 feet of the tunnel was driven through rock, which projected 4 feet to 5 feet into the tunnel section, and was removed with light charges of dynamite. The maximum depth is 102 feet below water, and the cover over the tunnel varies from 5 feet to 65 feet. Through the greater part of its length the shield was forced through the silt without requiring any excavation in front, under an air pressure of 30 lb. per square inch. Owing to the complete arrangements made for dealing with workmen coming out of the air pressure, no lives were lost, a very different state of affairs to that existing on the same work twenty years before.

THE ST. CLAIR RIVER TUNNEL, 1888.—This tunnel, which was one of the first modern subaqueous tunnels constructed with a shield, is of larger internal dimensions than any other shield driven tunnel, with the exception of the first Thames tunnel, the Blackwall and Rotherhithe tunnels, and the Boston Harbour tunnel described below.

The St. Clair River forms portion of the boundary between the United States and Canada, and extends between Lake Huron and Lake St. Clair. The tunnel, which is for railway purposes, was constructed by means of a shield and compressed air for a length of 6,000 feet, of which 2,300 feet is under the river. The cast iron lining is 21 feet external and 19 feet 10 inches internal diameter. The material was very soft clay, with pockets of gravel and sand, overlaid by sand, and extending to a bed of rock about 13 feet below the bottom of the tunnel. The two shields used were each 21 feet 6 inches external diameter,

and 15 feet 3 inches long, designed somewhat on the lines of the Beach shield. Work was commenced from either end, and bulk heads with airlocks were erected in the tunnel so soon as the shields reached the edges of the river, when compressed air was used up to a maximum of 35 lb. per square inch. On either side of the river the tunnel, for a total length of 3,710 feet was driven without compressed air.

The shell of the shields consisted of 1 inch plates. The main bulkhead was placed at 4 feet from the rear end, and was formed of $\frac{1}{2}$ inch plates, stiffened with girders, and having two openings each 6 feet x 4 feet 6 inches in the lower part, provided with sliding doors, which, however, were not required. About 4 feet in front of the bulkhead were the working platforms, which were connected to the bulkhead by straps, with a space between the platforms and the bulkhead, in which the excavated material was thrown down. A segment erector was provided in the rear end of the shield. The material passed through was in part of such a soft nature that it flowed through the bulkhead doors as the shield advanced. In other portions the clay was so stiff that it was excavated in front of the shield, but generally speaking, the shield followed close upon the excavation. There were 24 rams, each capable of exerting a pressure of 45 tons. The ground was always tested ahead of the shield for a distance of 8 feet to 10 feet by boring, and no great difficulties were experienced in completing the work, which progressed at the rate of 250 feet per month.

BOSTON HARBOUR TUNNEL.—This tunnel, which was constructed to give a railway connection between Boston and East Boston, crosses under the harbour obliquely, with a length of 2,400 feet, and an additional length of 1,100 feet under the docks on either side, or 3,500 feet of subaqueous tunnel in all. The tunnel (Plate 2, Fig. 1) is not circular in cross section, but is 23 feet 4 inches wide at springing, with a circular roof and invert, the maximum height being 20 feet 6 inches. Iron lining was not used. The tunnel is lined throughout with concrete, and is the most important structure constructed of this type by means of a shield. The material passed through was heavy clay, with some boulders, and in parts a sandy clay permeable by water. Compressed air was used to give additional security, though it is possible that the tunnel could have been driven without. The maximum pressure used was 25 lb. per square inch.

The maximum depth to the bottom of the tunnel was 90 feet below H.W.M., with a range of tide of 10 feet, and a minimum cover below the harbour bed of 18 feet above the top of the tunnel.

The shield used was of the "roof" pattern, somewhat on the lines of the shields used in underground work in Paris,

13 feet long on the top, tapering at the front face so that the bottom length was 12 feet. The shell was formed of plates supported upon two semi-circular box girders 4 feet 6 inches apart, connected by horizontal transverse girders at their bottom edges, and securely braced together. These girders were supported upon rolled girders 6 feet 6 inches long, which travelled upon nests of 8-inch. rollers, which moved on plates fixed on the concrete side walls (Fig. 2), which were constructed by means of timbered headings 8 feet square, driven about 100 feet in advance of the shield. For moving the shield there were sixteen hydraulic rams. The usual total pressure required was from 20 to 30 tons. In order to prevent undue pressure being brought upon the green concrete, an ingenious method was adopted, whereby the ram pistons took a bearing on sixteen lines of cast iron bars $3\frac{1}{4}$ inches diameter (Fig. 3), which were built into the concrete.

The shield was advanced in 2 feet 6 inches lengths, and the concrete was erected on steel framing, grout, which consisted of sand and cement, being forced through vertical pipes built into the concrete. The rear frame of the shield was cut away at the top to admit of keying the arch. The dumpling between the headings was excavated under the shield, and the invert was put in subsequently. Work was carried out satisfactorily at the rate of about 33 feet per week.

THE NEW YORK AND BROOKLYN TUNNEL FOR THE RAPID TRANSIT RAILROAD (BATTERY TUNNEL).—Among the most interesting of shield driven tunnels are those constructed 1903-7 under the East River, for the Rapid Transit Railroad, between Battery Park, New York, and Joralemon Street, Brooklyn. The tubes are each 15 feet 6 inches clear inside diameter, about 25 feet apart between centres, and about 6,550 feet long, of which about 4,200 feet is under the river. The maximum depth of water is about 50 feet, and the greatest depth from mean high water to the base of rails, about 94 feet. The cover over the top of the tubes varied from 9 feet to 50 feet. The shields used were 16 feet $11\frac{1}{4}$ inches diameter, 9 feet 5 inches long, and were fitted with a removable hood 3 feet 6 inches long, which projected in front of the face, and afforded protection for the miners working underneath. The working platform at the centre of each shield was also provided with a movable extension which could be pushed forward and supported on shores. The shields were equipped each with fourteen 8-inch. rams, 30-inch. stroke, and with the usual hydraulic segment erection and grouting apparatus. The spoil was removed in cars drawn by steel cables.

At the New York side of the river the tubes are through rock, after which they traverse about 600 feet of very fine sand and silt, and then meet a rock bar which is about 400 feet through; then through about 200 feet of hard stratum and 600 feet of fine sand and silt, to connect with the land section on the Brooklyn side, which is in clay and gravel.

The weight of each cast iron tube is about 8,000 lb. per lineal foot, or about 11,000 lb., including the concrete lining and track, while the live load amounts to 2,000 lb. per lineal foot. The air pressure used during construction varied from 20 to 35 lb. per square inch. So soon as this air pressure was released, the tubes commenced to settle along the sections on either side of the rock bar, where samples taken of the formation shewed, when placed in water as very fine sand, though when dry they had the appearance of putty-like mud. After the completion of the tubes, the settlement was found to be 28 inches maximum in the north tube, and 23 inches maximum in the south tube, while over portion of the north tube the bottom was above the true grade line for over 500 feet, the maximum variation amounting to 17 inches. In addition to the errors in grade, flattening occurred in portions of both cast iron tubes, amounting to a maximum of 10 inches in the north, and 7 inches in the south tube.

Where the departure from grade and section was sufficient to interfere with the passage of trains or to endanger the stability of the structure, extensive alterations were carried out, involving the reconstruction of about 210 feet of the roof and 2,676 feet of the invert.

The alteration of the invert was carried out by breaking out the cast iron segments and rebuilding, as shewn in Fig. 10. In altering the roof the segments were disconnected and forced upwards 2 or 3 by powerful hydraulic jacks into the sand above the tunnel (Fig. 9), the sand being allowed to run into the tunnel through holes cut in the plates. The jacks were removed and the segments shored up, after which the permanent brickwork and concrete was put in by the use of poling boards. The final section of the tunnels as amended is egg shaped in parts, instead of round.

In addition to the rectifications for grade, extensive alterations were carried out in the invert, where sections of tunnel have been underpinned. This was done to prevent risk of further settlement under vibration from the trains. The method adopted was to put in a series of reinforced concrete piles 20 inches diameter, and 7 feet apart, transversely between centres. The piles are spaced at irregular intervals of about 50 feet longitudinally, and are carried to rock or hardpan, at an average depth of 30 feet in the New York side of the rock

bar, and to a maximum depth of 50 feet on the Brooklyn side. The length of tunnel thus supported is about 600 feet on either side of the rock bar.

The method used for sinking the piles was to break out a section of the bottom of the tube and to excavate a horizontal transverse trench to about 18 inches below the middle of the invert, and extending for the full width of the tube. In this trench were placed two cylinders of thin steel, 20 inches diameter and about 6 feet long, on the centre line of the piles. In each of these cylinders was placed a 4 inch pipe on the centre, with four 1 inch square reinforcement rods, whose lower ends projected below the tube and were drawn in to form a pilot.

The cylinder was filled with concrete, and after allowing time for this to set, water was forced through the 4-inch tube, thus scouring out the sand underneath, when the piles sank either under their own weight, or with the assistance of a 30 ton jack. When the top of the first section reached to the bottom of the trench another section was built on to this, and the piles were sunk by this method until a hard stratum was reached.

The difficult work in connection with these alterations was successfully carried out under compressed air in 1906 and 1907.

THE NEW YORK AND LONG ISLAND RAILROAD TUNNEL—BELMONT TUNNEL.—These tunnels, Figure 6, were commenced in 1904, and completed in 1907. They extend from Long Island City to the Grand Central Depot, New York, passing under the East River and under 42nd Street, New York. The subaqueous portion is 3,173 feet long, and consists of two cast iron lined tunnels, each 15 feet 6 inches diameter inside the lining, 28 feet apart centres. The maximum depth of water is about 60 feet, and the maximum distance from mean high water to the base of rail in tunnels is 102 feet, while the minimum cover over the roof is about 23 feet. The material under the river bottom is rock and hardpan, overlaid by sand to a depth of from 5 feet to 30 feet. A considerable portion of the excavation was under atmospheric pressure in rock, the balance was carried out by shields of the type used in the Battery Tunnels.

For portion of the length in soft material the shields were driven forward without excavating, but the material soon compacted and necessitated the opening of the doors in the shields. The current in the river is about 5 miles per hour maximum. It was found that, if the shields were stopped for any length of time, holes were scoured out in the river bed by the compressed air escaping, and in some cases the shields were actually