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THE RAILWAY TUNNELS OF NEW YORK CITY.¹

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WHEN I accepted the invitation to address the Institute on the subject of the "Railway Tunnels of New York City," the full scope which might be contemplated did not occur to me. My first thought was rather of the high honor recently conferred on me by the Institute which made its invitation a command to be obeyed unhesitatingly.

By the term "tunnel" we usually refer to an underground passage formed by excavating a heading and enlarging this to the full section required; but a tunnel can be formed in other ways, as, for example, the tunnel under Detroit River, formed of sections built in part at a distance, towed to the site, sunk in a prepared trench, and then completed with floating plant and working force. The term may therefore be considered as referring to the completed structure rather than to the method for constructing it; and the view may be held that the subject assigned to me refers not merely to tunnels under the waterways around

¹ Presented at the stated meeting of the Institute held Wednesday, November 20, 1912.

[Dr. Noble received the Institute's Elliott Cresson Medal May 15, 1912, in recognition of his distinguished achievements in the field of civil engineering.—Ed.]

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Manhattan Island, but to all the sub-surface structures used for railway purposes within the limits of the city. Accepting this view for our present purpose, it is proposed to give in this paper a brief outline of the several railway tunnel and subway systems in New York City and to follow this with more particular reference to the construction of tunnels under the rivers enclosing the island of Manhattan.

To avoid confusion in referring to the several districts of Greater New York, the one formerly embraced within the older city of New York will be referred to as the island or borough of Manhattan, or simply as Manhattan; the former city of Brooklyn as the borough of Brooklyn, or Brooklyn; the north-westerly portion of Long Island, lying along East River north of Newtown Creek and extending eastward some distance along Long Island Sound, as the borough of Queens, or Queens, and the portion of Westchester County lying east of Harlem River and extending eastward for some distance along Long Island Sound, as the borough of The Bronx, or The Bronx.

OUTLINES OF EXISTING TUNNEL SYSTEMS.

New York Central & Hudson River Railroad Tunnel.

This is located under Park Avenue in New York City, and was built in 1872-5. It is the oldest railroad tunnel now in use in the city. It contains four tracks and extends from Fifty-sixth Street to Ninety-sixth Street, a total distance of two miles. A short section, 550 feet long, was built by ordinary tunnelling methods, the remainder in open cutting. It was a notable work when built.

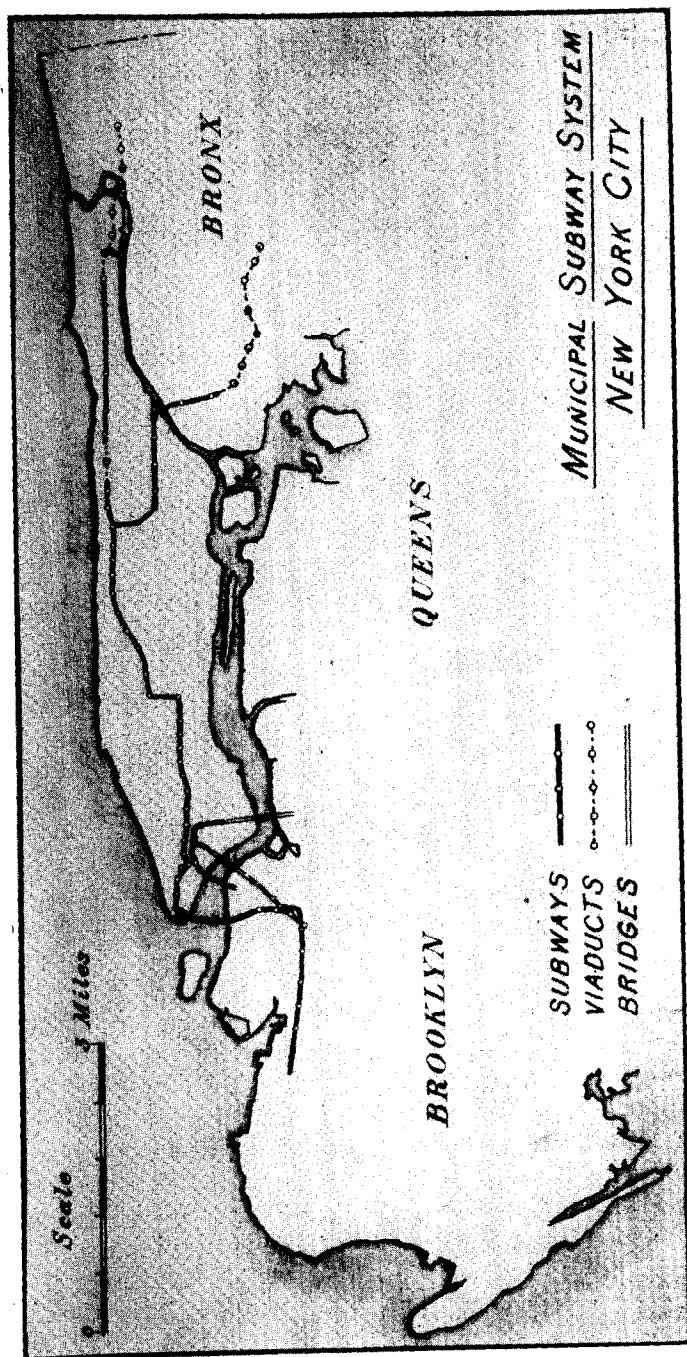
Long Island Railroad Tunnel in Brooklyn.

The so-called Atlantic Avenue Improvement of the Long Island Railroad, consisting in part of tunnel built in open-cutting and partly of elevated railroad, was carried out in 1904-8. The tunnel structure is about $2\frac{1}{4}$ miles long and provides for two tracks.

New York City Subway Tunnels.

The rapid transit subway system now in use, or nearly ready for use, is indicated in Plate I. The portions in Manhattan and Brooklyn consist almost entirely of tunnels, the total length of

PLATE 1.



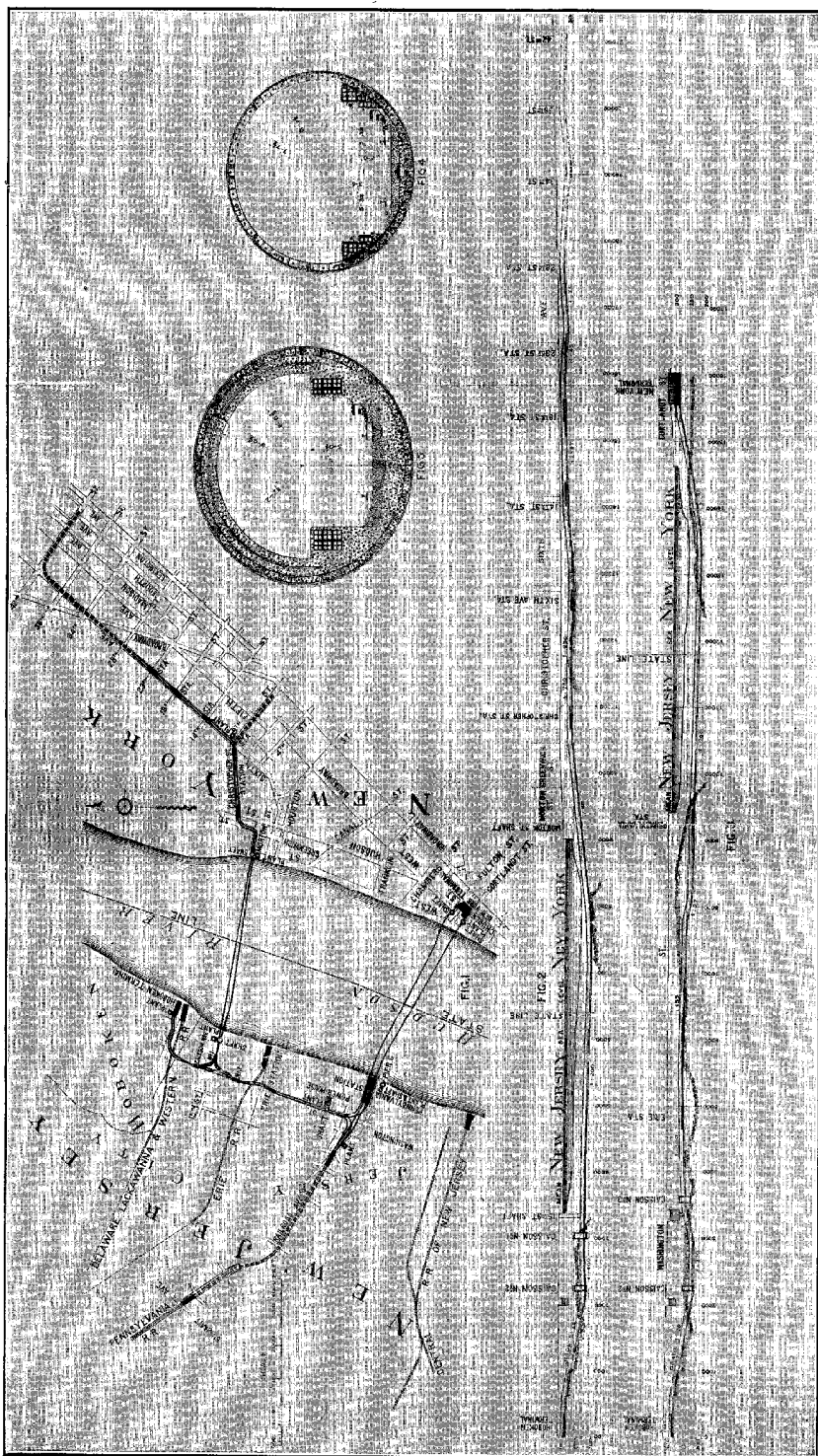
tunnel structures being 24.7 miles; of this length about 5.1 miles have been built by tunnelling methods, the remainder in trenches excavated from the surface of the ground, usually called open-cut. The interference with business along the streets was serious, and gave rise to much criticism of the method. These trenches were of sufficient width to accommodate two or more tracks, a large proportion containing four. In the Brooklyn and Center Street sections recently built these multiple track structures are

PLATE 2.



New York City Subway. Excavation under cover.

generally subdivided by longitudinal partitions forming two to eight single-track tunnels side by side in one excavation. The total track mileage of tunnels is 78 miles. In recent work in Manhattan the so-called open-cutting has really consisted of excavation and construction under cover, the only open-cutting consisting of the removal of the pavement and sufficient underlying earth to permit laying a planked roadway under which the work is continued. The open-cutting is done at night, so that the interference with street traffic is negligible. (Plate 2.) Openings along the sidewalk or in cross streets at intervals of a few



blocks are provided through which excavated materials are hoisted and materials for constructing the tunnels are lowered. The work is much more costly than if carried on in the open. Present convenience of the public is secured at the expense of greater capital cost and greater fixed charges, which the public must carry for a long, indefinite period.

It will be noted by reference to the map of existing subway lines (Plate 1) that there are river crossings at three localities, two of which, one from the lower end of Manhattan Island to Brooklyn under the East River, the other between the island and the borough of The Bronx near 145th Street, are by means of tunnels; while the third, from the upper end of Manhattan Island to the mainland, is by means of a three-track bridge.

Hudson & Manhattan Railroad System.

The tunnel system of the Hudson & Manhattan Railroad Company—commonly called the McAdoo tunnels in honor of the public-spirited man who pushed the project to completion—is shown in Plate 3. It embraces four tunnels under North River, with various extensions on both sides. The so-called uptown tunnels, two in number, pass eastward from Jersey City from a point near Fifteenth Street, about midway between the terminals of the Erie and the Delaware, Lackawanna & Western Railroads, and reach the Manhattan side at the foot of Morton Street, passing under Morton, Greenwich, and Christopher Streets and Sixth Avenue to the present terminal at Thirty-third Street. The two downtown tunnels start from the Manhattan terminal at Church Street, between Fulton and Cortlandt Streets, one tunnel passing under Fulton Street to the river, the other under Cortlandt Street; at the Church Street terminal they are connected by loops where the passenger platforms are placed; continuing westward under the river they pass under the Jersey City station of the Pennsylvania Railroad, with connections for passengers by means of elevators, and emerge into open air about 6800 feet farther westward. The uptown and downtown tunnels are connected on the New Jersey side by two tunnels running parallel with the river and extended northwards to the Delaware, Lackawanna & Western terminal. By means of these several connections passengers are carried quickly and directly

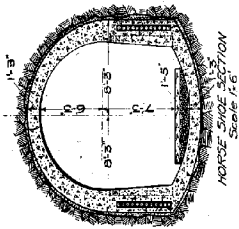
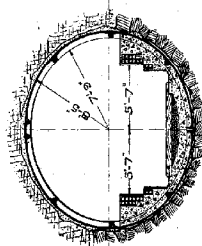
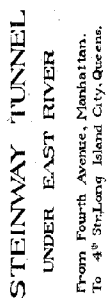
from either Manhattan terminal of the McAdoo tunnels to any of the three railroad terminals—the Pennsylvania, Erie, or Delaware, Lackawanna & Western—or by a somewhat circuitous route with two under-river crossings, from one Manhattan terminal to the other—that is, from Sixth Avenue and Thirty-third Street to Church and Cortlandt Streets. Profiles of the system are shown in Plate 3.

In the construction of this system a novel feature was introduced by sinking reinforced concrete caissons containing short sections of tunnels at several of the junction points.

In the McAdoo system there are about 7.6 miles of shield-driven tunnels. In addition to this mileage, a structure containing, by longitudinal subdivision, two single-track tunnels has been built in open-cutting under Sixth Avenue from Twelfth to Thirty-third Street, making a total of 9.6 miles of single-track tunnel now in operation.

Steinway or Belmont Tunnels.

Both the city subways and the McAdoo tunnels were designed for rolling stock of somewhat smaller dimensions than the standard railroad car. These systems provided means for quick transit between Manhattan Island and New Jersey and between Manhattan and the neighboring boroughs of Brooklyn and The Bronx, but left the rapidly-developing borough of Queens unprovided for. To meet this deficiency, Mr. August Belmont and his associates undertook, in 1905, the construction of two single-track tunnels for street car traffic from Park Avenue, Manhattan, eastward under Forty-second Street to East River, thence under the river to Long Island City, reaching the surface about 3000 feet inland. (See Plate 4 for map and profile.) This was undertaken under an old franchise granted in 1891 to Dr. Steinway. Unfortunately, unforeseen difficulties in their construction made it impossible to complete the tunnels within the term of the franchise, which expired January 1, 1907. They were completed in the summer of that year, but they have not been put in use because of dispute between the owners and the city, although urgently needed by the public. It is understood that an agreement has been reached under which these tunnels may be used.



This is a detailed map of the New York City area, showing the Hudson River, the East River, and the surrounding boroughs and islands. The map includes labels for New York City, the Borough of Manhattan, the Borough of Queens, the Borough of Brooklyn, and Staten Island. It also shows the New York Harbor, the Narrows, and the Lower Bay. The map is oriented with North at the top. A scale bar at the bottom indicates a distance of 4 miles. The map is dated November 1905.

STATEN
ISLAND

Scale 1 in. = 4 miles.
NOV. 1909

Pennsylvania Railroad Terminal.

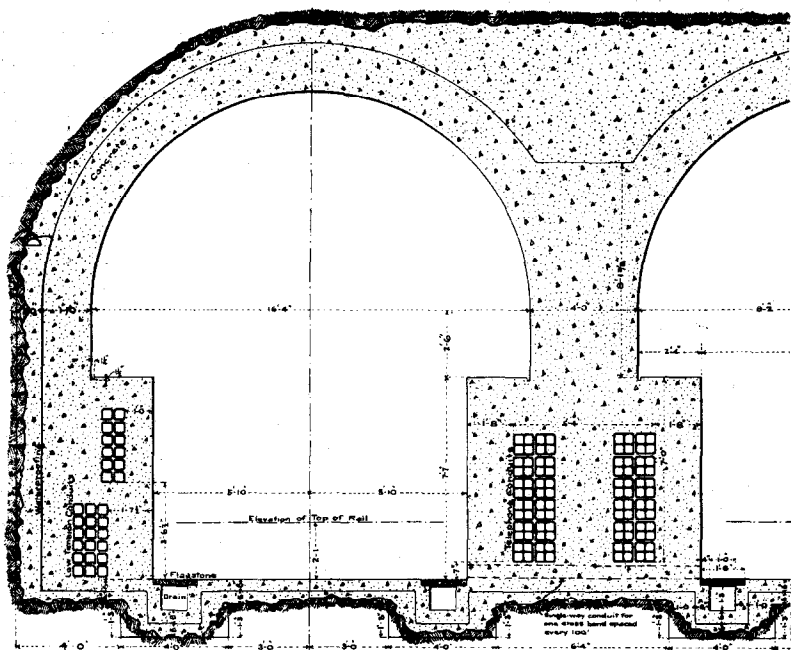
The project for a terminal on Manhattan Island was decided upon in the latter part of 1901, and surveys and preparations of plans were taken up at once. Construction was begun in 1903, and in 1910 the works were completed and put in use. The general features of the project may be outlined as follows:

Diverging from the former main line of the Pennsylvania Railroad at Harrison (Plate 5), about one-half mile east of Newark, a double-track railroad crosses the Hackensack Meadows on an embankment extending in a northeast direction, passing over other railroads, to the west face of the trap ridge known as Bergen Hill, which parallels the Hudson for several miles. The point where the line reaches Bergen Hill is nearly on the line of Thirty-second Street in New York City. Entering Hackensack portal, the two tracks pass under this hill in two single-track tunnels with a descending grade toward the river. A typical section and view of the completed tunnel are shown in Plate 6. The Bergen Hill section is about 6000 feet long. On the east face of the hill and about 1000 feet from the river is a large, open shaft across which the lines pass and enter the tunnels leading to and under the river to a point opposite a shaft near Eleventh Avenue in Manhattan, about 1300 feet east of the river bulkhead on the Manhattan side. The distance between the two shafts is about 6600 feet, about 4000 feet being under the water of the Hudson River. The maximum depth of the bottom of the tunnel below mean high tide is 96.9 feet. Except for a short distance from each shaft, the tunnels in this section are so-called tube tunnels and were built with the aid of shields. Eastward from Eleventh Avenue shaft the construction is twin-tunnel, so-called, this term being applied to the case where two tunnels are formed with concrete in a single excavation. This construction ends at the east side of Tenth Avenue, where the tracks enter the area of the station. From the river bulkhead to Tenth Avenue the tunnels are directly under Thirty-second Street. The station area extends eastward to Seventh Avenue, a distance of about one-half mile; eastward from Seventh Avenue the 21 station tracks converge into two three-track tunnels, one under Thirty-second Street, the other under Thirty-third Street. A typical cross-section and a view in the

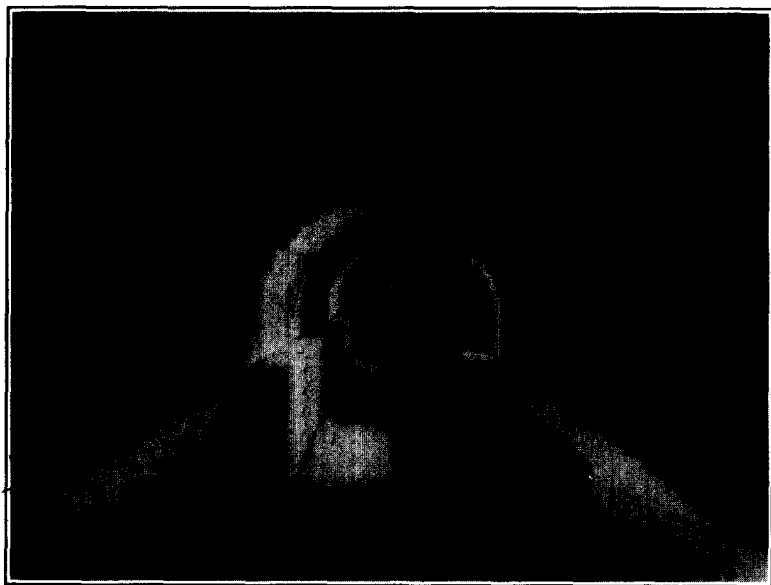
completed tunnel are given on Plate 7. Near Sixth Avenue the construction under each street changes to twin-tunnel, as shown on the plate, the four single-track tunnels thus formed continuing to Second Avenue, where they curve to the left and pass diagonally under the built-up blocks, the distance between tracks of each pair diverging somewhat, so that the twin-tunnel construction ends and each tunnel passes into a separate excavation before arriving at the shafts near First Avenue. A typical cross-section of the twin tunnel and a view in the completed tunnel are given on Plate 8. At the First Avenue shafts the type of construction again changes to tube-tunnel, which continue under East River and about 2000 feet beyond, from which locality the tunnels were built in open-cutting to portals in Long Island City. The greatest depth of the bottom of the river tunnels below mean high tide is 91.3 feet. Eastward from the portals the tracks enter a large storage and car-cleaning yard. It will be noted that there are only two tunnels under the North River, while there are four under East River. The Thirty-second Street tunnels are for the use of the Pennsylvania Railroad trains arriving from the West; after discharging the passengers at the central station they continue eastward by the southerly tunnel to the yard in Long Island City, where the cars are cleaned and trains made up for the trip westward, proceeding to the station by the northerly Thirty-second Street tunnel. The two tunnels under Thirty-third Street are for the service of the Long Island Railroad.

The tunnels under Thirty-second and Thirty-third Streets pass under the existing subway line at Fourth Avenue with a clearance of some 36 feet, and the tracks in these tunnels are from 50 to 85 feet below street surface.

The tunnel system of the New York Terminal of the Pennsylvania Railroad, just outlined, comprises about 0.2 mile of three-track tunnels and 14.6 miles of single-track tunnels. Of the latter, 5.5 miles were shield-driven; 4.0 miles were driven by ordinary tunnelling methods as single-track tunnels; 3.6 miles by like methods for twin-tunnel construction; and 1.5 miles were built in open-cutting. All of these tunnels, except for a short distance near the westerly face of Bergen Hill, are below sea level, and this is also true as to the tracks in the station, the latter condition resulting from a franchise requirement that all

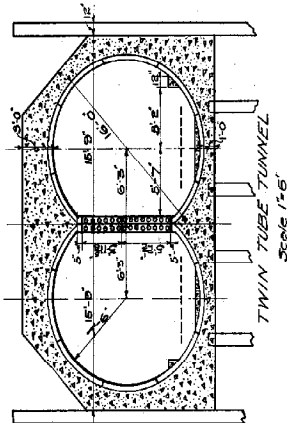
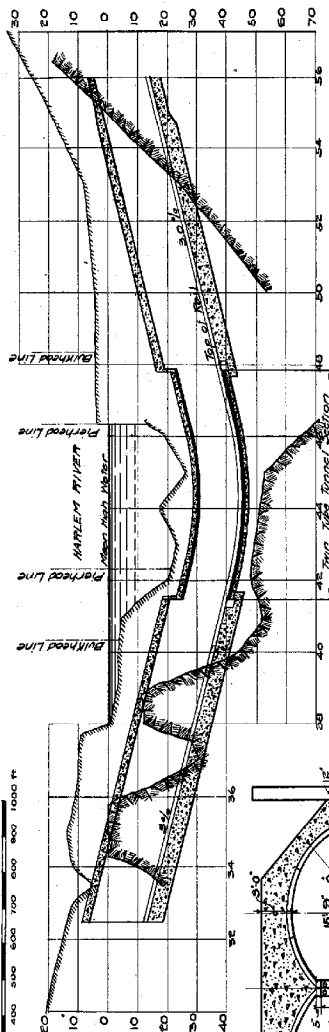
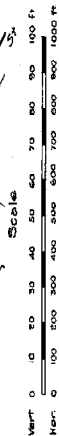
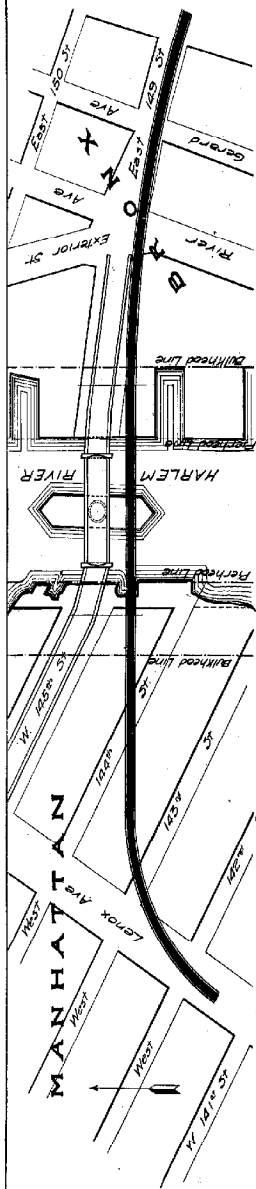


Cross-section, twin tunnel



View in twin tunnel.

PLATE 9.



NEW YORK CITY SUBWAY **HARLEM RIVER TUNNEL** Lenox Avenue, Manhattan East 149th Street, The Bronx.

parts of the structure under avenues must be at least 19 feet below the street surface, in order to permit the construction of subway railroads above them.

The several systems mentioned in the foregoing include six tunnels under Hudson River, eight under East River, and one under Harlem River. The tunnels under Hudson or North and East Rivers are single-track structures and were built in greater part by the shield method and by use of compressed air. The tunnel under the Harlem River is a twin-tunnel, for two tracks, the division wall being of cast iron.

CONSTRUCTION OF RIVER TUNNELS.

It may be said in a general way that three methods have been used in building the river tunnels: the first, in point of time (if we omit the earliest attempt of Haskin, which will be referred to further on), was the pilot-tube method, which was in use for a short time in a tunnel under the Hudson, the work being finally completed by the second, or shield, method, which has been adopted in all recent work in water-bearing materials under the rivers around Manhattan, except at the Harlem River tunnel, where the third method, devised and patented by the contractor, D. D. McBean, was used with success. Although this was one of the most recent works to be executed, it seems preferable to give a brief description of it in this place before dealing with the shield method by which the other fourteen tunnels were carried out.

The City Subway Tunnel Under Harlem River.

This tunnel connects the boroughs of Manhattan and The Bronx near 145th Street, Manhattan. A map, profile and cross-section are shown in Plate 9. The portion built by the method about to be outlined was 641 feet long. The depth of water required over the tunnel for navigation purposes was only 26 feet, which corresponded closely with the actual depth of water in mid-channel.

The contractor was permitted by the War Department to close one-half of the channel at a time. The Manhattan section was first taken in hand; three stages of the construction are shown in Figs. 1, 2 and 3 of Plate 10. The first step was to dredge a channel nearly to the full depth required for the con-

PLATE 10.

FIG. 1.

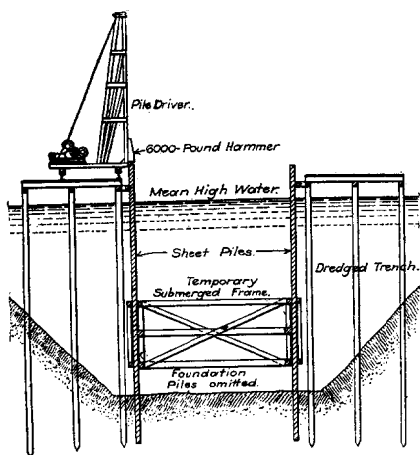


FIG. 2.

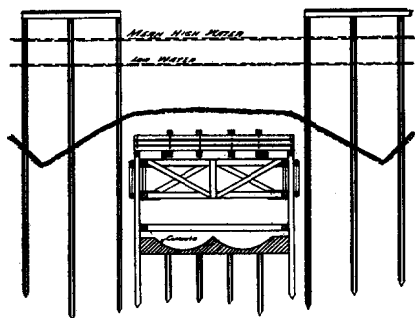


FIG. 3.

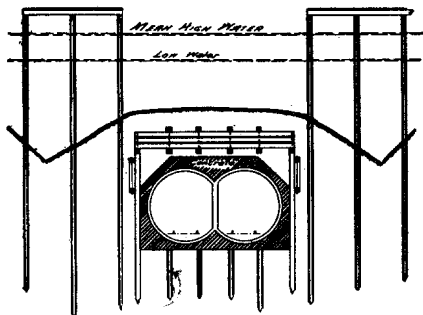


FIG. 4.

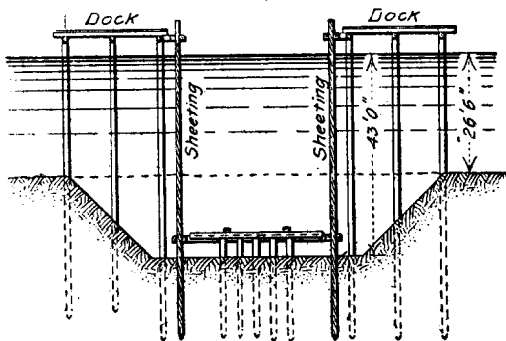


FIG. 5.

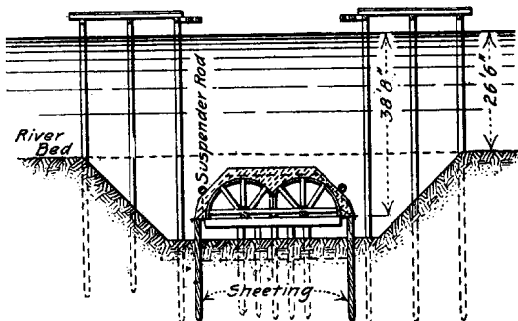
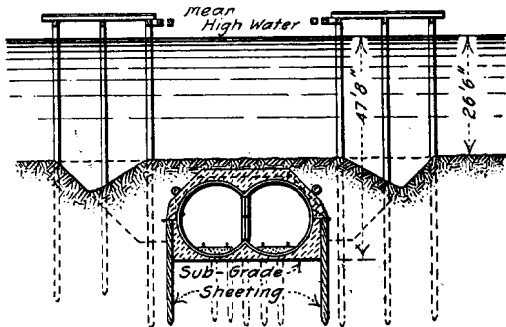


FIG. 6.



struction of the tunnel; a staging or wharf on piles was then built along each side of the trench; foundation piles, spaced 6 feet 4 inches by 8 feet, were placed in the central portion of the trench and sawed off to an exact height. A strong frame, carrying guides for sheet piling, was then lowered on the piles and placed accurately. Walings attached to the wharf near the level of the deck also guided the sheet piling. The sheet piling was tongued and grooved and unusually heavy, and, being thoroughly guided while driving, was placed with great accuracy. The top of each row of sheet piling was sawed off accurately at a height slightly above that required for the finished tunnel, and a strong timber platform carrying shafts to admit men underneath was lowered on the top of the sheet piling and loaded with earth sufficiently to hold it down; the chamber underneath the platform was then completed by driving sheet piling across each end; compressed air was then put on, the water withdrawn from the chamber, and the excavation completed, the cast-iron lining built, and the enveloping concrete placed in compressed air.

In building the Bronx section the method was modified, as indicated in Figs. 4, 5 and 6 of Plate 10, by erecting the upper half of the cast-iron lining on a pontoon and placing the enveloping concrete upon it. The ends were closed by steel plate diaphragms. The pontoon was then sunk and withdrawn, the tunnel construction floating by reason of the air chamber; it was then loaded and lowered carefully on the sheet piling, forming the roof of the working chamber, and leaving only the lower half of the tunnel to be built in compressed air.

In this brief description many interesting details are necessarily unmentioned; but the work was a good example of a project carefully studied and each successive step made easy by the steps preceding.

Haskin's Tunnel Work under North River.

The first tunnel construction undertaken under either of the rivers surrounding Manhattan Island was at the New Jersey end of the north tube of the McAdoo uptown tunnels. Soon after 1870 Dewitt C. Haskin proposed to use compressed air for tunnelling in Hudson River silt, believing that by laying painted canvas against the silt to prevent air seepage through it the compressed air would support it and tunnelling would be easily done.

He was the first to use compressed air in any important tunnel, and believed the idea to be original with himself, but this appears to have been erroneous, for a compressed-air system for this purpose had been patented in England by Admiral Cockrane fifty years before. Haskin began work for two tunnels under the Hudson River in 1874 by sinking a shaft in Jersey City, but the work was held up by litigation for several years, and tunnelling in compressed air was not begun until 1879. Unfortunately, Haskin's method was not practicable in the soft silt or mud of the bed of Hudson River, and on one occasion, after several accidents of less importance, an inrush of mud occurred and several lives were lost. His superintendent, John Anderson, then devised the so-called pilot-tube method, which consisted in first driving a small tunnel about 6 feet in diameter along the axis of the larger one; this pilot tunnel was lined with plates bolted together at the edges, and was built to a length of 50 or 60 feet. The excavation was then carefully enlarged around the rear end of the pilot tube to the full size desired and lined with thin plates, which were supported by radial struts from the pilot tube. After thus enlarging the excavation for a short distance the brick tunnel lining was built in and the rear plates of the pilot tunnel were removed and carried through the tube and again built in at its front end. After many vicissitudes Haskin was finally obliged to stop, in 1888, after having built the north tube for a length of about 2000 feet and the south tube about 570 feet from the New Jersey side. He had also sunk a shaft in Morton Street, Manhattan, near the river bulkhead, and had built the north tunnel for a distance of 160 feet. The distance between the shafts was about 5700 feet, so that there remained to be built about 3500 feet in the north tunnel and about 5100 feet in the south tunnel. In the following year the enterprise was taken up by English capitalists and contractors and work resumed by the shield method; with the single exception before noted, this method has been used for all tunnelling in soft ground under both rivers since that time.

DEVELOPMENT OF SHIELD METHOD.

The development of the shield method of tunnelling has covered a period of nearly 100 years, but it is only within a comparatively recent period that the method has come into frequent

FIG. 1.

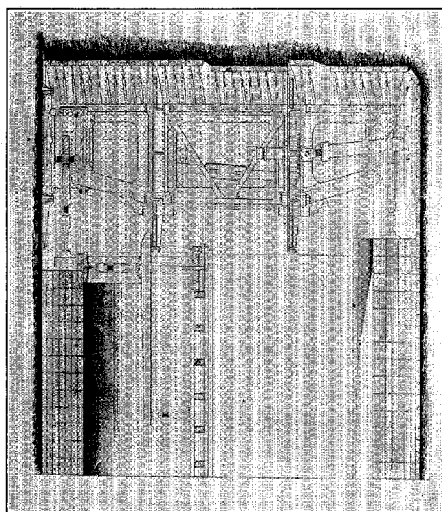


FIG. 2.

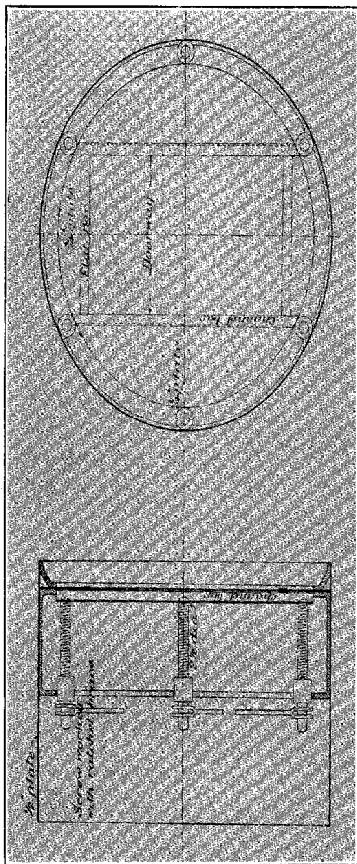


FIG. 4.

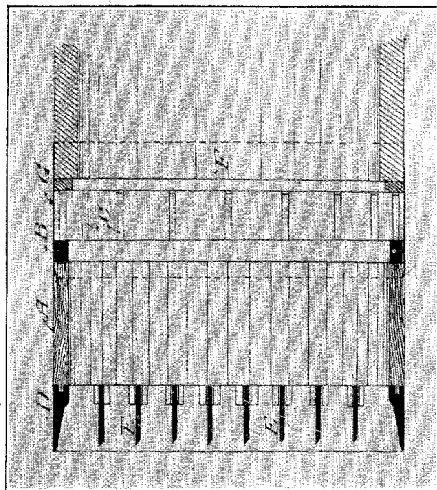
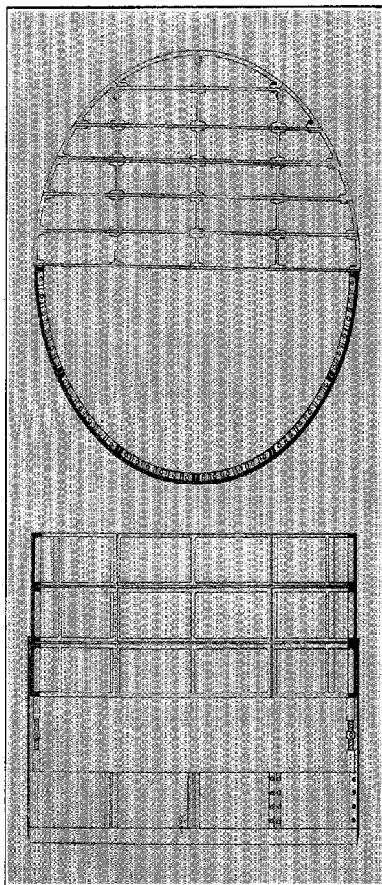


FIG. 3.



use. The first proposal for shield tunnelling, described in a British patent issued to Marc Isambard Brunel in 1818, included the essential features of modern shield tunnelling—a movable structure in advance of the completed tunnel, affording protection to the men at the face of the heading and provision for building the tunnel in short lengths inside the rear portion of the movable structure. Brunel's shield (Fig. 1, Plate II) was composed of a large number of sections separately controlled. With such devices Brunel completed a tunnel under the Thames at London between the years 1828 and 1843. While the principles involved were much the same as in the shield of the modern type, there was little other resemblance.

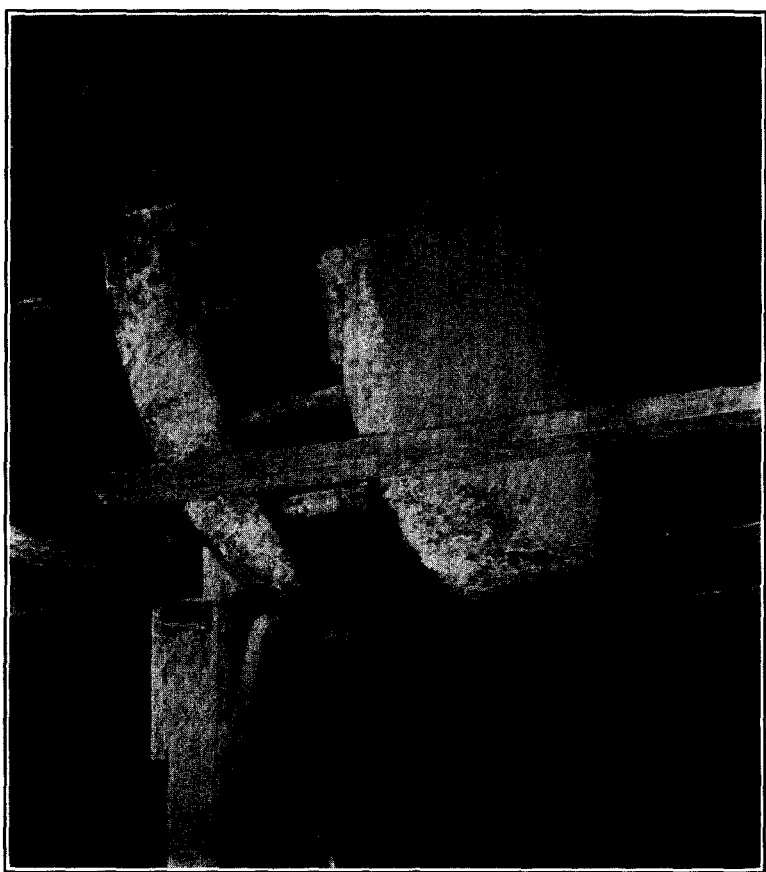
The next important development was covered by a British patent issued to P. W. Barlow in 1864. The shield was to be a single structure and was essentially a cylinder a little larger in diameter than the tunnel (Fig. 2, Plate II). As in Brunel's design, the tunnel was to be built up in short lengths within the rear portion, or tail, of the shield; the successive tunnel lengths were to be short, cylindrical iron rings. The shield was to be forced forward by means of screws. The use of hydraulic presses instead of screws to force the shield forward appears to have been first suggested by R. Morton, of Stockton-on-Tees, and is mentioned in a provisional patent issued to him in 1866. The use of the cast-iron cylindrical rings formed of segments, the segments and rings bolted together through inside flanges, is clearly defined in Morton's patent; the front of the shield, however, was to be (quoting the patent) "sharp or pointed like a wedge," an idea which has not yet been carried into practice.

Neither Barlow's nor Morton's shield was put into use, but a shield of similar type was designed, built, and used by J. H. Greathead in the construction of the Tower Subway under the Thames in 1869 (Fig. 3, Plate II). This was the first tunnel built of cast iron, and has been the model for nearly all shield-driven tunnels built since that time.

In the meantime the subject had received attention on this side of the Atlantic, and in 1869 a shield designed by A. E. Beach was put into use and a short piece of tunnel built under Broadway, New York. In Beach's shield (Fig. 4, Plate II), hydraulic presses were used for the first time to force the shield forward, antedating the use of hydraulic presses by Greathead in the con-

struction of the City & South London Railway tunnel under the Thames by several years. There has been much dispute in regard to the respective claims made in behalf of Greathead and Beach as to priority in design and actual use of the modern tunnel

PLATE 12.



Beach's shield.
Built 1869. Photographed 1912.

shield; there is hardly room for question, however, that modern shield tunnelling owes more to Greathead than to anyone else.

Beach's Broadway tunnel had been nearly forgotten until within the last year, when it was uncovered and removed in the building of a rapid transit subway. The shield was also found,

the wood nearly all rotted away, but the metal portions and the hydraulic presses still intact (Plate 12).

The history of the development of the shield system of tunnelling during the ensuing thirty years need not be followed in detail. It will suffice for our present purpose to point out more definitely than I have done hitherto the principal features of the shield-driven tunnels as usually constructed and the essential parts of the shield by means of which they are built.

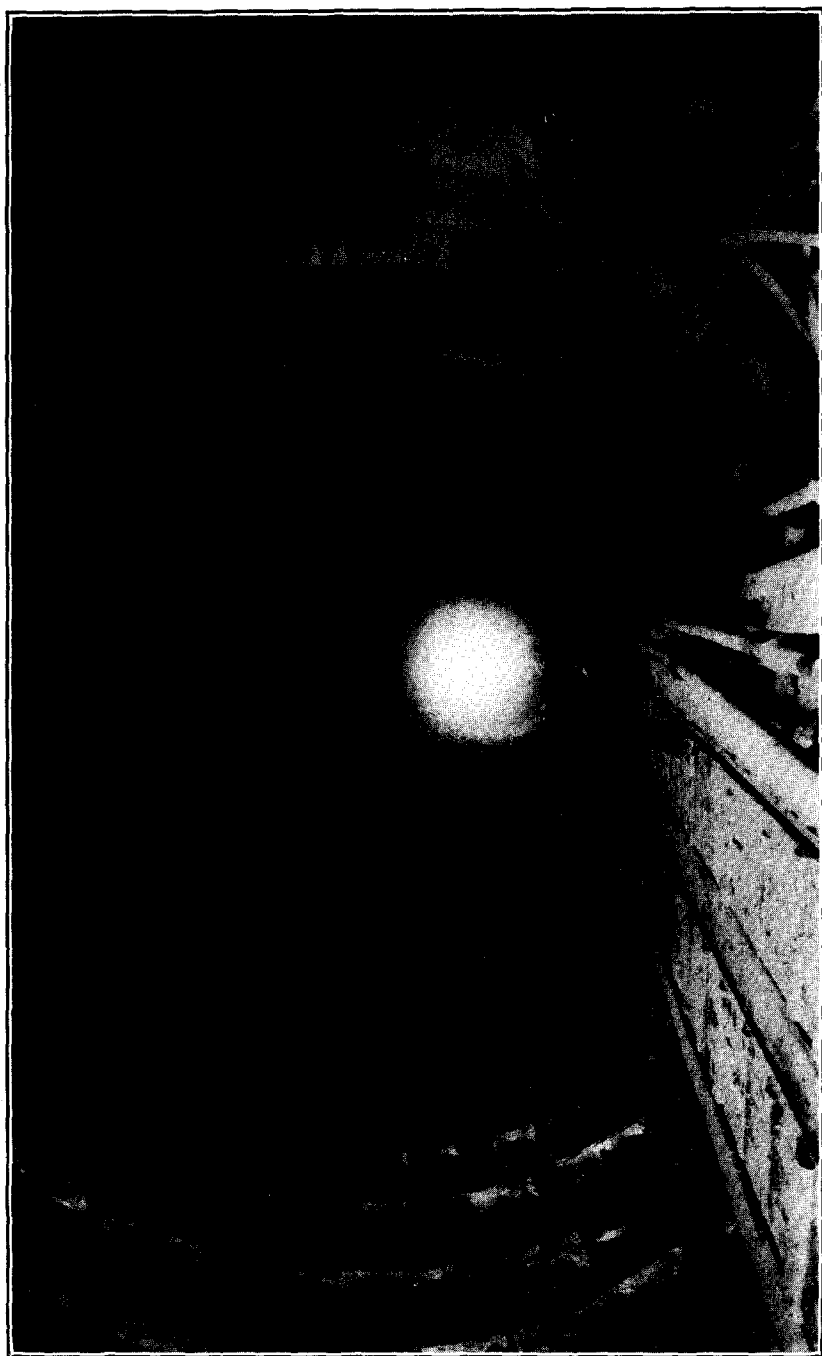
THE CAST-IRON TUBE.

The first stage in the construction of such a tunnel is to build the tube; this usually consists of cast-iron segments built into rings. Plate 13 shows the interior of such a tube, and Plate 14 shows details of the cast segments. The segments are 6 to 7 feet long, with radial joints, except a short closing segment or key in which the taper is reversed to facilitate building. Usually all meeting faces of the segments, including the joints between successive rings, are machined to true surfaces. The width of the rings varies in different tunnels from 18 to 30 inches. The segments and the rings are connected by bolts through inside flanges. Taper rings having a greater width on one side are used where it is desired to correct alignment or grade, or to pass along curves.

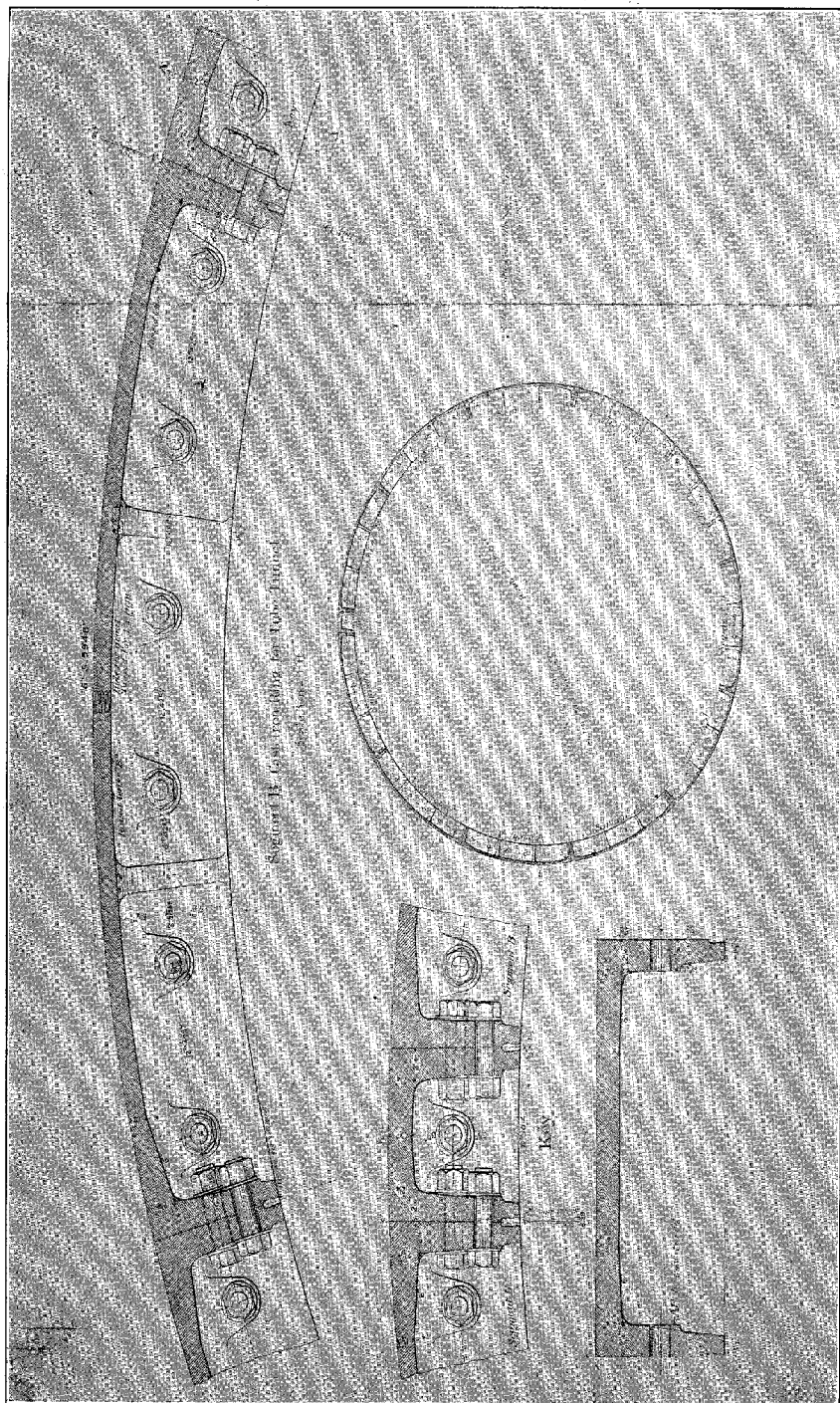
In the process of moulding a segment a rebate is formed around the inner edge of the side of the flange, resulting in a narrow but relatively deep groove after the segments are bolted together in the tunnel. In such material as the North River silt, which is nearly water-tight, a water-tight joint is secured by caulking ordinary rust-joint materials into the grooves. Where the material surrounding the tube is freely water-bearing the water filtering through the joints washes out the rusting ingredient before it has time to act, and rust-joint work is unsatisfactory. Better results are obtained by caulking lead into the joint, usually in the form of a rod or wire. After caulking the rod or wire into the bottom of the groove the remainder of the groove is filled with cement mortar.

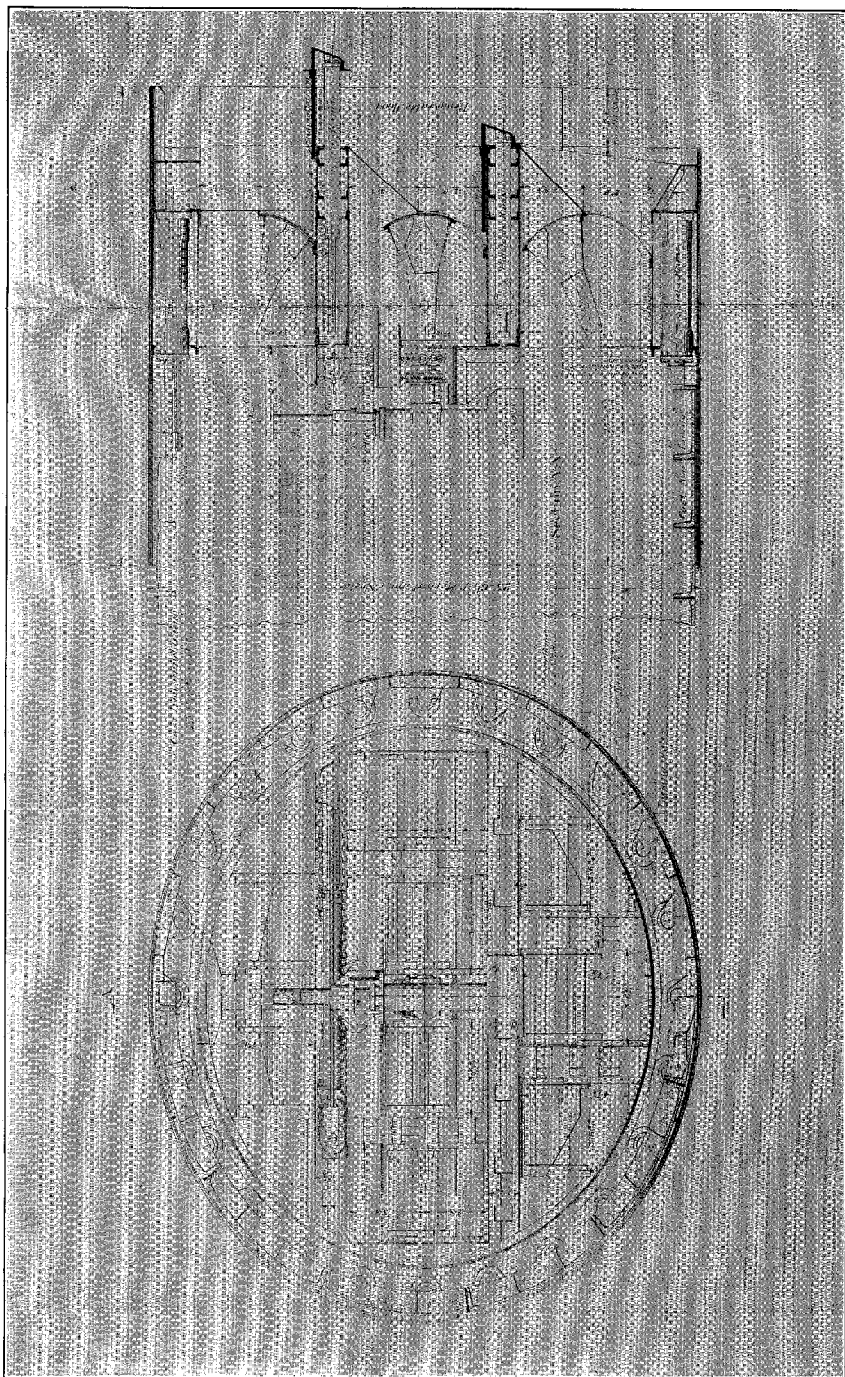
The bolt holes in the segments are cored considerably larger than the bolts to facilitate erection. They are usually made water-tight by grummets of hemp saturated with red lead and oil, or by winding the bolts with saturated hemp strand. These

PLATE 13.



Interior of tube tunnel.





wrappings or grumnets are placed between washers and the faces of the castings and afterward compressed when the bolts are tightened up.

It is probably not realized to what extent tunnel construction of this form has been carried out in connection with the tunnel systems referred to, the actual total being nearly 17 miles.

THE MODERN SHIELD.

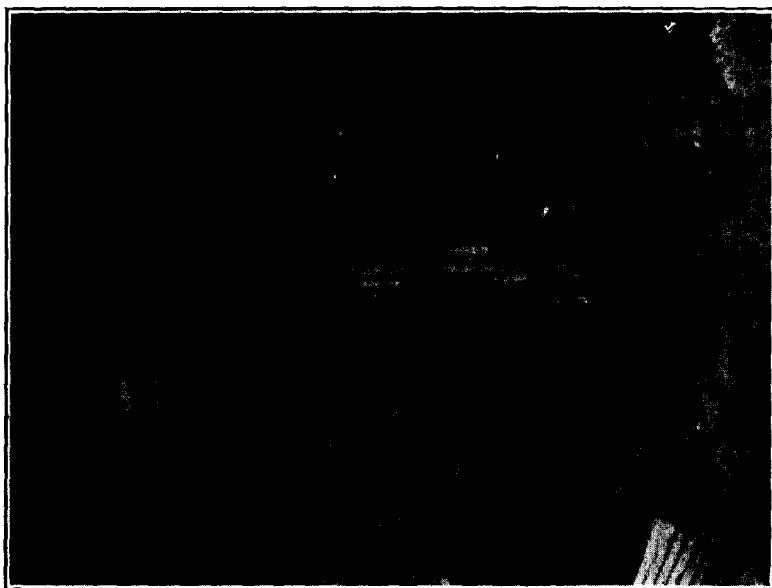
A shield may be defined as a short, movable length of tunnel, affording protection for excavating in the advancing face and for erecting successive rings of tunnel lining within the rear portion or tail. In the North River silt the shield could be pushed along without excavating in front, but in firmer materials, such as clay, sand, gravel, and rock, the shield must afford facilities for excavation before the shield can be advanced. The shield used in the Pennsylvania Railroad tunnels under North River is shown in sectional view on Plate 15. Front and rear views of a shield used in one of the Pennsylvania Railroad tunnels under East River are shown on Plate 16.

The structural portion of the shield may be considered as made up of three sections, as follows:

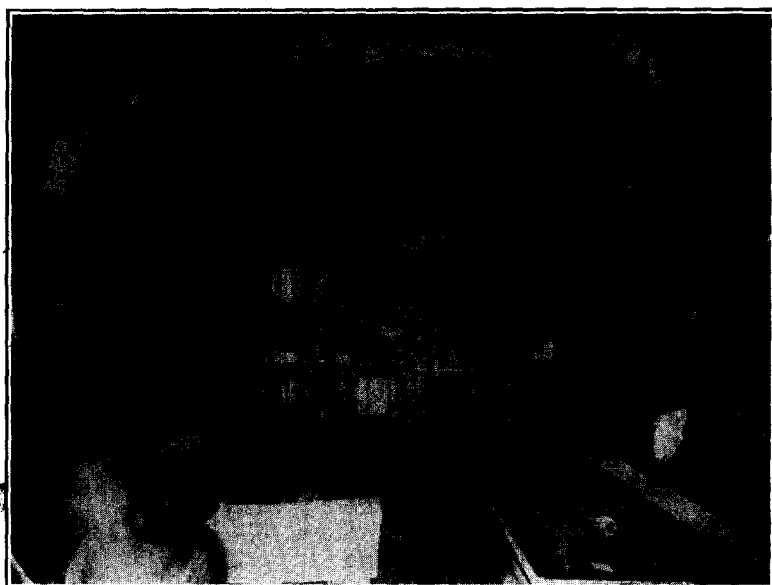
First.—The cutting edge, which for use in firm materials must be made very massive, as illustrated in the East River shields on Plate 16. In this shield the cutting edge was of heavy steel castings strongly connected with each other and with the cylindrical shell of the shield. This ring of heavy castings was continuous around the circumference of the shield, the projecting part shown in the upper portion, intended for use in sand, being temporarily attached to the true cutting edge. Such a heavy cutting edge was not needed in the silt of the North River, and the sectional view, Plate 15, shows a lighter construction.

Second.—The central portion or body of the shield carries an interior shell, concentric with the outer one, the two being connected by diaphragms or ribs forming longitudinal pockets, within which are placed the hydraulic jacks for pushing the shield forward. The circular girder formed by the two concentric and connected shells is further strengthened by one or more transverse plates or diaphragms connected all around with the circular girder, and (in the shield shown on Plate 16) by two horizontal floors and two vertical partitions, connected with the circular

PLATE 16.



Front of shield.



Rear of shield.

girder, the transverse diaphragm, and with each other. The number of floors and vertical partitions varies according to the dimensions of the shield. The body of the shield carries various devices for maintaining the face in soft ground, erectors for building the successive rings of the tube, etc. The transverse diaphragms has openings for passing men or materials. In the Hudson River shield shown on Plate 15 these openings were closed by swinging or "Taintor" gates. The hydraulic jacks take bearing against the face of the ring last erected (see Plate 16). After the shield has been pushed forward far enough to permit the erection of another ring of the tube, or, technically speaking, when the "shove" is completed, the jacks are closed, or "drawn home," leaving a space of sufficient width for the new ring.

Third.—The tail of the shield has no interior bracing. When the shield is in position for the erection of a new ring the tail should overlap the second ring back, as shown on Plate 16, in order to permit the removal of any broken segment in the ring last erected.

The resistance to the forward movement of the shield may be very great, and the equipment of hydraulic jacks in the New York tunnel shields could exert a pressure of 2000 to 6000 tons. When the material was rock, blasting was often carried on immediately in front of, and almost in contact with, the shield. Under such severe treatment some of the shields were much damaged.

The larger diameter of the shield as compared with that of the tunnel causes an annular void to be left immediately behind the shield sufficient to cause settlement at the surface of the ground, and, where the shield is driven under city streets, may cause injury to adjacent buildings. This result can usually be prevented, or at least minimized to a large extent, by forcing grout outside the lining through holes in the segments provided for this purpose, each hole being closed by a screw plug.

SHIELD TUNNELLING METHOD APPLIED IN NORTH RIVER.

The resumption of work in 1889 in the tunnels under North River begun by Dewitt C. Haskin, and the use of the shield method in continuing it, have been mentioned. This resumption related only to the north tube. The shield was of the Greathead

type, and was built in Scotland; the tunnel work was under the immediate superintendency of E. W. Moir, then a young man beginning a career in tunnelling operations which has covered a large amount and wide range of difficult work. In this shield Greathead's earlier design was modified to better adapt it to the soft, flowing silt which forms the bed of North River, producing an effective tool with which a length of about 1900 feet of tunnel was built without serious difficulty of any kind; the work was then suspended for financial reasons and not again resumed until 1902, when it was taken up by the New York & New Jersey Railroad Company, the predecessor of the Hudson & Manhattan Railroad Company, under the general management of W. G. McAdoo, with Charles M. Jacobs as chief engineer. Moir's shield, after submergence for twelve years, was found to be in excellent condition, requiring only cleaning the machinery and slight repairs, and the river tunnel was completed with it.

THE MCADOO TUNNELS.

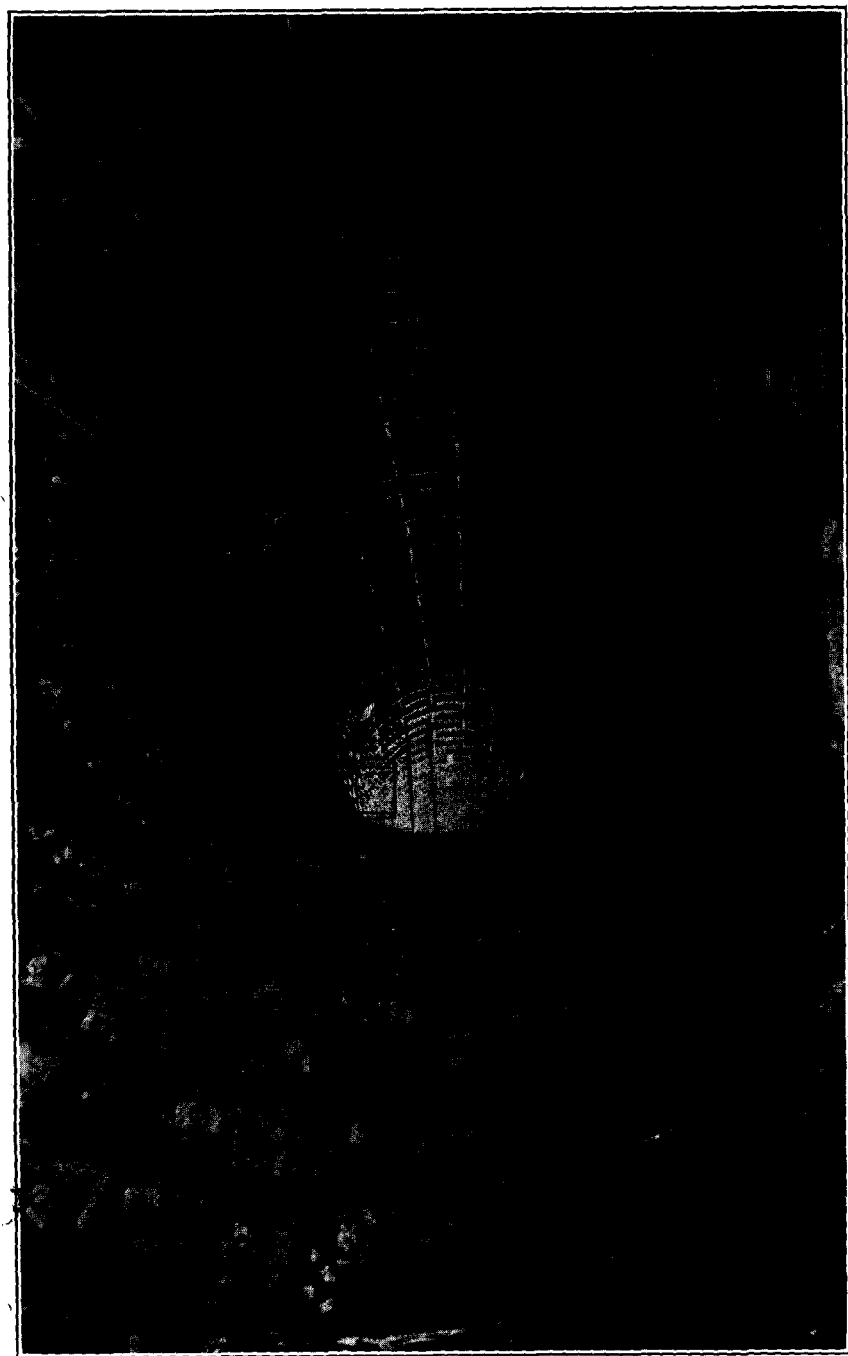
The problem of tunnelling through Hudson River silt had been substantially solved by Moir, but a new problem awaited, for soon after work was resumed in 1902 rock was encountered in the bottom of the excavation and continued for several hundred feet, and at its highest point was 15 feet above the bottom of the tunnel, giving nearly a full face of rock. While the tunnel was in silt but little excavation was necessary, and usually this could be made without going in front of the shield by opening a door or slide in the face of the shield and permitting the material to enter the tunnel; but when rock was met it was necessary to work in front of the shield in order to drill, blast, and remove it. The soft silt required support by timbering, which was usually practicable, but in one place where the silt was in a semi-fluid state this was found insufficient, and a novel scheme was tried—that of hardening the clay by heat. Blowpipes fed with kerosene were applied for eight hours, after which the clay was found solidified sufficiently to permit the work to be continued. After passing the rock, sand was encountered, and this continued until meeting the old tunnel extending westward from Haskin's Morton Street shaft. The work since resumption had occupied 505 days, during which 1625 feet of tube tunnel were built, an average of 3.2 feet per day. Has-

kin's bulkhead across his Manhattan heading was broken through March 11, 1904, thus completing the first tunnel under the Hudson River, about thirty years after it was begun.

The original project of Haskin was intended to provide for the passage of ordinary trains; the brick tunnel was 18 feet high inside and 16 feet wide, the cross-section being elliptical. The circular cast-iron tunnel subsequently built by Moir had a diameter of about 18 feet inside the flanges, giving an exterior diameter of about 19 feet 5 inches (Fig. 5, Plate 3), probably with the same traffic in view. When the New York & New Jersey Railroad Company took up the work, the Moir shield being still in place and usable, the north tunnel was completed with but slight change in diameters. This company, however, did not contemplate a tunnel system for ordinary railroad service, but for suburban trains with smaller cars, and therefore adopted smaller dimensions for the three remaining tunnels, reducing the exterior diameter to 16 feet 7 inches and the inside diameter, clear of the flanges, to 15 feet 2½ inches.² The exterior diameter of the new shields was 17 feet, a material reduction from the Moir shield, greatly facilitating pushing the shield through the North River mud, and while it became advisable, from time to time, to admit a small proportion of the material from the front of the shield into the tunnel, through the doors in the diaphragms of the shield, this only averaged about 5 per cent. of the amount displaced. The greatest caution was required in admitting this material on account of its semi-fluid character. When working alongside the coal wharf of the Delaware, Lackawanna & Western Railroad, where special care was needed to avoid injuring the wharf, the chief engineer issued stringent orders that the doors should be kept closed while the shield was moving forward. On one occasion a night superintendent, finding the shields moving very slowly, disobeyed orders and opened the door. The mud being compact and solidified required at first to be dragged through the opening. All went well for about half an hour, when suddenly a jet of silt of the cross-section of the opening shot through and buried one of the men, the remainder of the force escaping through the airlock some distance back in the tunnel. Within a short time the tunnel became solidly filled

² For details of dimensions and weights of cast-iron lining see table on page 384.

PLATE 17.



Hudson & Manhattan Railroad. McAdoo tunnels. Morton Street curve.

with mud back to the bulkhead in which the airlocks were placed. In order to recover the tunnel, the bed of the river over the end of the tunnel and just ahead of it was covered with a large canvas of double thickness. A valve at the outer end of the pipe which extended through the airlock bulkhead was then opened and the mud shot out a distance of 40 feet, and cars were filled with it for eight days; as mud was thus withdrawn through the bulkhead the tunnel between the bulkhead and the shield was kept filled by the mud entering through the open door of the shield, gradually forming a depression in the river bed, which the canvas followed until it finally reached the door and blocked it, after which the men worked their way into the tunnel, compressed air was again put on, and in nine days more the shield was reached and the door closed.

As experience was gained mishaps became infrequent and progress through the mud became rapid. In one week 346 lineal feet of tunnel were built, and about 70 lineal feet were built in one day of 24 hours. There were difficulties when rock was met and also when passing through sand, similar to those to be referred to in connection with the tunnels of the Pennsylvania Railroad.

In driving the shields landward from the Morton Street shaft toward Sixth Avenue it was necessary to build some sharp curves; one of these of 150 feet radius is shown on Plate 17.

Typical cross-sections are shown on Plate 3. All of the tunnels except the north uptown tunnel are of the standard section shown in Fig. 4. The track is of the ballasted type, laid on a concrete floor, the concrete being extended far enough up the sides of the tube to enclose the ducts for the electric cables required for operating the railroad. The north uptown tunnel was built of larger section, as before mentioned, but the interior section brought to standard dimensions by an interior lining of concrete as shown in Fig. 5.

The uptown tunnels from Hoboken were opened for traffic to Nineteenth Street and Sixth Avenue in February, 1908, and to Thirty-third Street in November, 1910. The downtown tunnels were opened from Church Street to the Pennsylvania Railroad station in Jersey City and successive portions of lines paralleling the river were put in service at various times in 1909 and 1910.

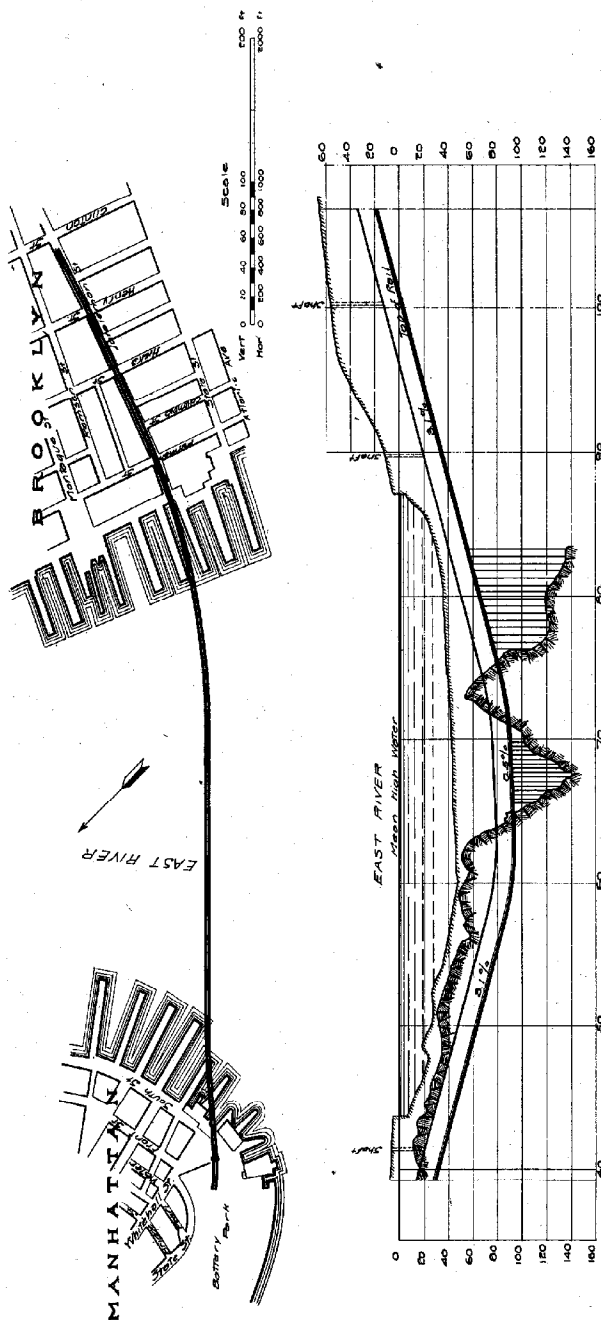
THE NEW YORK CITY SUBWAY TUNNELS UNDER EAST RIVER
BETWEEN MANHATTAN AND BROOKLYN.

The portions of the subway system here considered comprise two cast-iron tubes under East River from a point near South Ferry in Manhattan to the foot of Joralemon Street in Brooklyn, a distance of 4372 feet, and their extensions landward for a distance of 440 feet in Manhattan and 1978 feet in Brooklyn, making a total distance of 6790 feet, or 13,580 lineal feet of tube tunnel. A map, profile, and typical cross-section are shown on Plate 18. For the greater portion of their length under the river the tubes are 16 feet 8½ inches in diameter outside and 15 feet 5½ inches inside the flanges, and are of two types, one weighing 4545 pounds per lineal feet of tunnel, the other 5133 pounds. Somewhat heavier metal is used under the river bulkheads. In rock a lighter section is used, weighing 3992 pounds per lineal feet of tunnel, and is intended mainly for waterproofing.³ In Brooklyn the same lighter section is used in the tubes above tide level. The tunnels were begun in 1903 and completed in 1907.

Tunnelling in the rock from the Manhattan side presented no marked features, but the earth presented two troublesome types: a rather coarse sand on the Brooklyn side and an extremely fine quicksand in the middle of the river. The difficulties met in passing through the quicksand were duplicated in the construction of the Pennsylvania Railroad tunnels, and will be described more fully in connection with that work. On the Manhattan side the tunnels in rock were built in air of normal pressure until the river front was passed, when airlock bulkheads were built across the tunnels and the compressed air was put on. Toward the middle of the river, near the point where the rock surface was broken through, shields were erected and tunnelling was continued out of the rock and into the earth to the points of junction with the Brooklyn shields.

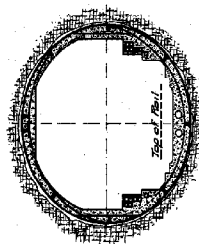
On the Brooklyn side two shafts, one for each tube, were sunk at the points where the tubes rise above tide level, about 2000 feet eastward from the water front; shields were erected and started eastward in the dry headings, after which two other

³ For details of dimensions and weights of cast-iron lining see table on page 384.

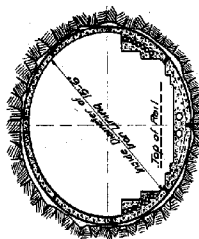


NEW YORK CITY SUBWAY EAST RIVER TUNNELS

Battery Park, Manhattan
Joralemon St., Brooklyn



TUBE TUNNEL IN EARTH
Scale 1/6



TUBE TUNNEL IN ROCK
Scale 1/6

shields were erected in the same shafts and driven westward to the points of junction with the Manhattan shields.

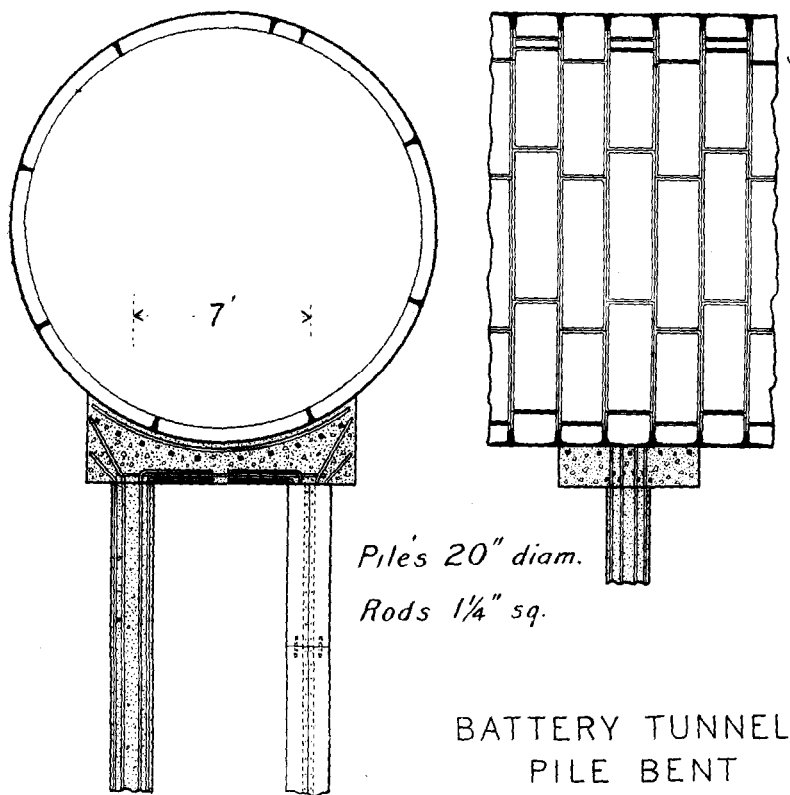
Tunnelling in quicksand was a new problem met here and in the Pennsylvania Railroad tunnels almost simultaneously. In places the shield settled below the proper grade line, and in some places the changes in grade were too sharp for convenient operation of trains. The diameter of the tunnel gave so little leeway for trains that it was necessary to depress the bottom or to raise the roof of the tunnel so as to permit easier vertical curves in laying the track. In quicksand these were extremely hazardous operations unless done with the greatest care and skill. The lowering of the bottom of the tunnel was accomplished by first raising the air pressure enough to dry the underlying material when exposed and successively removing the cast-iron segments in the lower half of the tube, replacing them with new segments curved to an elliptical form so as to give a greater vertical diameter and therefore a lower bottom. This was a less hazardous operation than to raise the roof, and was the method generally adopted in the reconstruction. For a short distance in each tunnel the roof was actually raised by powerful hydraulic jacks sufficiently to permit the construction of a new masonry roof with a greater vertical clearance.

During the construction of these tunnels in the section where quicksand was encountered sensational articles appeared in the newspapers alleging the impossibility of maintaining the tunnels in position under traffic, and it is to be regretted that this alarm was promoted by a few engineers. It was finally decided, although believed unnecessary by the city's engineers, to support the tunnels in quicksand by means of concrete columns or piles. In order to place them the bottom segments of the tunnels were removed at intervals of 30 to 50 feet and the piles sunk by use of the hydraulic jet to harder materials at depths ranging from 5 to 75 feet. They were placed in pairs 7 feet apart transversely to the tunnel and their tops connected after sinking by reinforced concrete cradles conforming to the transverse outline of the tunnel. The cast-iron segments were then replaced, and the tunnel rested, more or less completely, on the cradles. About 1200 lineal feet of each tunnel were thus underpinned (Plate 19).

Since this work was done, the Pennsylvania Railroad tunnels under the East River, passing through similar material and

unsupported except by the earth itself, have been in operation for about two years without the slightest settlement. The subway tunnel weighs considerably less than an equal volume of water; when filled with a train the weight is almost the same as that of an equal volume of water, and therefore much less than the displaced saturated earth. The Pennsylvania Railroad

PLATE 19.



New York City subway tunnels. Pile supports.

tunnels, with heavier construction, weigh somewhat more per lineal foot when loaded with a train than the displaced earth, and the tendency to settle would seem to be greater. It is well known that quicksand, when confined, will carry heavy loads without yielding, and, in fact, some of the high buildings in New York rest upon material undistinguishable from the river

quicksand. In view of all this there is no room for doubt that the opinion of the city's engineers was correct.

The cast-iron lining in the city's tunnels was of lighter section than in the McAdoo tunnels, the latter being about 25 per cent. heavier. This is compensated for by strongly reinforcing the concrete lining where the tunnel is in earth under the river, where the pressure upon it is the greatest. The tunnels were opened for traffic in January, 1908.

PENNSYLVANIA RAILROAD TUNNELS UNDER NORTH RIVER.

A map, profile, and typical cross-section of these tunnels are shown on Plate 20.

For some distance from the shafts on both sides of the river the tunnels are in rock and were driven in normal air by ordinary methods. When the excavation in each tunnel had arrived near the point where the tunnel would pass out of rock into earth it was enlarged sufficiently to permit the erection of the shield; there were four shields for the North River tunnels, one in each tunnel on each side of the river (Plate 15). They were designed under the direction of Charles M. Jacobs, chief engineer of the North River Division. As they were to be driven through silt they were somewhat less massive and powerful than those for East River, where the materials ranged from quicksand to gravel, boulders, and rock. Still, the large tunnel dimensions adopted by the railroad company, the exterior diameter of the tube being 23 feet,⁴ resulted in a very heavy shield, weighing, with all its accessories, 193 tons. To force it forward in the tunnel 24 hydraulic jacks were provided, capable of exerting a push of about 3300 tons.

After building the shield a concrete bulkhead was built across the tunnel behind it, containing three airlocks, two near the floor level through which the excavated materials were passed out and cast-iron tunnel lining, cement, and other material for construction were passed in. A third airlock was placed in the upper portion of the bulkhead for the use of the working force entering or leaving the tunnel. Each airlock was a steel tube about 7 feet in diameter and 20 to 25 feet long, with a door

⁴For details of dimensions and weights of the cast-iron lining see table on page 384.

at each end opening toward the tunnel and air tight when closed. The bulkhead also contained smaller airlocks for passing pipe and similar materials into or out of the tunnel, pipe for compressed air, for water under pressure to operate the shield jacks, electric light wires, etc.

After the bulkhead was completed compressed air was admitted to the tunnel and the advance of the tunnel excavation continued. The passing from rock to earth was a critical stage, when the danger of an inrush of earth was particularly great.

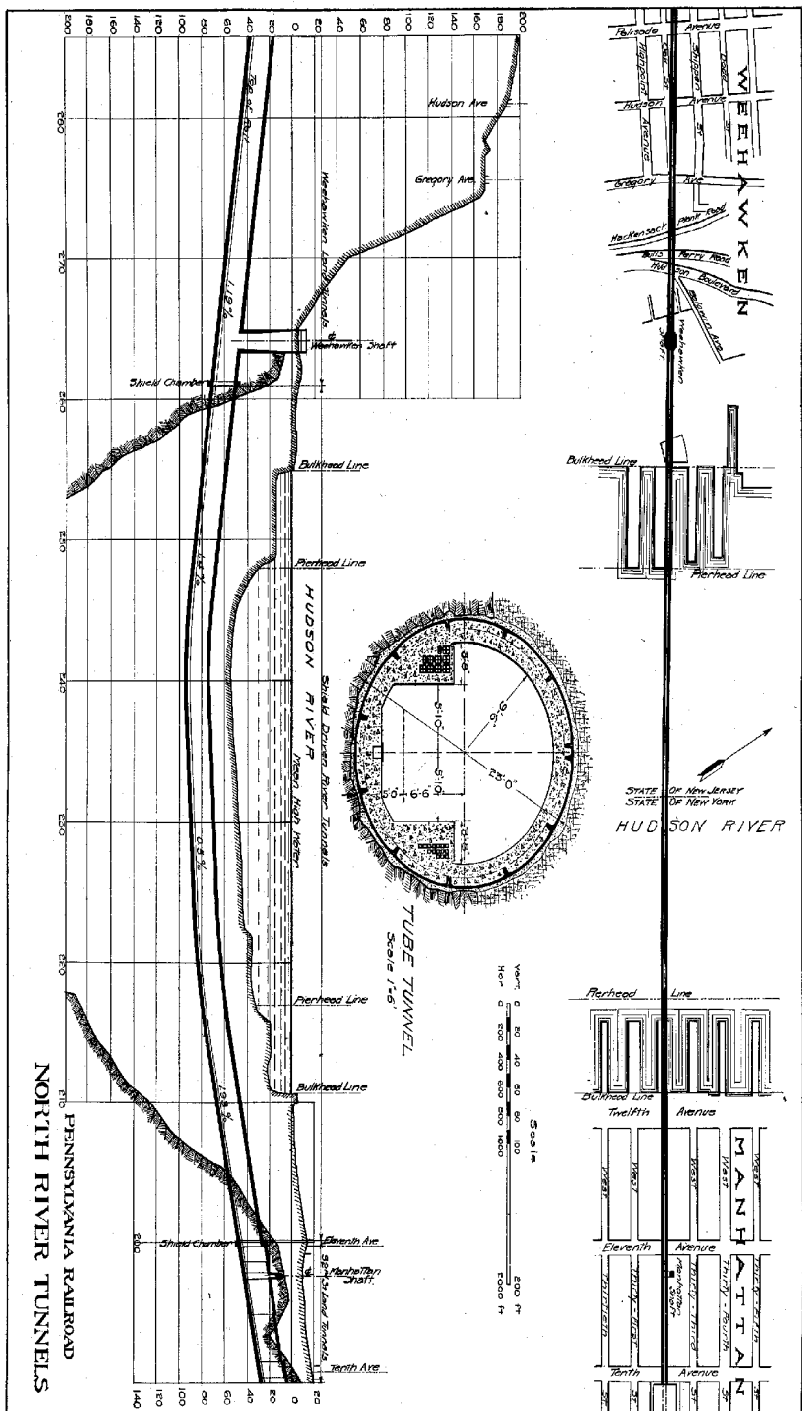
The first application of compressed air in these tunnels was in June, 1905. Prior to this the north tunnel of the uptown McAdoo tunnels had been completed under the river and a trained force was available for the Pennsylvania tunnels.

After passing out of rock and entering silt or mud it was seldom necessary to go in front of the shields. The hydraulic jacks could exert sufficient pressure to force the shield through the mud, but it was found impossible to keep the shield down to grade unless a portion of the mud in front was received into the tunnel. The portion required was, on an average, about 33 per cent. The principal office of the diaphragm, therefore, aside from the important one of stiffening the cylinder of the shield, was to furnish suitable openings for the admission of mud and sure means of closing them when desired.

Each shield was provided with one erector. It rotated on an axis on the centre line of the shield, in a plane normal to the tunnel and corresponding with the middle of the ring to be erected. It was rotated by a chain gear moved by two hydraulic rams. The erector itself was a hydraulic ram with devices for attaching the end of the piston rod to a segment to be erected. A segment could thus be picked up, the erector rotated, and the segment pushed into place by the erector.

With a suitable shield and an experienced working force the operation of tunnelling under the North River became mainly one of erecting tunnel lining, and the men became very proficient. A ring was frequently erected in 30 minutes; the maximum day's work was 15 rings, or $37\frac{1}{2}$ lineal feet of tunnel, done in two 8-hour shifts. One gang working eight hours erected 8 rings, or 20 lineal feet of tunnel. They promptly advertised as the "8-ring gang," and were in evidence on exhibition occasions.

It was not necessary in North River mud to raise the air pressure to meet the full hydraulic head except when working



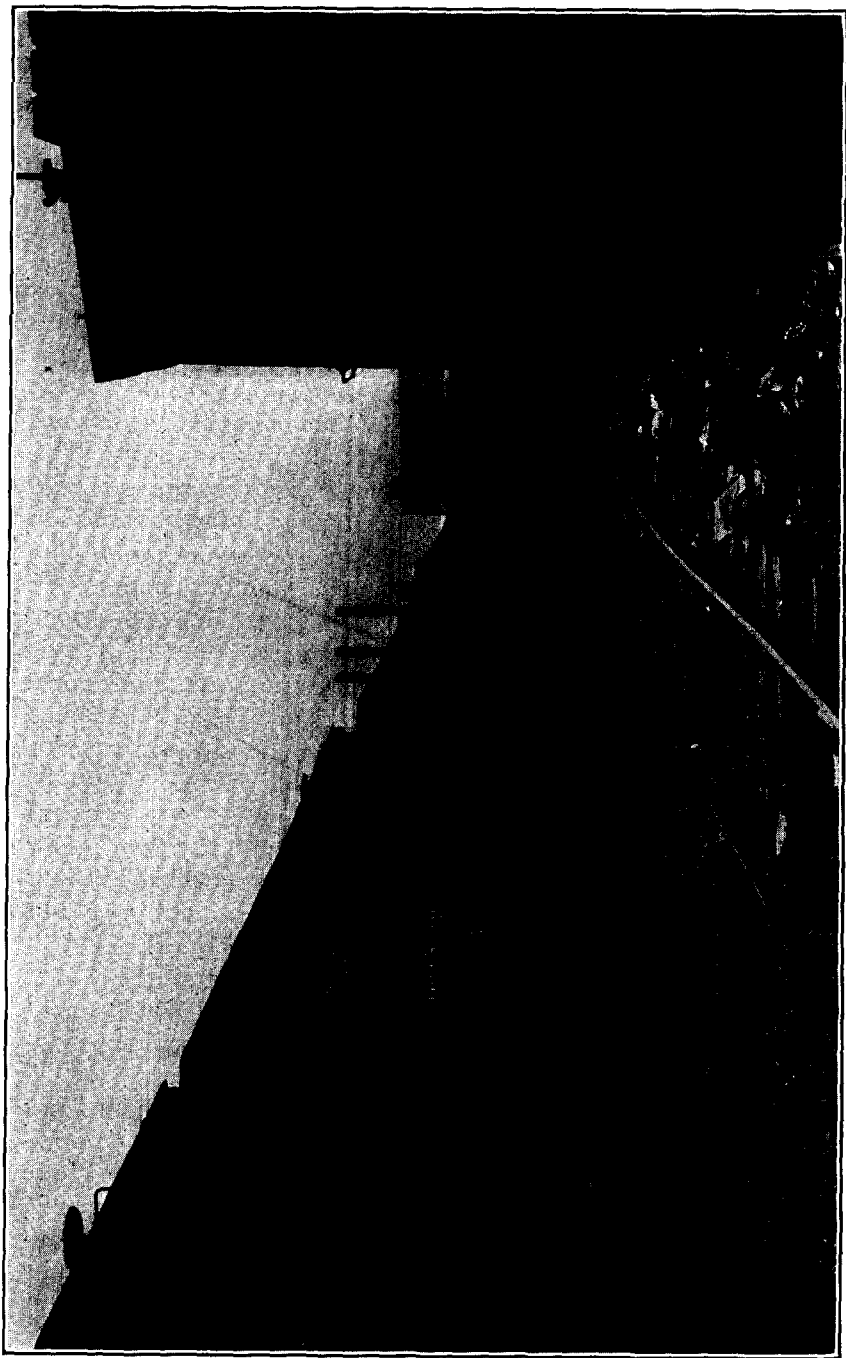
outside the diaphragm, as, for example, when cutting off piles projecting below the top of the shield. In such cases the pressure would be raised, effecting a stiffening of the mud and making it practicable to excavate a small volume, protecting carefully by timbering, and to remove the obstruction.

On account of the low air pressure usually carried, "blows," so-called, were infrequent. These are among the most picturesque, costly, and hazardous incidents of shield tunnelling. They can be dealt with more appropriately in connection with the East River tunnels, where they occurred with appalling frequency.

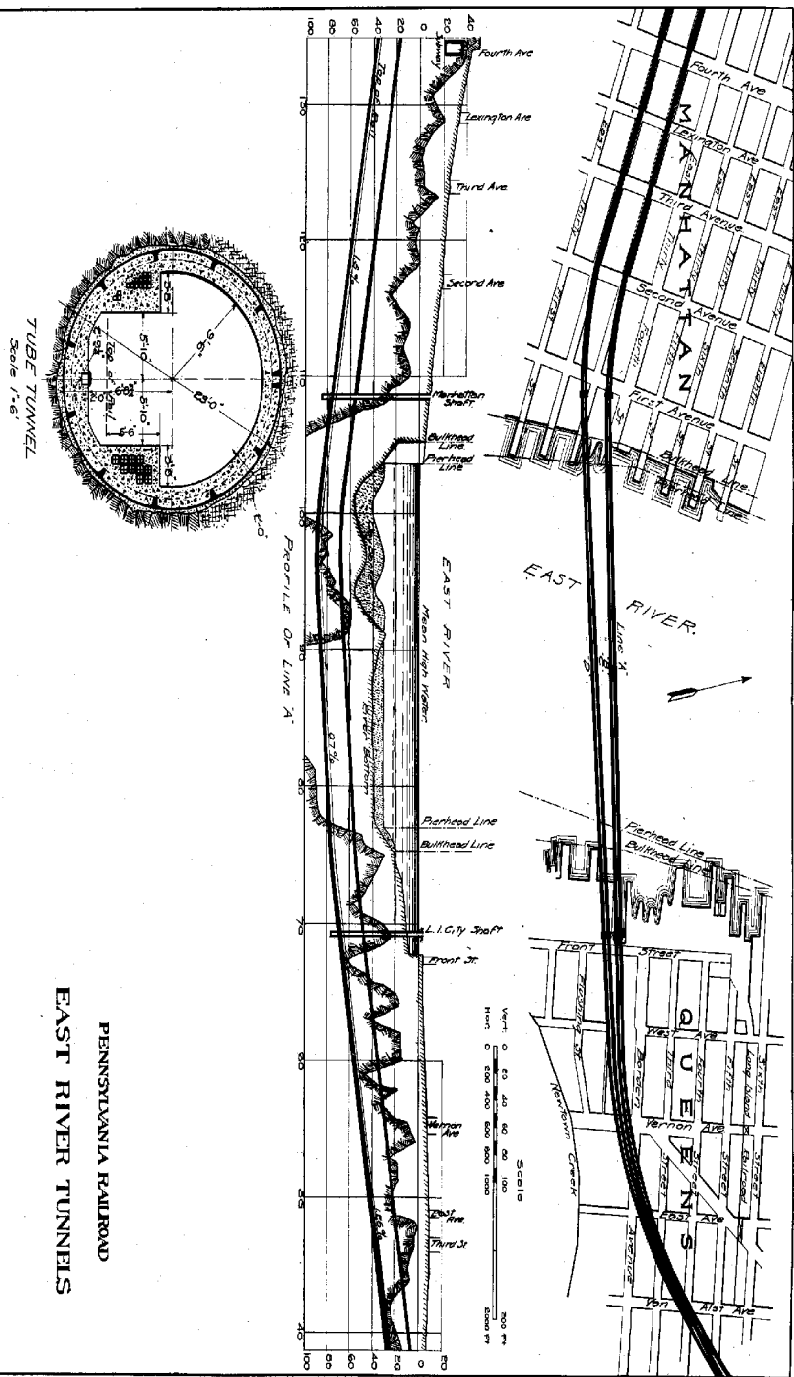
Pushing the shield through the mud without excavating the full tunnel displacement resulted in a ridge along the bed of the river over the tunnel lines as revealed by soundings. For some distance eastward from the river bulkhead on the Manhattan side the tunnels were driven under a freight yard of the New York Central Railroad, with the result of lifting the surface, which was some 50 feet above the tunnel (Plate 21).

During a period of many years preceding the inauguration of traffic through the uptown tunnels of the McAdoo system there was much discussion in regard to the stability of tunnels in the North River mud. They were to sink in the mud; when it was pointed out that the cast-iron tubes weighed less than the displaced mud, or less, even, than the same volume of water, then the mud was said to be a viscous fluid through which the tubes would certainly rise. It was even urged that the bed of the river was a mass of flowing mud gradually but surely moving into the upper bay. These views were little affected by the fact that the Haskin-Moir tunnel had neither risen nor moved down stream, so far as could be ascertained. Still, it seemed possible that the condition of the material might change under the vibration set up by traffic, being more liquefied and causing the tunnels to rise or sink—views differed as to the direction. In order to meet this contingency plans were made to sink screw piles through the bottom of the tube, and their sufficiency either to carry loads or to serve as anchors fully tested by experiment. Before it became necessary to place them in the due progress of the work the uptown McAdoo tunnels had been in operation for several months without any of the dire results apprehended, giving confidence that the supports would not be required, and they were omitted.

PLATE 21



Surface of ground lifted by shield.



PENNSYLVANIA RAILROAD TUNNELS UNDER EAST RIVER.

The materials met with under East River were very different from those just referred to. For about half the distance under the river the excavation was in sand, with a little clay, mostly quicksand (Plate 22). Rock, wherever met, was overlaid by a few feet of gravelly material freely water-bearing. Here were practically two new problems: one where the excavation was partly in rock with open gravel over it. At the Blackwall tunnel under the Thames, built a few years before, the excavation was in gravel, but was not complicated by blasting rock, which in East River frequently brought down the timbering by which the face above was protected. A face partly in rock was met previously, as already mentioned, in the north tube of the uptown McAdoo tunnel in 1903, but the overlying material held air better. The other problem—tunnelling in quicksand—was far more difficult. These problems were being met almost simultaneously in the city tunnels between South Ferry and Brooklyn, but were less difficult there because of the smaller diameter of the tunnels and the lighter shields. The increase of diameter from about 17 feet in the McAdoo and city tunnels to 23 feet⁵ in the Pennsylvania Railroad tunnels nearly doubled the area to be excavated; the weight of metal in the lining and the amount of compressed air required increased even more.

The shields were designed under the direction of E. W. Moir, a member of the same contracting firm for whom as engineer he designed the shield used in the North River tunnel in 1889. They were massive, weighing about 270 tons each when fully equipped, and cost about \$44,000 each. The cutting edge was made up of heavy steel castings, as already described. There were 27 hydraulic jacks, each 9 inches in diameter, to move the shields forward. A push of 5600 tons has been exerted, but under ordinary circumstances 3000 to 4000 tons were sufficient. Each shield carried two erectors. Because of the unprecedented conditions many ingenious devices were provided to facilitate the excavation. When put in use they failed quickly, and simpler and stronger devices were adopted.

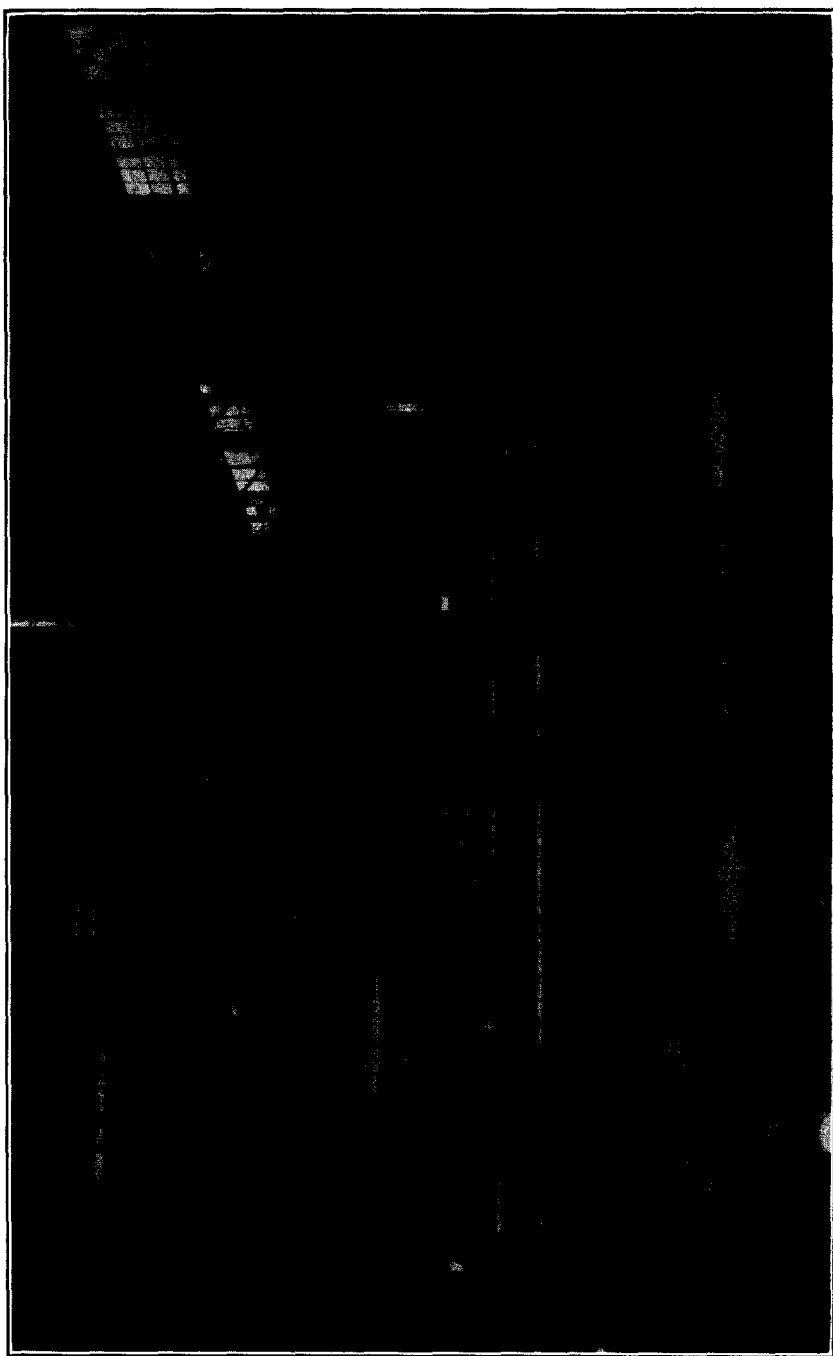
The tunnels approaching the river from the central station

⁵ For details of dimensions and weight of cast-iron tunnel lining see table on page 384.

were in pairs, one pair under Thirty-second Street, the other under Thirty-third Street, as already explained. At the working shafts near the river on the Manhattan side the tunnels of each pair were 11 feet apart, and at the Long Island City shafts 14 feet apart. It was convenient, therefore, to make each shaft large enough to cross both tunnels of a pair. Each shaft was a steel caisson; the two on the Manhattan side were about 300 feet from the river, and were sunk without compressed air. The Long Island City shafts were on the river side of the bulkheads, and compressed air was used; after sinking to full depth a strong concrete floor was put in below the tunnel level and the roof of the caisson removed. The shields for the work under the river were then built inside the shafts, the caisson roof with suitable airlocks replaced above the tunnel level, compressed air put on, and the shields started on their way. On the Manhattan side the shields were also built in the shafts and then pushed eastward, in tunnel excavation previously made, the cast-iron tunnel lining being built as the shields were moved forward, and the space between the tubes and the rock thoroughly filled with riprap and cement grout. After moving about 100 feet, nearly to the place where the shields would break out of rock, airlock bulkheads were built between the shields and the shafts and compressed air put on. Quicksand was met almost immediately after breaking out of rock, and the most serious difficulties of the work were at once encountered, with methods unperfected and working force untrained.

One of the difficulties anticipated and encountered was the escape of large quantities of air from the face of the heading, and two precautions were taken: one consisted of covering the bed of the river over the tunnel with a thick bed of clay to hinder the escape of air through it, and this proved very helpful. The amount thus used was more than 300,000 cubic yards, most of it obtained from a place 35 miles distant. After the tunnels were built this clay had to be removed and dumped at sea, a distance of about 24 miles. This was a large item of cost, but there is no doubt that it was wisely incurred. The other precaution taken was to provide a very extensive plant for compressing air to be sent into the tunnels. At the beginning of the work the plant provided on each side of the river to supply four headings had a capacity of 25,000 cubic feet per minute of free air—that

PLATE 23.



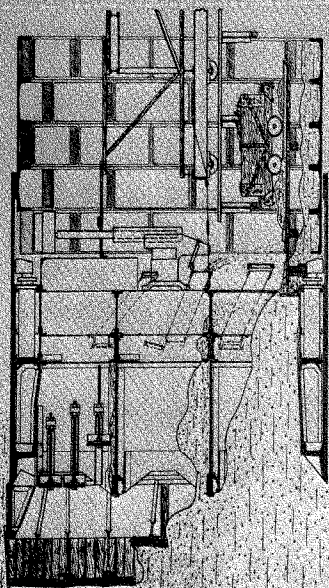
Pennsylvania Railroad. Manhattan air compressors for East River tunnels.

is to say, measured at normal pressure. The first tunnels to emerge from rock into the quicksand were three on the Manhattan side, and it was quickly found that the plant intended for prosecuting the work simultaneously in four tunnels was barely sufficient for two. The Manhattan plant was enlarged as soon as possible to a capacity of 35,000 cubic feet per minute; the plant on the opposite side of the river was enlarged still more, and finally had a capacity of 45,000 cubic feet of free air per minute. It may be mentioned that the cost of plant of all kinds for the construction of these tunnels was about \$2,500,000.

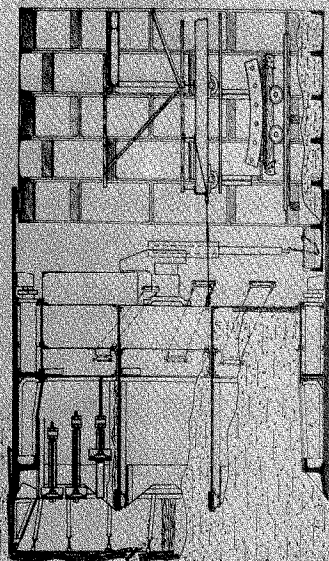
It would be tedious if I were to follow the various methods of working tried and abandoned; the discouragement when it became clear that unless better methods could be devised disaster could hardly be avoided; but we will pass at once to the methods finally developed by which, in the hands of a trained force, success was finally attained.

The successful method in quicksand is illustrated on Plate 24. The right hand portion of the plate represents the stage of the work when the shove of a shield has just been completed; the erection of a ring is being commenced; excavation must be resumed in the face, the breasting planks advanced and strutted, and the condition obtained which is shown in the left-hand side of the view, where the preparation is complete for another shove. It will be readily understood that if the quicksand is fully saturated it will be impossible to advance the planking, because any void excavated will be filled immediately by the liquid quicksand; therefore, the condition of the quicksand must be changed so that it will not flow, or, in other words, it must be dried out. This is effected by maintaining the air pressure slightly greater than that required to balance the hydrostatic head, which results in driving the water back from the face, drying it sufficiently to permit removing the top plank, or the top but one, excavating, and replacing it in the advanced position desired; this gives access behind the next plank, where excavation is made and the plank placed in the new, advanced position, and so on until the entire face has been advanced, with only a small portion open at any time.

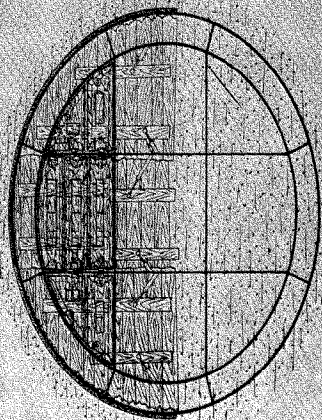
It will be noticed that but little more than half the face is shown in the figure as protected, and the question will arise whether the air pressure could be raised sufficiently to dry and



Preparing for Shot



After Shot



Preparing for Shot

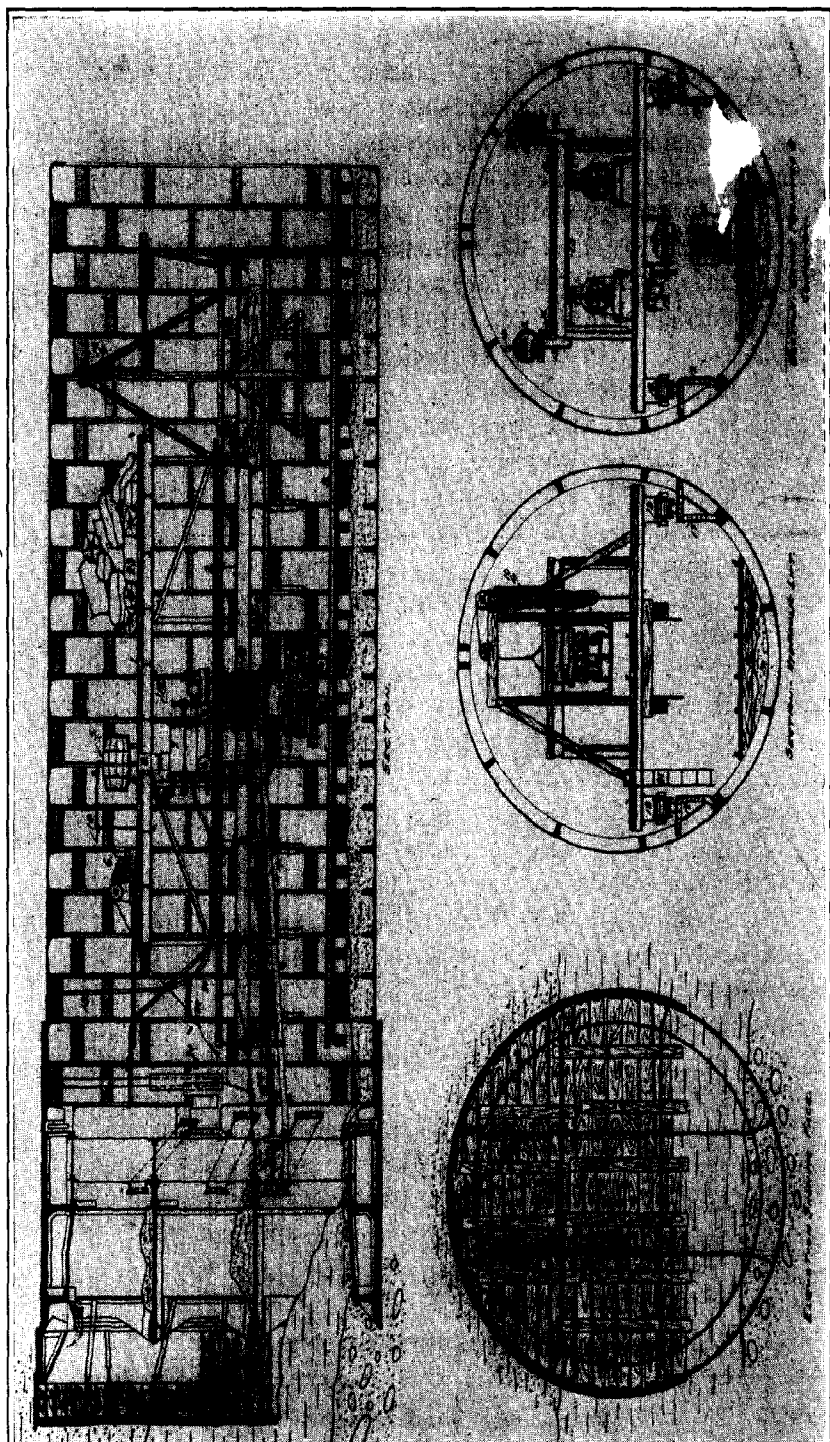
plank the heading to the very bottom. In quicksand this was not necessary, for it was found practicable to shove the shield forward when in the condition shown in the left-hand figure—the operation being to apply the pressure to the jacks and shovel the sand back from the bottom pockets as vigorously as possible; the facility thus given for more material to enter the bottom pockets tends to relieve the resistance at the cutting edge. It was found extremely dangerous to raise the pressure sufficiently to dry the sand at the bottom of the excavation, as will be briefly explained. Of course, the air pressure in the tunnel is practically the same everywhere at any given moment, but in a tunnel 23 feet in diameter the water pressure in the face is about 10 pounds per square inch greater at the bottom than at the top; therefore, if the air pressure were raised sufficiently to dry the materials at the bottom, the excess pressure at the top would be ten pounds per square inch. Under such a pressure the escape of air through the joints of the facing plank would become very great; the sand would soon be carried away in considerable quantity; an opening would be forced through the overlying earth; the escape of air would be then greatly increased, and some portion of the planking, deprived of the earth backing, would collapse, and the air would rush out in large volume, forming what is known as a “blow.”

Usually, in the East River tunnels, the air balanced the water near the tunnel axis, varying with the nature of the material and the skill and judgment of the tunnel boss. With firmer material than quicksand, the planking was carried farther down, as shown in Plate 25, the material in the central portion containing more clay, holding air better, and flowing less readily, with gravel in the bottom giving greater resistance to the forward movement of the shield.

Even when skill had been acquired and care was exercised the escape of air would sometimes get beyond control. I have no doubt that as much as 40,000 to 50,000 cubic feet per minute was blown out during short periods from a single heading. The escape has been as much as 25,000 cubic feet per minute for 24 hours or more. The most effective way to stop a blow was to dump quickly a large amount of clay from a dump scow.

Many blows were checked in their incipient stage in the tunnel by throwing bundles of hay or sacks or balls of clay into

PLATE 25.



Pennsylvania Railroad, East River tunnels. Method of tunnelling in sand, clay, and gravel.

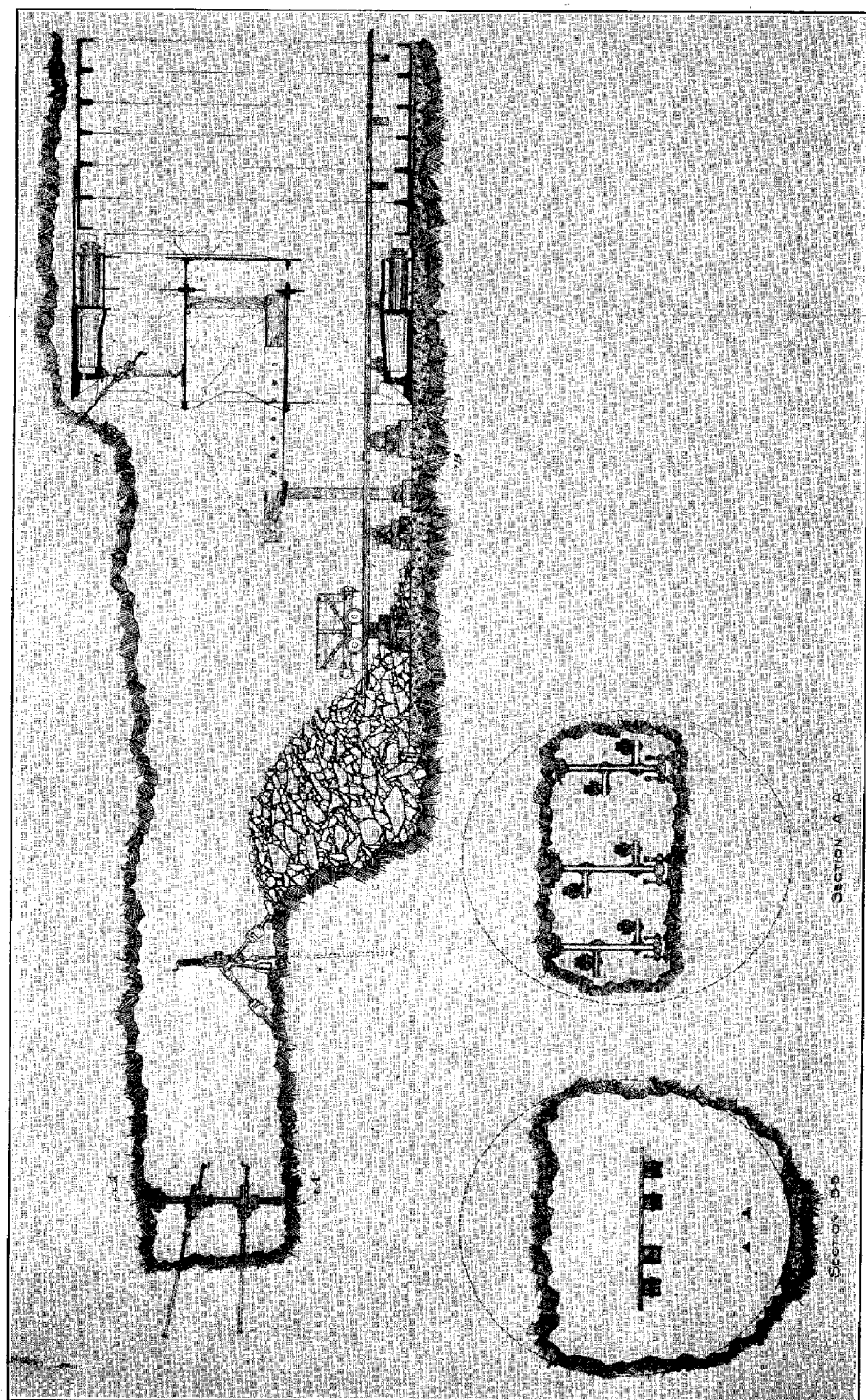
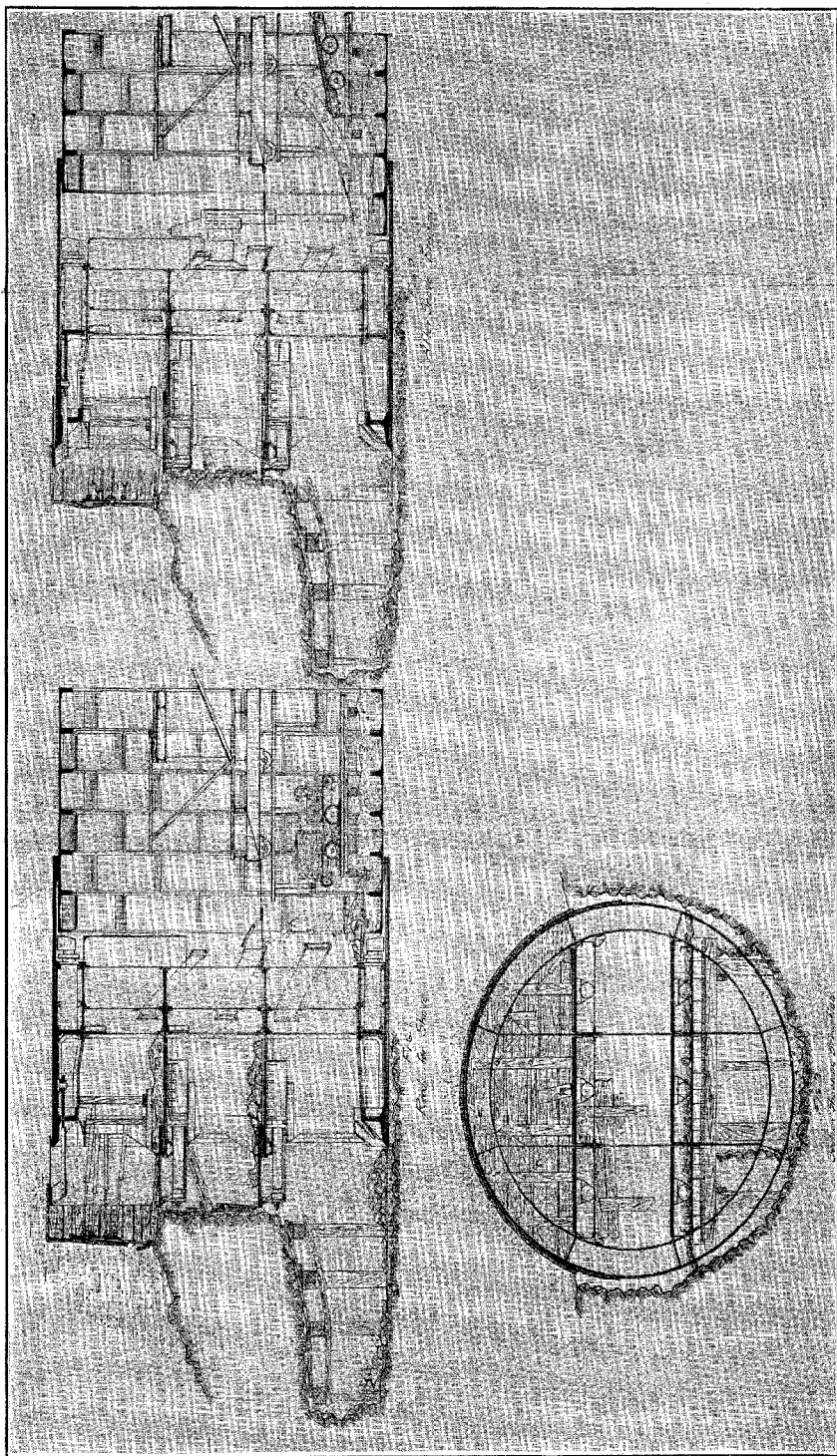
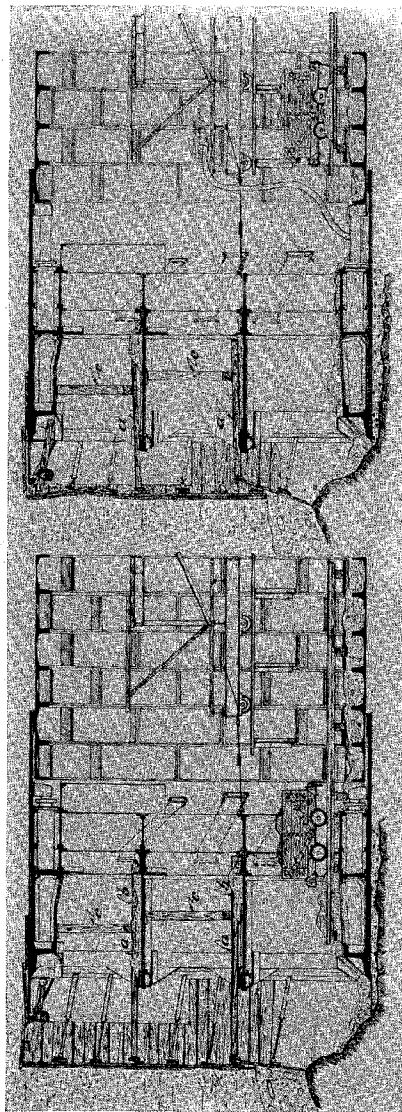
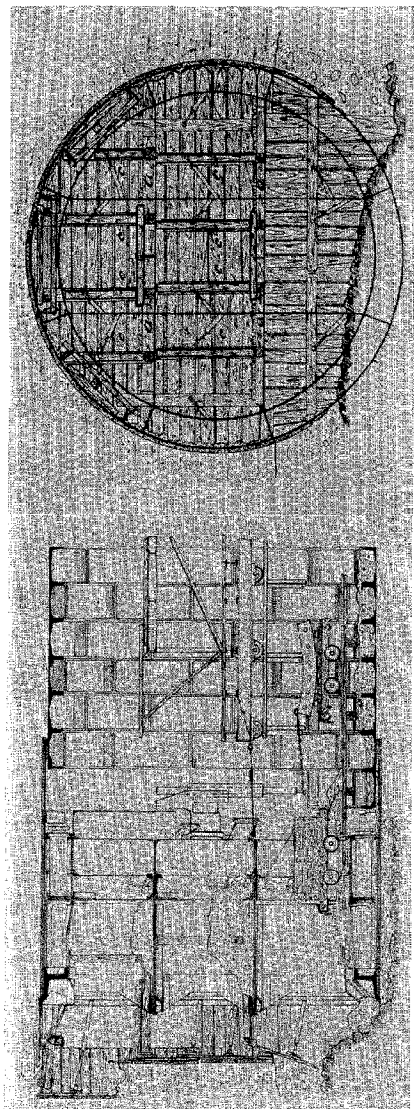


PLATE 27.



Pennsylvania Railroad East River tunnels. Method of tunnelling free rock and earth. Bottom heading.

PLATE 28.



Pennsylvania Railroad, East River tunnels. Method of tunnelling, rock in bottom.

the opening being formed. This involved much danger to the men attempting it; if the attempt failed and a great outrush of air occurred the men were liable to be drawn into it and disappear in the river bed. Several such cases have occurred in recent years; only one man has escaped after being drawn into the opening.

A very severe blow, one wrecking the face protection, would be followed by an inrush of water and earth, and not only the men in front of the shield but those in the tunnel would be in danger.

It will doubtless be realized from this description that success depended on experience acquired on that work. In the early period progress averaged less than a foot a day for many weeks. In the first tunnel the shield settled a foot below the desired grade in moving a distance of 25 feet; many tunnel castings were broken; the risks constantly met were appalling; a large loss to the contractors seemed impending, and the railroad company's entire terminal project seemed at stake. The sensible course was taken by suspending work in this tunnel, giving the quicksand time to settle together and become compacted, and transferring the working force to other tunnels where the difficulties were somewhat less. Methods were studied and improved from day to day, and when work was resumed in the troublesome tunnel no great trials were encountered. The daily programme increased steadily, and finally became an average of 10 feet per day, month after month, and the contractors made a handsome profit.

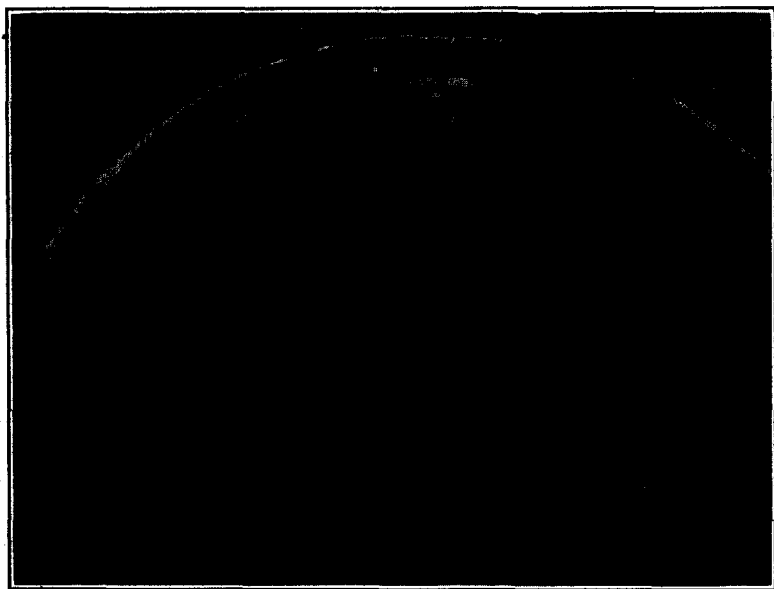
When rock was encountered, percussion air drills were used. Where the excavation was all rock the method finally adopted was to drive a large centre heading 30 feet or more in advance (Plate 26). The bench was also taken out well in advance of the shield. A light track was laid through the shield for the muck cars, and the greater part of excavation was thus kept at some distance from the shields. The drilling for enlargement to full size was done with drills mounted in the forward part of the shield. With these arrangements the average daily programme became about 3 feet.

Where the surface of the rock was a little below the top of the tunnel the heading was smaller and usually became a bottom heading, and in poor rock could not be kept far in advance of

the shield (Plate 27). Where the rock was not high enough to permit driving a heading the rock was all excavated immediately in front of the shield (Plate 28), and the progress was the slowest under this condition. Whenever the rock surface was below the top of the tunnel some form of timbering the earth face above the rock was necessary.

As the shields approached each other from opposite sides of the river some anxiety in regard to the accurate meeting of the two headings was unavoidable.

PLATE 29.



Pennsylvania Railroad, East River tunnels. View in completed tunnel.

As a precautionary measure, the relative positions of the approaching shields were ascertained while they were some 50 or 60 feet apart by pushing a large pipe from the face of one heading to the other, through which line and levels were checked, and accurate meetings of the shields assured. In the four East River tunnels the discrepancies in alignment and levels varied from $\frac{1}{8}$ inch to $\frac{3}{8}$ inch, with an average of $\frac{1}{4}$ inch.

The placing of the concrete lining followed next. The view (Plate 29) shows a tunnel lined with concrete and ready for

track. The trough-like form of section was devised by Mr. A. J. Cassatt, late president of the Pennsylvania Railroad. The width of the trough is about one foot greater than that of the widest Pullman car now in use, and the benches are a few inches below the level of the car windows. It is believed that in case of derailment the train will come to a stop without a shock and passengers may reach the benches readily from the platforms or the windows.

LEAKAGE IN PENNSYLVANIA RAILROAD RIVER TUNNELS.

The cast-iron lining is an effective waterproofing, and, while not absolutely water-tight, the leakage is insignificant. A sump of some form is provided at the lowest point of each tunnel or pair of tunnels and pumped out when necessary by pumps regularly installed. The daily leakage into the $5\frac{1}{2}$ miles of river tunnels of the Pennsylvania Railroad is 2300 gallons. The magnitude of this may be better appreciated by stating that it amounts to one drop per lineal foot of tunnel every 17 seconds, or by stating that the entire amount of leakage for one day would be removed in one or two minutes by a pump of the capacity ordinarily used by contractors for foundations. The pumps provided at the new dry docks at the Brooklyn Navy Yard would remove the day's leakage in about two seconds.

OPERATION.

The tunnels eastward from the station were put in operation for the use of the Long Island Railroad, September 8, 1910; the entire system came into use November 27, 1910, and has continued in service without interruption of any kind.

VENTILATION OF RIVER TUNNELS.

While doubt was entertained as to its necessity, mechanical ventilation was provided for all the tunnels except the Hudson River tunnel, largely as a measure of insurance; if not provided and found required after the tunnels were put in use the resulting loss in traffic might not be recovered for a long time. Experience has shown that the movement of trains, forcing the air ahead, causes an entire change of air in the Pennsylvania Railroad tunnels within a short time, and the fans provided for

ventilation are not used. They may prove useful, however, in the possible occurrence of fire in the tunnel, to remove smoke and facilitate the escape of passengers. Such an occurrence, by reason of the extraordinary precautions taken, is an extremely remote contingency. In the Hudson and Manhattan Railroad tunnels, where the distances between shafts are greater, the fans are used occasionally.

TABLE OF DIMENSIONS AND WEIGHTS OF CAST-IRON TUNNEL LININGS.

Tunnel.	Outside diameter of tube.	Width of ring.	Minimum thickness of metal.	Width of flanges.	Weight per lin. ft. of tunnel, lbs.	
Hudson & Manhattan:						
Uptown:						
Moir's section						
(1889).....	19' 6"	20"	1 1/4"	9"	8,280	
New sec.(1902):						
North tube....	19' 5 1/4"	20 1/4"	1 1/2"	8"	7,565	
South tube....	16' 7"	24"	1 1/8"	8"	5,670	Standard.
South tube....	16' 7"	18"	1 1/8"	8"	6,340	Heavy.
Downtown.....	16' 7"	24"	1 1/8"	8"	5,670	Standard.
South tube....	16' 7"	18"	1 1/8"	8"	6,340	Heavy.
N. Y. City Subway.	16' 8"	22"	1 1/8"	7"	3,992	In rock and above water in earth.
Manhattan to	16' 8 1/2"	22"	1 1/8"	7 1/2"	4,545	Standard.
Brooklyn.....	16' 8 1/2"	22"	1 1/8"	7 1/2"	5,133	In Brooklyn slip.
	16' 8 1/2"	22"	2"	7 1/2"	5,593	Under bulkhead.
Belmont.....	16' 10"	26"	1 1/8"	8"	4,615	
Pennsylvania R. R.:						
North River Div....	23' 0"	30"	1 1/2"	11"	9,609	Standard.
North River Div....	23' 0"	30"	2"	11"	12,127	Heavy.
East River Division.	23' 0"	30"	1"	8"	5,166	Under land; full rock section.
East River Division.	23' 0"	30"	1 1/4"	9"	6,776	Under land; surface of rock between top and centre of tunnel.
East River Division.	23' 0"	30"	1 1/2"	11"	9,102	Standard.

Spectrographic Study of Tellurium. WM. L. DUDLEY and E. V. JONES. (*J. Am. Chem. Soc.*, xxxiv, 995.)—Tellurium, well purified, was converted into the tetra-chloride, and fractionally precipitated by hydrazine hydrochloride. The spectrographs of 20 fractions showed no variations, except that in the last fractions copper lines appeared. On this basis the theory of a higher homologue as an impurity is rejected, and the authors are led to account for the anomaly of the atomic weight of tellurium by the assumption that it is "a mixture of nearly equal parts of substances differing but little in atomic weight and remarkably similar in other properties."