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Paper No. 1159

THE NEW YORK TUNNEL EXTENSION OF THE PENNSYLVANIA RAILROAD.

THE EAST RIVER TUNNELS.[A]

By James H. Brace, Francis Mason, and S. H. Woodard, Members, Am. Soc. C. E.

This paper will be limited to a consideration of the construction of the tunnels, the broader questions of design, etc., having already been considered in papers by Brig.-Gen. Charles W. Raymond, M. Am. Soc. C. E., and Alfred Noble, Past-President, Am. Soc. C. E.

The location of the section of the work to be considered here is shown on Plate XIII of Mr. Noble's paper. There are two permanent shafts on each side of the East River and four single cast-iron tube tunnels, each about 6,000 ft. long, and consisting of 3,900 ft. between shafts under the river, and 2,000 ft. in Long Island City, mostly under the depot and passenger yard of the Long Island Railroad. This tube-tunnel work was naturally a single job. The contract for its construction was let to S. Pearson and Son, Incorporated, ground being broken on May 17th, 1904. Five years later, to a day, the work was finished and received its final inspection for acceptance by the Railroad Company.

The contract was of the profit-sharing type, and required an audit, by the Railroad Company, of the contractor's books, and a careful system of cost-keeping by the Company's engineers, so that it is possible to include in the following some of the unit costs of the work. These are given in two parts: The first is called the unit labor cost, and is the cost of the labor in the tunnel directly chargeable to the thing considered. It does not include the labor of operating the plant, nor watchmen, yardmen, pipemen, and electricians. The second is called "top charges," a common term, but meaning different things to different contractors and engineers. Here, it is made to include the cost of the contractor's staff and roving laborers, such as pipemen, electricians, and yardmen, the cost of the plant and its operation, and all miscellaneous expenses, but does not include any contractor's profit, nor cost of materials entering permanent work.

The contractor's plant is to be described in a paper by Henry Japp,[B] M. Am. Soc. C. E., and will not be dealt with here.

The contractors carried on their work from three different sites. From permanent shafts, located near the river in Manhattan, four shields were driven eastward to about the middle of the river; and, from two similar shafts at the river front in Long Island City, four shields were driven westward to meet those from Manhattan. From a temporary shaft, near East Avenue, Long Island City, the land section of about 2,000 ft. was driven to the river shafts.

Tunnels From East Avenue To the River Shafts.

The sinking of the temporary shaft at East Avenue was a fairly simple matter. Rough 6 by 12-in. sheet-piling, forming a rectangle, 127 by 34 ft., braced across by heavy timbering, was driven about 28 ft. to rock as the excavation progressed. Below this, the shaft was sunk into rock, about 27 ft., without timbering. As soon as the shaft was down, on September 30th, 1904, bottom headings were started westward in Tunnels *A*, *B*, and *D*. When these had been driven about half the distance to the river shafts, soft ground was encountered. (See Station 59, Plate XIII.) As the ground carried considerable water, it was decided to use compressed air. Bulkheads were built in the heading, and, with an air pressure of about 15 lb. per sq. in., the heading was driven through the soft ground and into rock by ordinary mining methods. The use of compressed air was then discontinued. West of this soft ground, a top heading, followed by a bench, was driven to the soft ground at about Station 66. Tunnel *C*, being higher, was more in soft ground, and at first it was [Pg 421] the intention to delay its excavation until it had been well drained by the bottom headings in the tunnels on each side. A little later it was decided to use a shield without compressed air. This shield had been used in excavating the stations of the Great Northern and City Tunnel in London. It was rebuilt, its diameter being changed from 24 ft. 8-1/2 in. to 23 ft. 5-1/4 in. It proved too weak, and after it had flattened about 4 in. and had been jacked up three times, the scheme was abandoned, the shield was removed, and work was continued by the methods which were being used in the other tunnels. The shield was rather light, but probably it would have been strong enough had it been used with compressed air, or had the material passed through been all earth. Here, there was a narrow concrete cradle in the bottom, with rock up to about the middle of the tunnel, which was excavated to clear the shield, and gave no support on its sides. The shield was a cylinder crushed between forces applied along the top and bottom.

With the exception of this trial of a shield in Tunnel *C*, and a novel method in Tunnel *B*, where compressed air, but no shield, was used, the description of the work in one tunnel will do for all.

From the bottom headings break-ups were started at several places in each tunnel where there was ample cover of rock above. Where the roof was in soft ground, top headings were driven from the points of break-up and timbered. As soon as the full-sized excavation was completed, the iron lining was built, usually in short lengths.

It will be noticed on Plate XIII that there is a depression in the rock between Station 65 and the river shafts, leaving all the tunnels in soft ground. As this was directly under the Long Island Railroad passenger station, it was thought best to use a shield and compressed air. This was done in Tunnels *A*, *C*, and *D*, one shield being used successively for all three. It was first erected in Tunnel *D* at Station 64 + 47. From there it was driven westward to the river shaft. It was then taken apart and re-erected in Tunnel *C* at Station 63 + 63 and driven westward to the shaft. It was then found that there would not be time for one shield to do all four lines. The experience in Tunnels *C* and *D* had proven the ground to be much better than had been expected. There was considerable clay in the sand, and, with the water blown out by compressed air, it was very stable. A special timbering method was devised, and Tunnel *B* was driven from Station 66 + 10 to the shaft with compressed air, but without a shield. In the meantime the shield was re-erected in [Pg 422] Tunnel *A* and was shoved through the soft ground from Station 65 + 48 nearly to the river shaft, where it was dismantled.

There was nothing unusual about the shield work; it was about the same as that under the river, which is fully described elsewhere. In spite of great care in excavating in front of the shield, and prompt grouting behind it, there was a small settlement of the building above, amounting to about 1-1/2 in. in the walls and about 5 in. in the ground floors which were of concrete laid like a sidewalk directly upon the ground. Whether this settlement was due to ground lost in the shield work or to a compacting of the ground on account of its being dried out by compressed air, it is impossible to say.

The interesting features of this work from East Avenue to the river shafts are the mining methods and the building of the iron tube without a shield.

Excavation In All Rock.

Where the tunnel was all in good rock two distinct methods were used. The first was the bottom-heading-and-break-up, and the second, the top-heading-and-bench method. The first is illustrated by Figs. 1 and 2, Plate LXIII. The bottom heading, 13 ft. wide and 9 ft. high, having first been driven, a break-up was started by blasting down the rock, forming a chamber the full height of the tunnel. The timber platform, shown in the drawing, was erected in the bottom heading, and extended through the break-up chamber. The plan was then to drill the entire face above the bottom heading and blast it down upon the timber staging, thus maintaining a passage below for the traffic from the heading and break-ups farther down the line. Starting with the condition indicated by Plate XIII, the face was drilled, the columns were then taken down and the muck pile was shoveled through holes in the staging into muck cars below. The face was then blasted down upon the staging, the drill columns were set up on the muck pile, and the operation was repeated. This method has the advantage that the bottom heading can be pushed through rapidly, and from it the tunnel may be attacked at a number of points at one time. It was found to be more expensive than the top-heading-and-bench method, and as soon as the depression in the rock at about Station 59 was passed, a top heading about 7 ft. high, and roughly the segment of a 23-ft. circle, was driven to the next soft ground in each of the four tunnels. The remainder of the [Pg 423] section was taken out in two benches, the first, about 4 ft. high, was kept about 15 ft. ahead of the lower bench, which was about the remaining 11 ft. high.

Excavation in Earth and Rock.

About 2,500 ft. of tunnel, the roof of which was in soft ground, was excavated in normal air by the mining-and-timbering method. In the greater part of this the rock surface was well above the middle of the tunnel. The method of timbering and mining, while well enough known, has not been generally used in the United States.

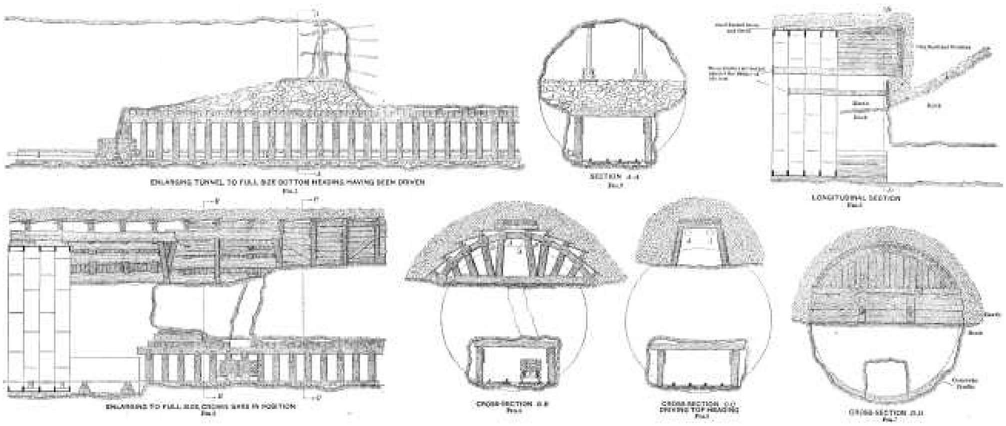

Plate LXIII

Starting from the break-up in all rock, as described above, and illustrated on Plate XIII, when soft ground was approached, a top heading was driven from the rock into and through the earth. This heading was about 7 ft. high and about 6 ft. wide. This was done by the usual post, cap, and poling-board method. The ground was a running sand with little or no clay, and, at first, considerable water, in places. All headings required side polings. The roof poling boards were about 2-1/2 or 3 ft. above the outside limit of the tunnel lining, as illustrated by Figs. 3, 4, and 5, Plate LXIII. The next step was to place two crown-bars, *AA*, usually about 20 ft. long, under the caps. Posts were then placed under the bars, and poling boards at right angles to the axis of the tunnel were then driven out over the bars. As these polings were being driven, the side polings of the original heading were removed, and the earth was mined out to the end of these new transverse polings. Breast boards were set on end under the ends of the transverse polings when they had been driven out to their limit. Side bars, *BB*, were then placed as far out as possible and supported on raking posts. These posts were carried down to rock, if it was near, if not, a sill was placed.

A new set of transverse polings was driven over these side bars and the process was repeated until the sides had been carried down to rock or down to the elevation of the sills supporting the posts, which were usually about 4 ft. above the axis of the tunnel.

The plan then was to excavate the remainder of the section and build the iron lining in short lengths, gradually transferring the weight of the roof bars of the iron lining as the posts were taken out. This meant that not more than four rings, and often only one ring, could be built before excavation and a short length of cradle became necessary. Before the posts under the roof [Pg 424] bars could be built and the weight transferred to the iron lining, a grout dam was placed at the leading end of the iron lining, and grout was brought up to at least 45° from the top. Such workings were in progress at as many as eight places in one tunnel at the same time. Where there was only the ordinary ground-water to contend with, the driving of the top heading drained the ground very thoroughly, and the enlarging was done easily and without a serious loss of ground. Under these conditions the surface settlement was from 6 in. to 2 ft.

Under Borden Avenue, there was more water, which probably came from a leaky sewer; it was not enough to form a stream, but just kept the ground thoroughly saturated. There was a continued though hardly perceptible flow of earth through every crevice in the timbering during the six or eight weeks between the driving of the top heading and the placing of the iron lining; and here there was a settlement of from 4 to 8 ft. at the surface.

When it became evident that there would not be time for one shield to do the soft ground portions of all four tunnels under the Long Island Railroad station, a plan was adopted and used in Tunnel B which, while not as rapid, turned out to be as cheap as the work done by the shields. Figs. 6 and 7, Plate LXIII, and Fig. 1, Plate LXIV, illustrate this work fairly well. The operation of this scheme was about as follows: Having the iron built up to the face of the full-sized excavation, a hole or top heading, about 3 ft. wide and 4 or 5 ft. high, was excavated to about 10 ft. in advance. This was done in a few hours without timbering of any kind; but, as soon as the hole or heading was 10 ft. out, 6 by 12-in. laggings or polings were put up in the roof, with the rear ends resting on the iron lining and the leading ends resting on vertical breast boards. The heading was then widened out rapidly and the lagging was placed, down to about 45° from the crown. The forward ends of the laggings were then supported by a timber rib and sill. Protected by this roof, the full section was excavated, and three rings of the iron lining were built and grouted, and then the whole process was repeated.

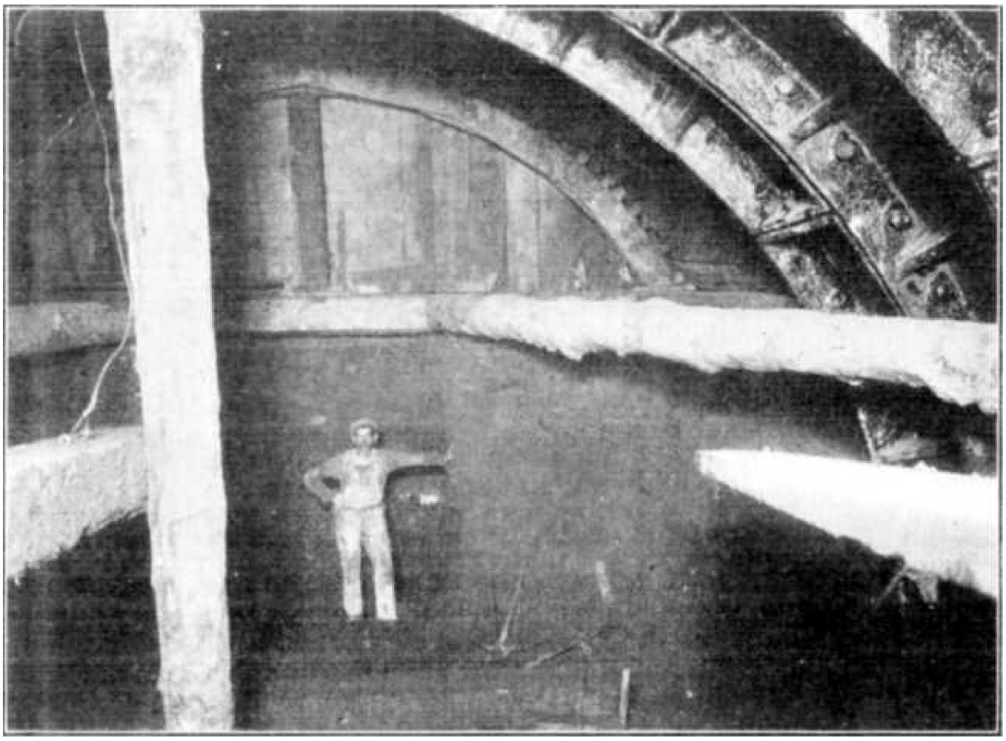

PLATE LXIV, FIG. 1.—TUNNELING IN COMPRESSED AIR WITHOUT SHIELD.

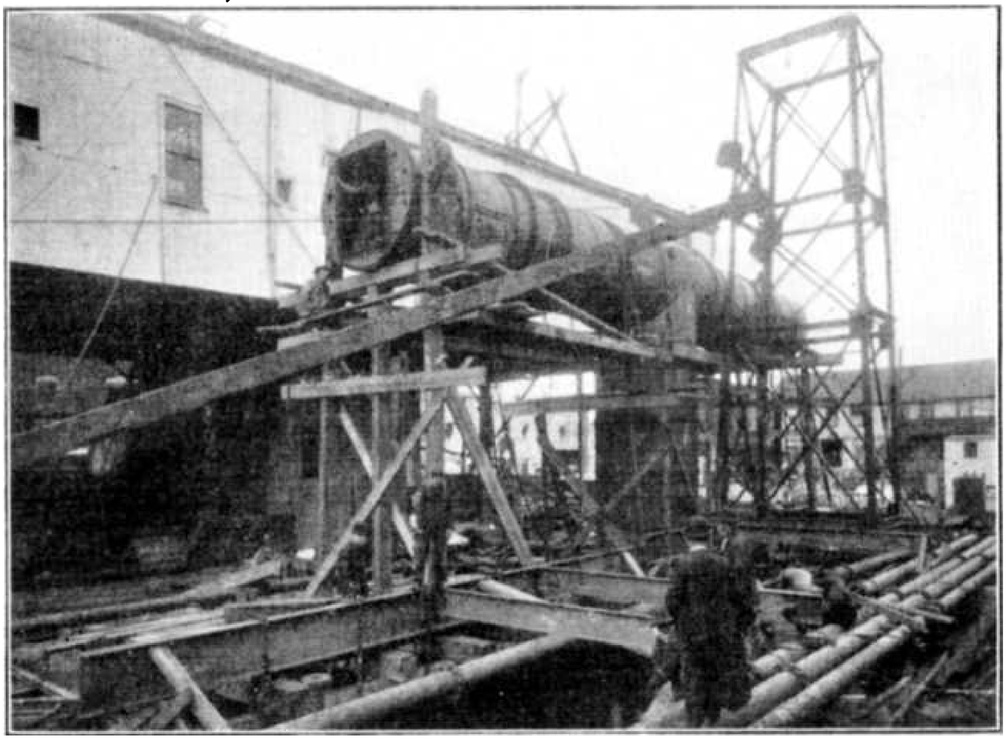

PLATE LXIV, FIG. 2.—T-HEAD AIR-LOCK.

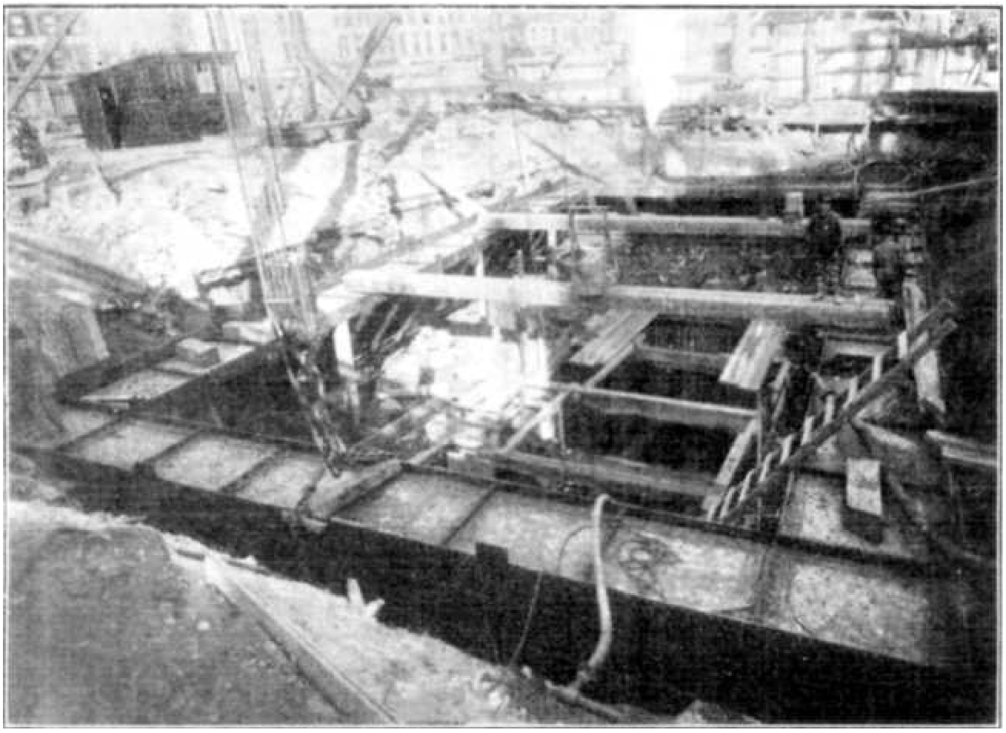

Plate LXIV, Fig. 3.—Cutting Edge of Caisson Assembled.

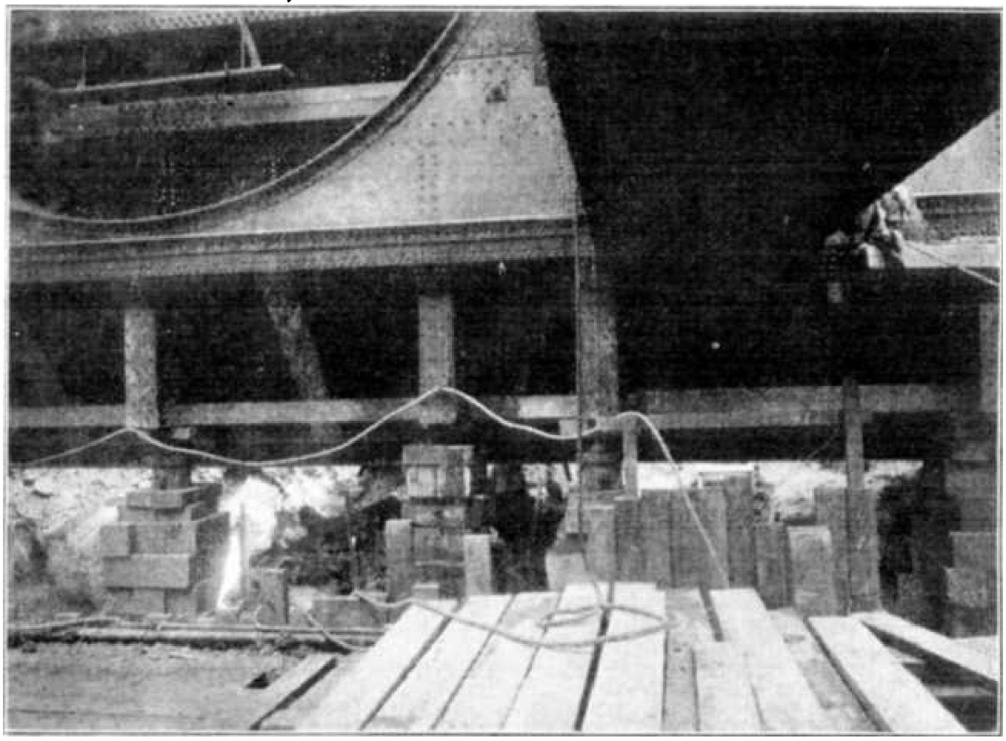

Plate LXIV, Fig. 4.—Caisson Supported on Jacks and Blocks.

Concrete Cradles, Hand-Packed Stone and Grouting.

[Pg 425]

Had the East Avenue Tunnel been built by shields, as was contemplated at the time of its design, the space between the limits of excavation and the iron lining would have been somewhat less than by the method actually used, especially in the earth portions. This space would have been filled with grout ejected through the iron lining. The change in the method of doing the work permitted the use of cheaper material, in place of part of the grout, and, at the same time, facilitated the work.

The tube of cast-iron rings is adapted to be built in the tail of the shield. Where no shield was used, after the excavation was completed and all loose rock was removed, timbers were fixed across the tunnel from which semicircular ribs were hung, below which lagging was placed. The space between this and the rough rock surface was filled with concrete. This formed a cradle in which the iron tube could be erected, and, at the same time, occupied space which would have been filled by grout, at greater cost, had a shield been used.

As soon as each ring of iron was erected, the space between it and the roof of the excavation was filled with hand-packed stone. At about every sixth ring a wall of stone laid in mortar was built between the lining and the rock to serve as a dam to retain grout. The interstices between the hand-packed stones were then filled with 1 to 1 grout of cement and sand, ejected through the iron lining. The concrete cradles averaged 1.05 cu. yd. per ft. of tunnel, and cost, exclusive of materials, $6.70 per cu. yd., of which $2.25 was for labor and $4.45 was for top charges. The hand-packed stone averaged 1-1/2 cu. yd. per ft. of tunnel, and cost $2.42 per cu. yd., of which $0.98 was for labor and $1.44 was for top charges.

Erection of Iron Lining.

The contractors planned to erect the iron lining with erectors of the same pattern as that used on the shield under the river, mounted on a traveling stage. These will be described in detail in Mr. Japp's paper. Two of these stages and erectors worked in each tunnel at different points. The tunnel was attacked from so many points that these erectors could not be moved from working to working. The result was that about 58% of the lining was built by hand. At first thought, this seems to be a crude and extravagant method, as the plates weighed about 1 ton each and about 20,000 were erected by hand. As it turned out, the cost was not greater than for those erected by [Pg 426] machinery, taking into account the cost of erectors and power. This, however, was largely because the hand erection reduced the amount of work to be done by the machines so much that the machines had an undue plant charge.

The hand erection was very simple. A portable hand-winch, with a 3/8-in. wire rope, was set in any convenient place. The wire rope was carried to a snatch-block fastened to the top of the iron previously built; or, where the roof was in soft ground, the timbering furnished points of attachment. The end of the wire rope was then hooked to a bolt hole in a new plate, two men at the winch lifted the plate, and three or four others swung it into approximate place, and, with the aid of bars and drift-pins, coaxed it into position and bolted it. Where there was no timbering above the iron, sometimes the key and adjoining plates were set on blocking on a timber staging and then jacked up to place.

Long Island Shafts.

The river shafts were designed to serve both as working shafts and as permanent openings to the tunnels, and were larger and more substantial than would have been required for construction purposes. Plate X of Mr. Noble's paper shows their design. They consist of two steel caissons, each 40 by 74 ft. in plan, with walls 5 ft. thick filled with concrete. A wall 6 ft. thick separated each shaft into two wells 29 by 30 ft., each directly over a tunnel. Circular openings for the tunnel, 25 ft. in diameter, were provided in the sides of the caissons. During the sinking these were closed by bulkheads of steel plates backed by horizontal steel girders. The shafts were sunk as pneumatic caissons to a depth of 78 ft. below mean high water. There have been a few caissons which were larger and were sunk deeper than these, but most large caissons have been for foundations, such as bridge piers, and have been stopped at or a little below the surface of the rock. The unusual feature of the caissons for the Long Island shaft is that they were sunk 54 ft. through rock.

It had been hoped that the rock would prove sound enough to permit stopping the caissons at or a little below the surface and continuing the excavation without sinking them further; for this reason only the steel for the lower 40 ft. of the caissons was ordered at first.

The roof of the working chamber was placed 7 ft. above the cutting edge. It was a steel floor, [Pg 427] designed by the contractors, and consisted of five steel girders, 6 ft. deep, 29 ft. long, and spaced at 5-ft. centers. Between were plates curved upward to a radius of 4 ft. Each working chamber had two shafts, 3 ft. by 5 ft. in cross-section, with a diaphragm dividing it into two passages, the smaller for men and the larger for muck buckets. On top of these shafts were Moran locks. Mounted on top of the caisson was a 5-ton Wilson crane, which would reach each shaft and also the muck cars standing on tracks on the ground level beside the caissons. Circular steel buckets, 2 ft. 6 in. in diameter and 3 ft. high, were used for handling all muck. These were taken from the bottom of the working chamber, dumped in cars, and returned to the bottom without unhooking. Work was carried on by three 8-hour shifts per day. The earth excavation was done at the rate of about 67 cu. yd. per day from one caisson. The rock excavation, amounting to about 6,200 cu. yd. in each caisson, was done at the rate of about 44.5 cu. yd. per day. The average rate of lowering, when the cutting edge of the south caisson was passing through earth, was 0.7 ft. per day. In rock, the rate was 0.48 ft. per day in the south caisson, and 0.39 ft. per day in the north caisson.

At the beginning all lowering was done with sixteen hydraulic jacks. Temporary brackets were fastened to the outside of the caisson. A 100-ton hydraulic jack was placed under each alternate bracket and under each of the others there was blocking. The jacks were connected to a high-pressure pump in the power-house. As the jacks lifted the caisson, the blocking was set for a lower position, to which the caisson settled as the jacks were exhausted. After the caisson had penetrated the earth about 10 ft., the outside brackets were removed and the lowering was regulated by blocking placed under brackets in the working chamber. The caisson usually rested on three sets of blockings on each side and two on each end. The blocking was about 4 ft. inside the cutting edge. In the rock, as the cutting edge was cleared for a lowering of about 2 ft., 6 by 8-in. oak posts were placed under the cutting-edge angle. When a sufficient number of posts had been placed, the blocking on which the caisson had rested was knocked or blasted out, and the rock underneath was excavated. The blocking was then re-set at a lower elevation. The posts under the cutting edge were then chopped part way through and the air pressure was lowered about 10 lb., which increased the net weight to more than 4,000,000 lb. The posts then gradually [Pg 428] crushed and the caissons settled to the new blocking. The tilt or level of the caisson was controlled by chopping the posts more on the side which was desired to move first.

The caisson nearly always carried a very large net weight, usually about 870 tons. The concrete in the walls, which was added as the caisson was being sunk, was kept at about the elevation of the ground. There was generally a depth of from 5 to 20 ft. of water ballast on top of the roof of the working chamber. The air pressure in the working chamber was usually much less than the hydrostatic head outside the caisson. For example, the average air pressure in the south caisson during January, 1906, was 16-1/2 lb., while the average head was 62.5 ft., equivalent to 27 lb. per sq. in. Under these conditions, there was a continued but small leakage into the caisson of from 15,000 to 20,000 gal. per day.

In the rock the excavation was always carried from 2 to 5 in. outside the cutting edge. As soon as the cutting edge was cleared, bags of clay were placed under it in a well-tiered, solid pile, so that when the caisson was lowered the bags were cut through and most of the clay, bags and all, was squeezed back of the cutting edge between the rock and the caisson.

Table 1 shows the relation of the final position of the caissons to that designed.

The cost of rock excavation in the caisson was $4.48 per cu. yd. for labor and $10.54 for top charges.

The bottom of the shaft is an inverted concrete arch, 4 ft. thick, water-proofed with 6-ply felt and pitch. As soon as the caisson was down to its final position and the excavation was completed, concrete was deposited on the uneven rock surfaces, brought up to the line of the water-proofing, and given a smooth 1-in. mortar coat. The felt was stuck together in 3-ply mats on the surface with hot coal-tar pitch. These were rolled and sent down into the working chamber, where they were put down with cold pitch liquid at 60° Fahr. Each sheet of felt overlapped the one below 6 in. The water-proofing was covered by a 1-in. mortar plaster coat, after which the concrete of the 4-ft. inverted arch was placed. While the water-proofing and concreting were being done, the air pressure was kept at from 30 to 33 lb. per sq. in., the full hydrostatic head at the cutting edge. After standing for ten days, the air pressure was taken off, and the removal of the roof of the working chamber was begun. The water-proofing was done by the Union Construction and Waterproofing Company.

TABLE 1.—Relation of the Final Position of the Caissons to That Designed.

Location.	Long Island City.					
Shaft.	North.			South.		
Corner.	High.	East.	North.	High.	East.	North.
Northeast	0.21 ft.	0.08 ft.	0.05 ft.	0.32 ft.	0.15 ft.	0.28 ft.
Northwest	0.22 "	0.08 "	0.02 "	0.00 "	0.15 "	0.12 "
Southwest	0.27 "	0.14 "	0.02 "	0.18 "	0.45 "	0.12 "
Southeast	0.23 "	0.14 "	0.05 "	0.39 "	0.45 "	0.28 "

Location.	Manhattan.					
Shaft.	North.			South.		
Corner.	High.	East.	South.	High.	East or West.	North or South.
Northeast	0.23 ft.	0.74 ft.	0.38 ft.	0.00 ft.	0.06 ft. east.	0.04 ft. south.
Northwest	0.00 "	0.74 "	0.22 "	0.08 "	0.06 " "	0.13 " north.
Southwest	0.11 "	0.31 "	0.22 "	0.21 "	0.45 " west.	0.13 " "
Southeast	0.46 "	0.31 "	0.38 "	0.04 "	0.45 " "	0.04 " south.

The cost of labor in compressed air chargeable to concreting was $3.40 per cu. yd.

After the roof of each working chamber had been removed, the shield was erected on a timber cradle in the bottom of the shaft, in position to be shoved out of the opening in the west side of the caisson. Temporary rings of iron lining were erected across the shaft in order to furnish something for the shield jacks to shove against.

The roof of the working chamber was then re-erected about 35 ft. above its original position and about 8 ft. above the tunnel openings. This time, instead of the two small shafts which were in use during the sinking of the caisson, a large steel shaft with a T-head lock was built. This is illustrated in Fig. 2, Plate LXIV. The shaft was 8 ft. in diameter. Inside there was a ladder and an elevator cage for lowering and hoisting men and the standard 1-yd. tunnel cars. At the top, forming the head of the T, there were two standard tunnel locks.

Manhattan Shafts.

A permanent shaft, similar to the river shafts in Long Island City, was constructed at Manhattan over each pair of tunnels. Each shaft was located across two lines, with its longer axis transverse to the tunnels. Plate XIII shows their relative positions. They were divided equally by a reinforced concrete partition wall transverse to the line of the tunnels. On completion, the western portions were turned over to the contractor for the cross-town tunnels for his exclusive use.

South Shaft.—Work on the south shaft was started on June 9th, 1904, with the sinking of a 16 by 16-ft. test pit in the center of the south half of the south shaft, which reached disintegrated rock at a depth of about 20 ft.

Starting in August, the full shaft area, 74 by 40 ft., was taken out in an open untimbered cut to the rock, and a 20 by 50-ft. shaft was sunk through the rock to tunnel grade, leaving a 10 or 12-ft. berm around it. (Fig. 1, Plate LXX.)

The erection of the caisson was started, about the middle of January, on the rock berm surrounding the 20 by 50-ft. shaft and about 15 ft. below the surface. Fig. 3, Plate LXIV, shows [Pg 431] the cutting edge of the caisson assembled. The excavation of the small shaft had shown that hard rock and only a very small quantity of water would be encountered, and that the caisson need be sunk only a short distance below the rock surface. Therefore, no working-chamber roof was provided, the caisson was built to a height of only 40 ft., and the circular openings were permanently closed.

The assembling of the caisson took 2-1/2 months, and on April 2d lowering was started. Inverted brackets were bolted temporarily to the cutting-edge stiffening brackets, and the sinking was carried on by methods similar to those used at Long Island. The jacks and blocking supporting the caisson are shown in Fig. 4, Plate LXIV. As soon as the cutting edge entered the rock, which was drilled about 6 in. outside of the neat lines, the space surrounding the caisson was back-filled with clay and muck to steady it and provide skin friction. As the friction increased, the walls were filled with concrete, and as the caisson slowly settled, it was checked and guided by blocking. The cutting edge finally came to rest 31 ft. below mean high water, the sinking having been accomplished in about seven weeks, at an average rate of 0.50 ft. per day.

The final position of the cutting edge in relation to its designed position is shown in Table 1.

A berm about 4 ft. wide was left at the foot of the caisson below which the rock was somewhat fissured and required timbering. The cutting edge of the caisson was sealed to the rock with grout on the outside and a concrete base to the caisson walls on the inside, the latter resting on the 4-ft. berm. Following the completion of the shaft, the permanent sump was excavated to grade for use during construction.

North Shaft.—The north shaft had to be sunk in a very restricted area. The east side of the caisson cleared an adjoining building at one point by only 1 ft., while the northwest corner was within the same distance of the east line of First Avenue. As in the case of the Long Island shafts, the steelwork for only the lower 40 ft. was ordered at the start. This height was completely assembled before sinking was begun. The caisson was lowered in about the same manner as those previously described. The bearing brackets for the hydraulic jacks were attached, as at the south shaft, to the inside of the cutting-edge brackets. The east side of the caisson was in contact with the foundations of the neighboring building, while the west side was in much softer [Pg 432] material. As a consequence, the west side tended to settle more rapidly and thus throw the caisson out of level and position. To counteract that tendency, it was necessary to load the east wall heavily with cast-iron tunnel sections, in addition to the concrete filling in the walls.

Soon after sinking was begun, a small test shaft was sunk to a point below the elevation of the top of the tunnels. The rock was found to be sound, hard, and nearly dry. It was then decided to stop the caisson as soon as a foundation could be secured on sound rock. The latter was found at a depth of 38 ft. below mean high water. With the cutting edge seated at that depth, the top of the caisson was only 2 ft. above mean high water, and as this was insufficient protection against high tides, a 10-ft. extension was ordered for the top. Work, however, went on without delay on the remainder of the excavation. The junction between the cutting edge and the rock was sealed with concrete and grout. The caisson was lowered at an average rate of 0.53 ft. per day. The size of the shaft below the cutting edge was 62 ft. 7 in. by 32 ft. The average rate of excavation during the sinking in soft material was 84 cu. yd. per day. The average rate of rock excavation below the final position of the cutting edge was 125 cu. yd. per day. There were night and day shifts, each working 10 hours. Excavation in earth cost $3.96 per cu. yd., of which $1.45 was for labor and $2.51 for top charges, etc. The excavation of rock cost $8.93 per cu. yd., $2.83 being for labor and $6.10 for top charges.

The final elevations of the four corners of the cutting edge, together with their displacement from the desired positions, are shown in Table 1.

River Tunnels.

The four river tunnels, between the Manhattan and Long Island City shafts, a distance of about 3,900 ft., were constructed by the shield method. Eight shields were erected, one on each line in each shaft, the four from Manhattan working eastward to a junction near the middle of the river with the four working westward from Long Island City. Toward the end of the work it was evident that the shields in Tunnels *B*, *C*, and *D* would meet in the soft material a short distance east of the Blackwell's Island Reef if work were continued in all headings. In order that the junction might be made in firm material, work from Manhattan in those three tunnels was suspended [Pg 433] when the shields reached the edge of the ledge. The shields in Tunnel *A* met at a corresponding point without the suspension of work in either. An average of 1,760 ft. of tunnel was driven from Manhattan and 2,142 ft. from Long Island City.

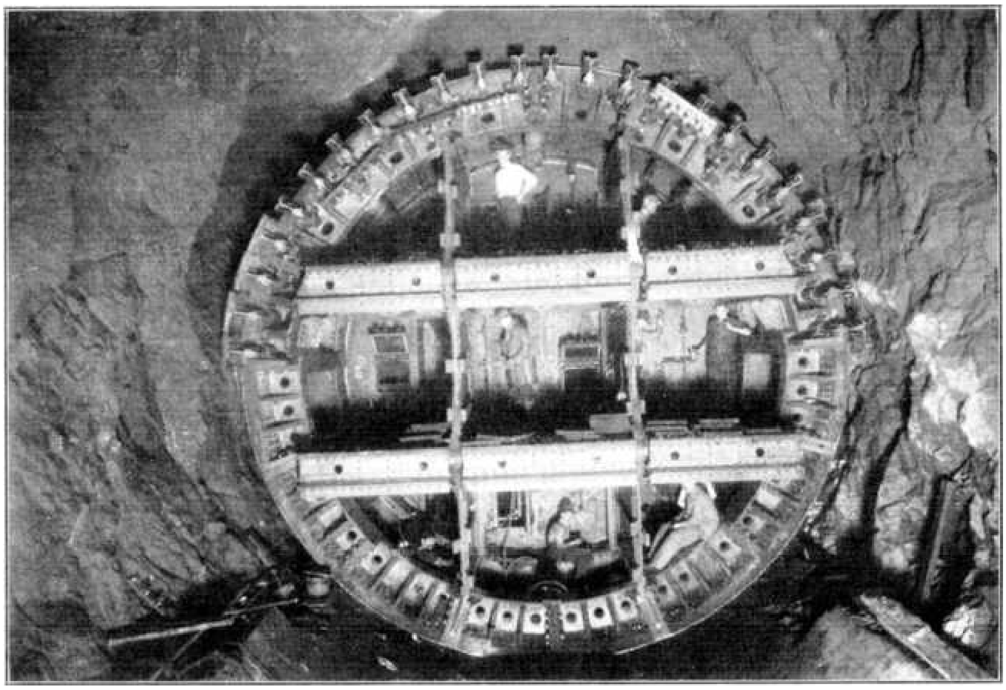

Plate LXV, Fig. 1.—Shield Fitted with Sectional Sliding Hoods and Sliding Extensions to the Floors.

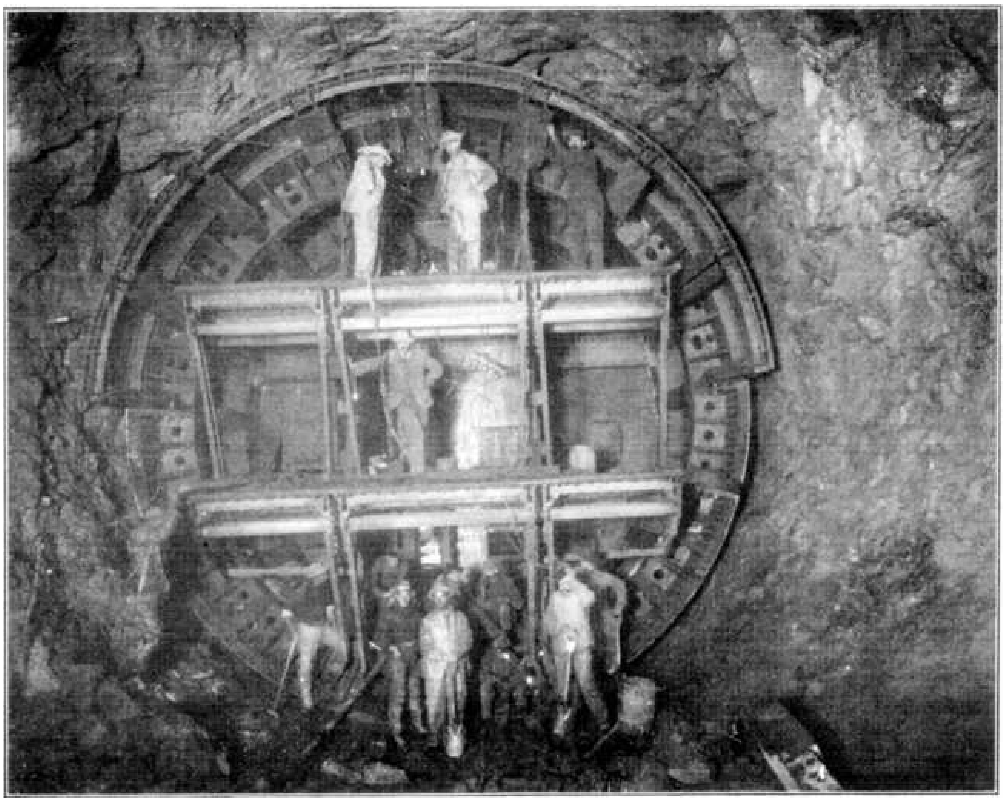

Plate LXV, Fig. 2.—Shield Fitted with Fixed Hoods and Fixed Extensions to the Floors.

Tunnels Driven Eastward from Manhattan.

Materials and Inception of Work.—The materials encountered are shown in the profile on Plate XIII, and were similar in all the tunnels. In general, they were found to be about as indicated in the preliminary borings. The materials met in Tunnel *A* may be taken as typical of all.

From the Manhattan shaft eastward, in succession, there were 123 ft. of all-rock section, 87 ft. of part earth and part rock, 723 ft. of all earth, 515 ft. of part rock and part earth, 291 ft. of all rock, and 56 ft. of part rock and part earth.

The rock on the Manhattan side was Hudson schist, while that in the reef was Fordham gneiss. Here, as elsewhere, they resembled each other closely; the gneiss was slightly the harder, but both were badly seamed and fissured. Wherever it was encountered in this work, the rock surface was covered by a deposit of boulders, gravel, and sand, varying in thickness from 4 to 10 ft. and averaging about 6 ft.

The slope of the surface of the ledge on the Manhattan side averaged about 1 vertical to 4 horizontal. The rock near the surface was full of disintegrated seams, and was badly broken up. It was irregularly stratified, and dipped toward the west at an angle of about 60 degrees. Large pieces frequently broke from the face and slid into the shield, often exposing the sand. The rock surface was very irregular, and was covered with boulders and detached masses of rock embedded in coarse sand and gravel. The sand and gravel allowed the air to escape freely. By the time the shields had entirely cleared the rock, the material in the face had changed to a fine sand, stratified every few inches by very thin layers of chocolate-colored clayey material. This is the material elsewhere referred to as quicksand. As the shield advanced eastward, the number and thickness of the layers of clay increased until the clay formed at least 20% of the entire mass, and many of the layers were 2 in. thick.

At a distance of about 440 ft. beyond the Manhattan ledge, the material at the bottom of the face changed suddenly to one in which the layers of clay composed probably 98% of the whole. The sand layers were not more than 1/16 in. thick and averaged about 2 in. apart. The surface of the clay rose gradually for a distance of 40 ft. in Tunnels *A* and *B*, and 100 ft. in Tunnels *C* and *D*, when gravel and boulders appeared at the bottom of the shield. At that time the clay composed about one-half of the face.

The surfaces of both the clay and gravel were irregular, but they rose gradually. After rock was encountered, the formations of gravel and clay were roughly parallel to the rock surface.

As the surface of the rock rose they disappeared in order and were again encountered when the shields broke out of rock on the east side of the Blackwell's Island Reef. East of the reef a large quantity of coarse open sand was present in the gravel formations before the clay appeared below the top of the cutting edge. In Tunnels *C* and *D* this was especially difficult to handle. It appears to be a reasonable assumption that the layer of clay was continuous across the reef. Wherever the clay extended above the top of the shield it reduced the escape of air materially. It is doubtless largely due to this circumstance that the part-rock sections in the reef were not the most difficult portions of the work.

While sinking the lower portions of the shafts the tunnels were excavated eastward in the solid rock for a distance of about 60 ft., where the rock at the top was found to be somewhat disintegrated. This was as far as it was considered prudent to go with the full-sized section without air pressure. At about the same time top headings were excavated westward from the shafts for a distance of 100 ft., and the headings were enlarged to full size for 50 ft. The object was to avoid damage to the shaft and interference with the river tunnel when work was started by the contractor for the cross-town tunnel.

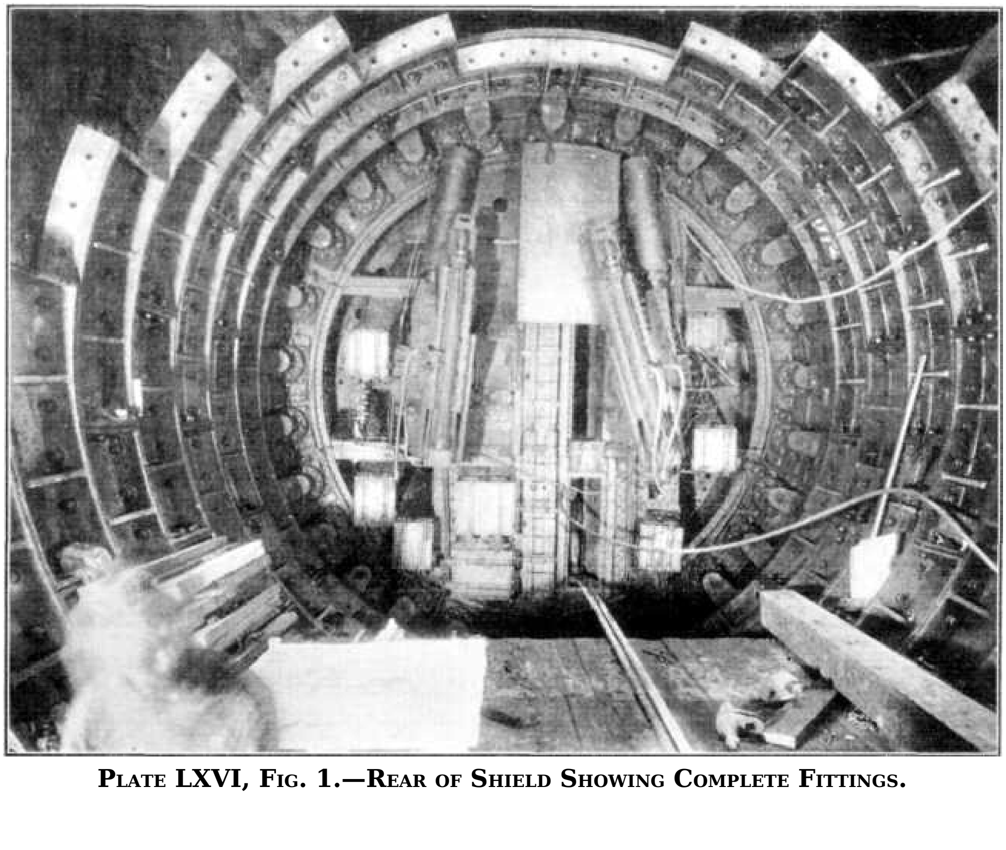

Plate LXVI, Fig. 1.—Rear of Shield Showing Complete Fittings.

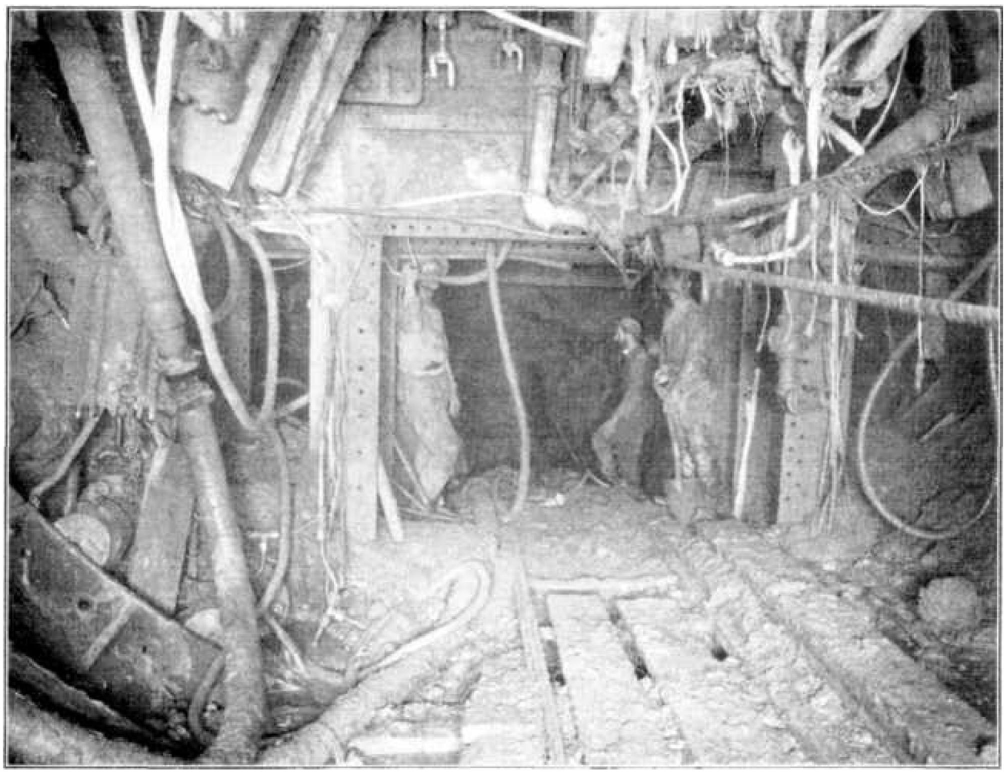

Plate LXVI, Fig. 2.—Shield with Lower Portion of Bulkhead Removed.

The shields were erected on timber cradles in the shaft, and were shoved forward to the face of the excavation. Concrete bulkheads, with the necessary air-locks, were then built across the tunnels behind the shields. The shields were erected before the dividing walls between the two contracts were placed. Rings of iron tunnel lining, backed by timbers spanning the openings on the west side, were erected temporarily across the shafts in order to afford a bearing for the shield jacks while shoving into the portals. The movement of the shield eastward was continued in each tunnel for a distance of about 60 ft., and the permanent cast-iron tunnel lining was erected as the shield advanced. Before breaking out of rock, it was necessary to have air pressure in the tunnels. This required the building of bulkheads with air-locks inside the cast-iron linings just east of the portals. Before erecting the bulkheads it was necessary to close the annular space between the iron tunnel lining and the rock. The space at the portal was filled with a concrete wall. After about twenty permanent rings had been erected in each tunnel, two rings were pulled apart at the tail of the shield and a second masonry wall or dam was built. The space between the two dams was then filled with grout. To avoid the possibility of pushing the iron backward after the air pressure was on, rings of segmental plates, 5/8 in. thick and 13-7/8 in. wide, were inserted in eighteen circumferential joints in each tunnel between the rings as they were erected. The plates contained slotted holes to match those in the segments. After the rings left the shield, the plates were driven outward, and projected about 5 in. When the tunnel was grouted, the plates were embedded.

The bulkheads were completed, and the tunnels were put under air pressure on the following dates:

Line *D*, on October 5th, 1905;
Line *C*, on November 6th, 1905;
Line *B*, on November 25th, 1905;
Line *A*, on December 1st, 1905.

This marked the end of the preparatory period.

In the deepest part of the river, near the pier-head line on the Manhattan side, there was only 8 ft. of natural cover over the tops of the tunnels. This cover consisted of the fine sand previously described, and it was certain that the air would escape freely from the tunnels through it. To give a greater depth of cover and to check the loss of air, the contractor prepared to cover the lines of the tunnels with blankets of clay, which, however, had been provided for in the specifications. Permits, as described later, were obtained at different times from the Secretary of War, for dumping clay in varying thicknesses over the line of work. The dumping for the blanket allowed under the first permit was completed in February, 1906. The thickness of this blanket varied considerably, but averaged 10 or 12 ft. on the Manhattan side. The original blanket was of material advantage, but the depth of clay was insufficient to stop the loss of air.

The essential parts of the shields in the four tunnels were exactly alike. Those in Tunnels *B* and *D*, however, were originally fitted with sectional sliding hoods and sliding extensions to the floors of the working chambers, as shown by Fig. 1, Plate LXV. The shields in Tunnels *A* and *C* were originally fitted with fixed hoods and fixed extensions to the floors, as shown in Fig. 2, Plate LXV. A full description of the shields will be found in Mr. Japp's paper.

The shields in each pair of tunnels were advanced through the solid rock section about abreast of each other, until test holes from the faces indicated soft ground within a few feet. As the distance between the sides of the two tunnels was only 14 ft., it was thought best to let Tunnels *B* and *D* gain a lead of about 100 ft. before Tunnels *A* and *C* opened out into soft ground, in order that a blow from one tunnel might not extend to the other. Work in Tunnel *C* was shut down on December 23d, 1905, after exposing sand to a depth of 3 ft. at the top, and it remained closed for seven weeks. Work in Tunnel *A* was suspended on September 29th, 1905. By the time Tunnel *B* had made the required advance, it, together with Tunnels *C* and *D*, was overtaxing the capacities of the compressor plant. Only a little work was done in Tunnel *C* until July, 1906, and work in Tunnel *A* was not resumed until October 22d, 1906.

Tunnels Driven Westward from Long Island City.

Materials and Inception of the Work.—The materials met in Tunnel A are typical of all four tunnels. From the Long Island shafts westward, in succession, there were 124 ft. of all-rock section, 125 ft. of part rock and part earth section, 22 ft. of all-rock section, 56 ft. of part rock and part earth section, 387 ft. of all-rock section, 70 ft. of part earth and part rock section, and 1,333 ft. of all-earth section.

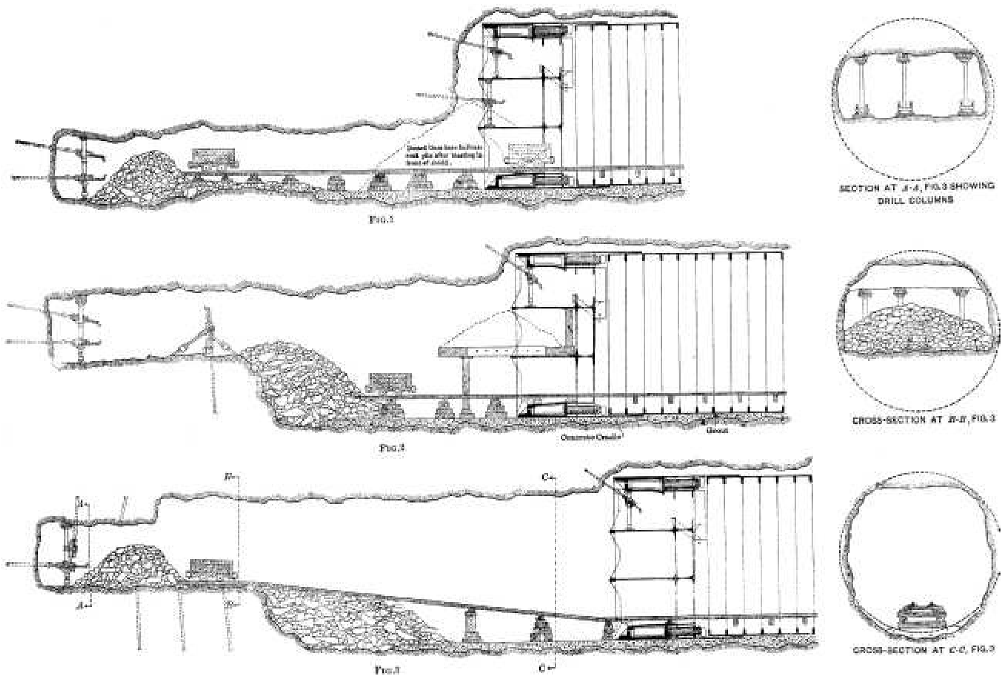

Plate LXVII

The materials passed through are indicated on Plate XIII. The rock was similar to that of the Blackwell's Island Reef, and was likewise covered by a layer of sand and boulders. The remainder of the soft ground was divided into three classes. The first was a very fine red sand, which occurred in a layer varying in thickness from 6 ft. to at least 15 ft. It may have been much deeper above the tunnel. It is the quicksand usually encountered in all deep foundations in New York City. The following is the result of the sifting test of this sand:

[Pg 437]

		Held on	No. 30	sieve	0.6%
Passed	No. 30,	" "	No. 40	"	0.4%
"	No. 40,	" "	No. 50	"	0.7%
"	No. 50,	" "	No. 60	"	2.4%
"	No. 60,	" "	No. 80	"	14.9%
"	No. 80,	" "	No. 100	"	54.0%
"	No. 100,	" "	No. 200	"	8.0%
"	No. 200			"	19.0%
					100.0%

This means that grains of all but 4% of it were less than 0.0071 in. in diameter. The 19% which passed the No. 200 sieve, the grains of which were 0.0026 in. or less in diameter, when observed with a microscope appeared to be perfectly clean grains of quartz; to the eye it looked like ordinary building sand, sharp, and well graded from large to small grains. This sand, with a surplus of water, was quick. With the water blown out of it by air pressure, it is stable, stands up well, and is very easy to work. It appears to be the same as the reddish quicksand found in most deep excavations around New York City.

The second material was pronounced "bull's liver" by the miners as soon as it was uncovered. "Bull's liver" seems to be a common term among English-speaking miners the world over. It is doubtful, however, if it is always applied to the same thing. In this case it consisted of layers of blue clay and very fine red sand. The clay seemed to be perfectly pure and entirely free from sand. It would break easily with a clean, almost crystalline, fracture, and yet it was soft and would work up easily. The layers of clay varied in thickness from 1/16 in. to 1 in., while the thickness of the sand layer varied from 1/4 in. to several inches. The sand was the same as the quicksand already described.

The "bull's liver" was ideal material in which to work a shield. It stood up as well and held the air about as well as clay, and was much easier to handle.

The third material was a layer of fine gray sand which was encountered in the top of all the tunnels for about 400 ft. just east of Blackwell's Island Reef. It was very open, and had grains of rather uniform size.

[Pg 438] During the starting out of the tunnels from the shafts, and for more than a year afterward, the roof of the working chamber in the caissons and the locks previously described under the Long Island shafts took the place of the bulkhead across the tunnels for confining the air pressure.

The first work in air pressure was to remove the shield plug closing the opening in the side of the shaft. This being done, the shield was shoved through the opening, and excavation begun.

At the start the shields were fitted with movable platforms, but no hoods of any kind were placed until after the rock excavation was completed.

Methods of Excavation.

The distribution of materials to be excavated, as previously outlined, divided the excavation into three distinct classes, for which different methods had to be developed.

These three classes were:

First.—All-rock section.
Second.—Rock in the bottom, earth in the top.
Third.—All-earth section.

The extent of the second and third classes was much greater than that of the first, and they, of course, determined the use of the shield. Shields had not previously been used extensively in rock work, either where the face was wholly or partly in rock, and it was necessary to develop the methods by experience. The specifications required that where rock was present in the bottom, a bed of concrete should be laid in the form of a cradle on which to advance the shield.

All Rock.—At different times, three general methods were used for excavating in all-rock sections. They may be called: The bottom-heading method; the full-face method; and the center-heading method.

The bottom-heading method was first tried. A heading, about 8 ft. high and 12 ft. wide, was driven on the center line, with its bottom as nearly as possible on the grade line of the bottom of the tunnel. It was drilled in the ordinary manner by four drills mounted on two columns. The face of the headings varied from 10 to 30 ft. in advance of the cutting edge. After driving the heading for about 10 ft., the bottom was cleared out and a concrete cradle was set. The width of the cradles varied, but was generally from 8 to 10 ft.

[Pg 439] The excavation was enlarged to full size as the shield advanced, the drills being mounted in the forward compartments of the shield, as shown by Fig. 1, Plate LXVII, which represents the conditions after the opening had been cut in the bulkhead, but before the new methods, mentioned later, had been developed.

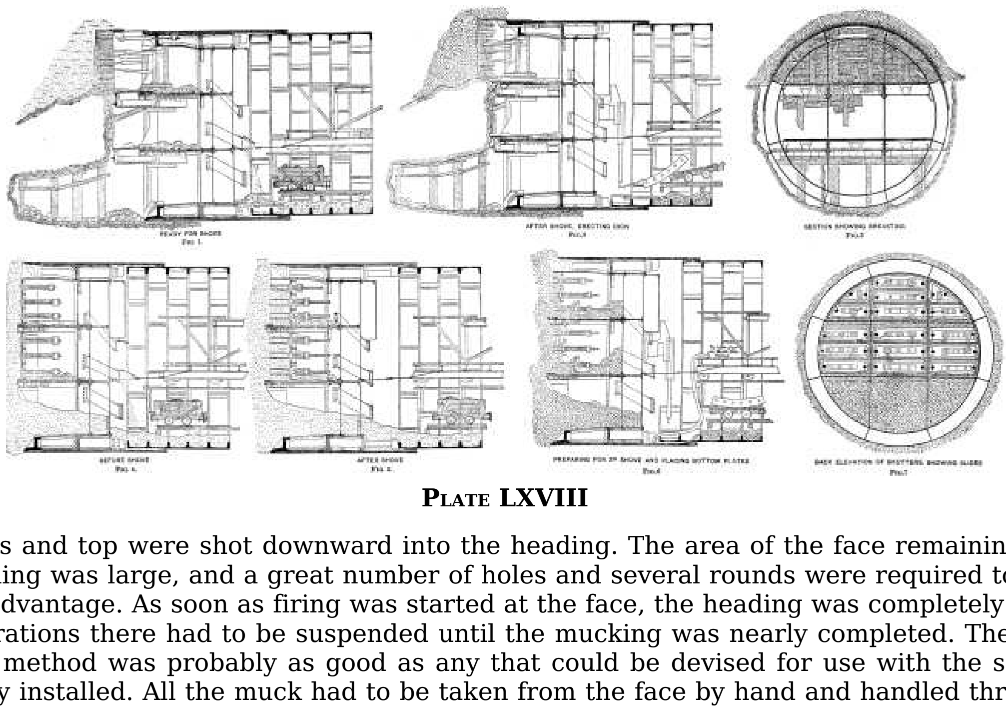

Plate LXVIII

The sides and top were shot downward into the heading. The area of the face remaining behind the heading was large, and a great number of holes and several rounds were required to fire the face to advantage. As soon as firing was started at the face, the heading was completely blocked, and operations there had to be suspended until the mucking was nearly completed. The bottom-heading method was probably as good as any that could be devised for use with the shields as originally installed. All the muck had to be taken from the face by hand and handled through the chutes or doors. By drilling from the shield, some muck was blasted on to the extensions of the floors and could be handled from the upper compartments. At best, however, the shield with the closed transverse bulkhead was a serious obstacle to rapid work in rock sections.

The full-face method was only used where the rock was not considered safe for a heading. A cut was fired at the bottom, together with side holes, in a manner quite similar to that adopted in the first set of holes for a bottom heading. The cradle was then placed, in lengths of either 2.5 or 5 ft., after which the remainder of the face was fired in the same manner as for the bottom-heading method. The closed transverse bulkhead with air-locks, as shown in Fig. 1, Plate LXVI, was placed in the shield in the hope that it would only be necessary to maintain the full air pressure in the working compartments in front of the bulkhead. It was also thought that some form of bulkhead which could be closed quickly and tightly would be necessary to prevent flooding the tunnel in case of blows. While no attempt was ever made to reduce the pressure behind the shield bulkhead, it was obvious from the experience with Tunnels *B* and *D,* while working in the sand between Manhattan and the reef, that the plan was not practicable, and that the closed bulkhead in the bottom was a hindrance instead of a safeguard. As soon as rock was encountered in those tunnels at the west edge of the reef, the contractor cut through the bulkheads and altered them, as shown in Fig. 2, Plate LXVI.

Taking advantage of the experience gained, openings were cut through the bulkheads in Shields *A* and *C*, while they were shut down near the edge of the Manhattan ledge. In erecting the [Pg 440] shields at Long Island City in May and June, 1906, openings were also provided. These shields had to pass through about 700 ft. of rock at the start, the greater portion of which was all-rock section. It was at that point that openings were first used extensively and methods were developed, which would not have been possible except where ears could be passed through the shield. The bottom-heading method was first tried, but the working space in front of the shield was cramped, and but few men could be employed in loading the cars. To give more room, the heading was gradually widened. The enlargement at the top, when made from the shield, blocked all work at the face of the heading while the former operation was in progress. To reduce the delays, the heading was raised, thus reducing the quantity of rock left in the top, and the bottom was taken out as a bench. To avoid blocking the tracks when firing the top, a heavy timber platform was built out from the floors of the middle working compartments. Most of the muck from the top was caught on the platform and dropped into cars below. This method of working is shown by Fig. 2, Plate LXVII. The platforms were not entirely satisfactory, and, later, the drills in the heading were turned upward and a top bench was also drilled and fired, as shown by Fig. 3, Plate LXVII. There was then so little excavation left in the top that the muck was allowed to fall on the tracks and was quickly cleared away. The method just outlined is called the center-heading method, and was the most satisfactory plan devised for full-rock sections.

Excavation in Part Rock and Part Earth.—This was probably the most difficult work encountered, particularly when the rock was covered with boulders and coarse sharp sand which permitted a free escape of air. It was necessary, before removing the rock immediately under the soft ground, to excavate the earth in advance of the shield to a point beyond where the rock was to be disturbed, and to support, in some way, the roof, sides, and face of the opening thus made. The hoods were designed mainly for the purpose of supporting the roof and the sides. With the fixed hood it was necessary either to excavate for the distance of the desired shove in front of it or else to force the hood into the undisturbed material. To avoid this difficulty, the sliding hoods were tried as an experiment.

In using the sliding hood, which will be described in detail in Mr. Japp's paper, the segments [Pg 441] commencing at the top were forced forward by the screw rod, one at a time, as far as possible into the undisturbed material. Just enough material was then removed from underneath and in front of the section to free it, and it was again forced forward. These operations were repeated until the section had been extended far enough for a shove. As soon as two or three sections had been pushed forward in this way, the face near the advance end of the sliding hood was protected by a breast board set on edge and braced from the face. Gradually, all the segments were worked forward, and, at the same time, the whole soft ground face was sheeted with timber. At times polings were placed over the extended segments in order to make room for a second shove, as shown on Plate LXVIII. When the shield was advanced the nuts on the screw rods were loosened and the sections of the hoods were telescoped on to the shield. The idea was ingenious, but proved impracticable, because of the unequal relative movements of the top and bottom of the shield in shoving, bringing transverse strains on the hood sections.

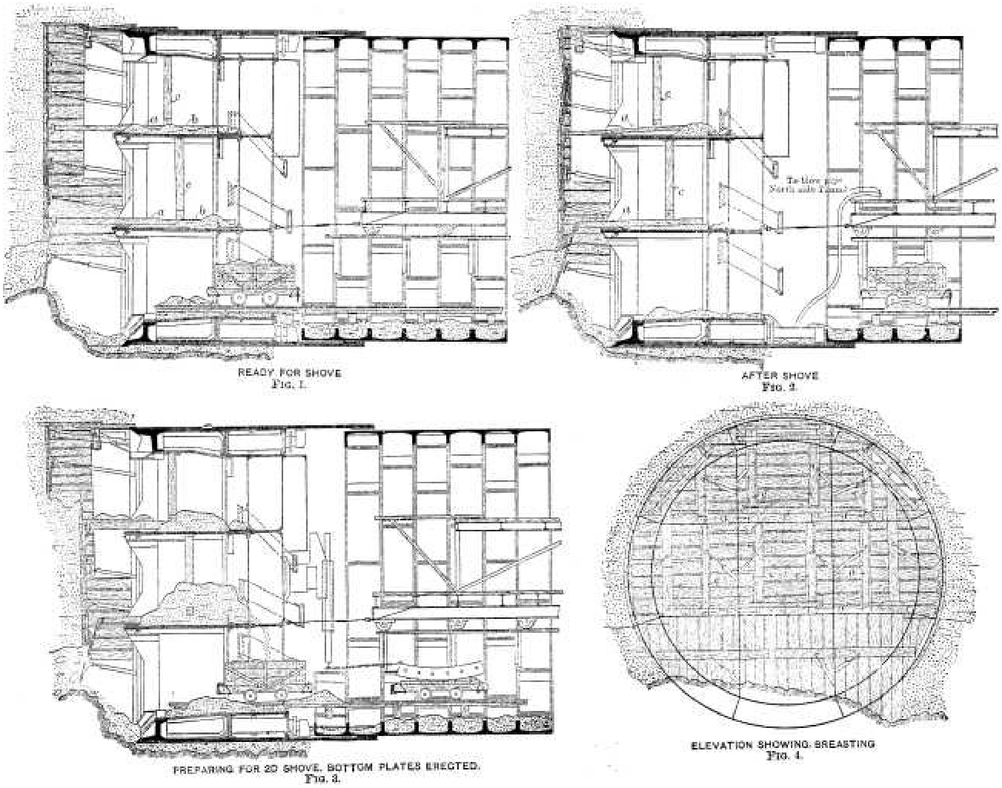

Plate LXIX

With the fixed hood, poling boards were used to support the roof and sides, and the face was supported in the manner described for the sliding hoods. The polings were usually maple or oak planks, 2 in. thick, about 8 in. wide, and 6-1/2 ft. long. In advancing the face, the top board of the old breast was first removed, then the material was carefully worked out for the length of the poling. The latter was then placed, with the rear end resting over the hood and the forward end forced as far as possible into the undisturbed material. When two or three polings had been placed, a breast board was set. After several polings were in position, their forward ends were supported by some form a cantilever attached to the hood. Plate LXIX shows one kind of supports. In this way all the soft material was excavated down to the rock surface, and the roof, sides, and face were sheeted with timber. In shoving, the polings in the roof and sides were lost. It was found that the breast could usually be advanced 5 ft. with safety. The fixed hood made it possible to set the face about 7 or 8 ft. in front of the cutting edge without increasing the length of the polings. This distance was ample for two shoves, and was generally adopted, although a great many faces were set for one shove only.

Fixed hoods were substituted for those of the sliding type, originally placed on Shields *B* and *D* at
[Pg 442] Manhattan, at about the time the latter encountered the rock at the reef.

In placing the polings and breasting, all voids behind them were filled as far as possible with marsh hay or bags of sawdust or clay. To prevent loss of air in open material, the joints between the boards were plastered with clay especially prepared for the purpose in a pug mill. The sliding extensions to the floors of the working compartments were often used, in the early part of the work, to support the timber face or loose rock, as shown in Fig. 1, Plate LXVIII. At such times the front of the extensions was held tightly against the planking by the pressure of the floor jacks. While shoving, the pressure on the floor jacks was gradually released, allowing the floors to slide back into the shield and still afford support to the face. The extensions also afforded convenient working platforms. They were subject to severe bending strains while the shield was being shoved, however, and the cast-iron rams were frequently broken or jammed. The extensions did not last beyond the edge of the ledge at Manhattan, nor more than about half through the rock work at Long Island City. The fixed extensions originally placed on Shields *A* and *C* at Manhattan were not substantial enough, and lasted only a few days.

Wherever the rock face was sufficiently sound and high, a bottom heading was driven some 20 or 30 ft. in advance of the shield. The heading was driven and the cradle placed independently of the face of the soft ground above, and in the manner described for all-rock sections. The remainder of the rock face was removed by firing top and side rounds into the bottom heading after the soft ground had been excavated. Great care had to be taken in firing in order not to disturb the timber work or break the rock away from under the breast boards. If either occurred, a serious run was likely to follow. The bottom-heading method is shown by Figs. 1, 2, and 3, Plate LXVIII, and the breasting and poling by Fig. 2, Plate LXX.

In the early part of the work, where a bottom heading was impracticable, the soft ground was first excavated as described above, and the rock was drilled by machines mounted on tripods, and fired as a bench. By this plan no drilling could be done until the soft ground was removed. This is called the rock-bench method.

Later the rock-cut method was devised. Drills were set up on columns in the bottom compartments of the shield, and the face was drilled while work was in progress on the soft ground above. The drilling was done either for a horizontal or vertical cut and side and top rounds. The drillers were protected while at work by platforms of timber built out from the floors of the compartments above. This plan, while probably not quite as economical of explosives, saved nearly all the delay due to drilling the bench.

Plate LXX, Fig. 1.—Small Shaft Sunk to Rock.

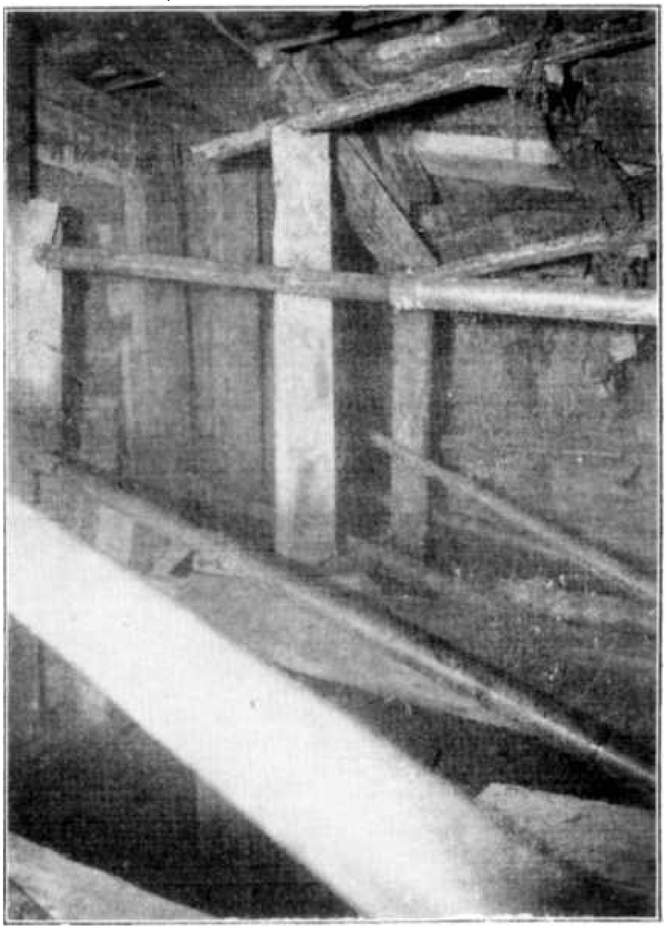

Plate LXX, Fig. 2.—Breasting and Poling in Front of Shield.

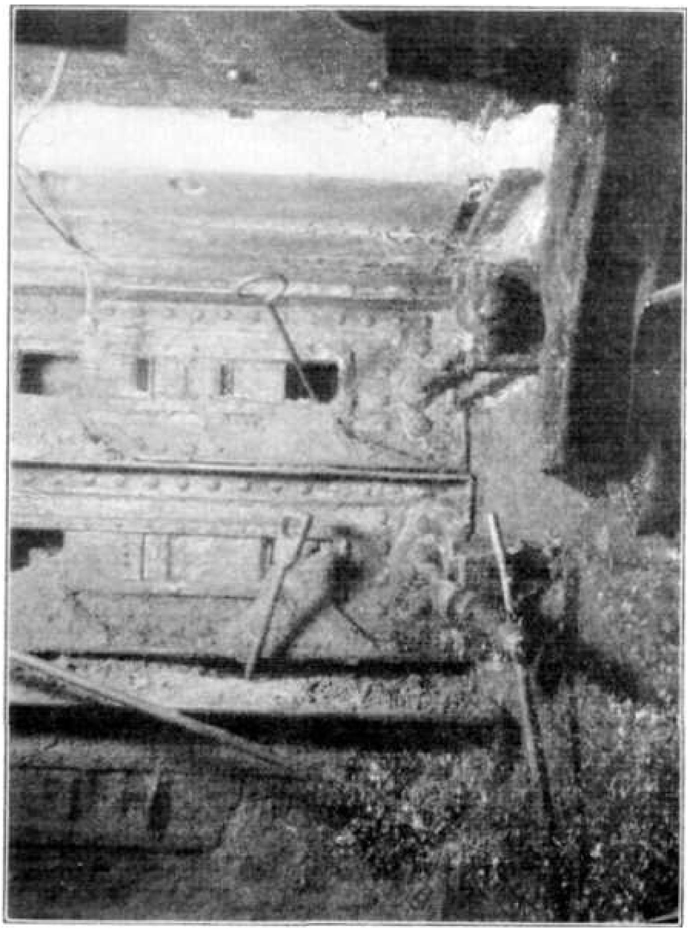

Plate LXX, Fig. 3.—Shutters on Front of Shield.

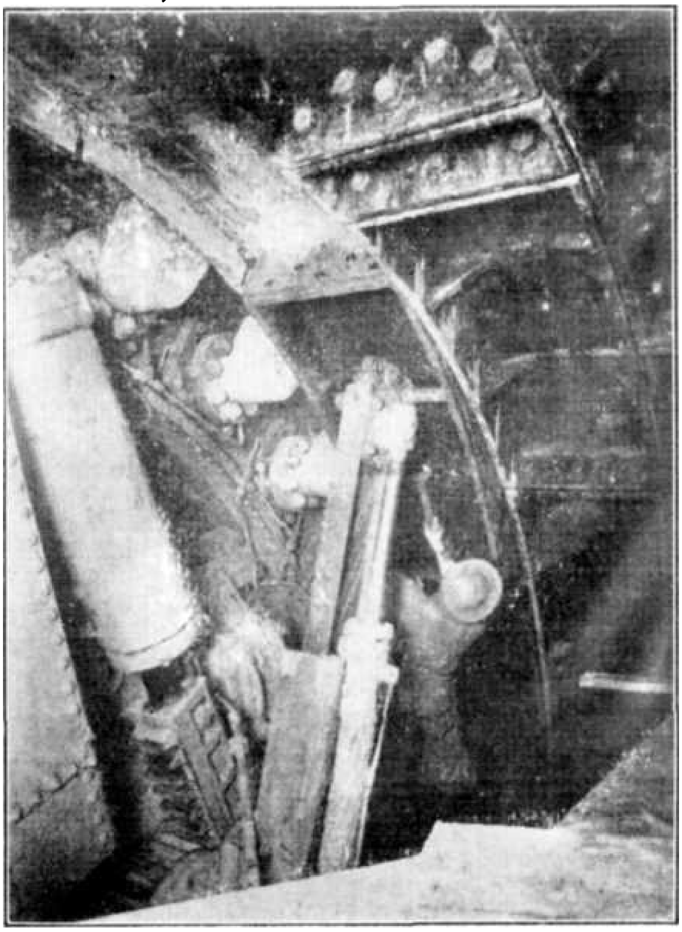

Plate LXX, Fig. 4.—Hydraulic Erector Placing Segment.

All-Earth Section.—As described by Messrs. Hay and Fitzmaurice, in a paper on the Blackwall Tunnel,[C] the contractor had used, with marked success, shutters in the face of the shield for excavating in loose open material. He naturally adopted the method for the East River work. When the shields in Tunnels *B* and *D*, at Manhattan, the first to be driven through soft ground, reached a point under the actual bulkhead line, work was partly suspended and shutters were put in place in the face of the top and center compartments. The shutters in the center compartments in Shield *D* are shown in Fig. 3, Plate LXX, while the method of work with the shutters is shown by Figs. 4, 5, 6, and 7, Plate LXVIII. Fig. 4 on that plate shows the shield ready for a shove. As the pressure was applied to the shield jacks, men loosened the nuts on the screws holding the ends of the shutters, and allowed the latter to slide back into the working compartments. At the end of the shove, the shutters were in the position shown in Fig. 5, Plate LXVIII. In preparing for a new shove, the slides in the shutters were opened, and the material in front was raked into the shield. At the same time, the shutters were gradually worked forward. The two upper shutters in a compartment were generally advanced from 12 to 15 in., after which the muck could be shoveled out over the bottom shutters, as shown on Fig. 6, Plate LXVIII, and Fig. 3, Plate LXX. No shutters were placed in the bottom compartments, and as the air pressure was not generally high enough to keep the face dry at the bottom, these compartments were pretty well filled with the soft, wet quicksand. Just before shoving, this material was excavated to a point where it ran in faster than it could be taken out. Much of the excavation in the bottom compartment was done by the blow-pipe. During the shove the material from the bottom compartment often ran back through the open door in the transverse bulkhead, as shown by Fig. 5, Plate LXVIII.

In the Blackwall Tunnel the material was reported to have been loose enough to keep in close contact with the shutters at all times. In the East River Tunnels this was not the case. The sand at the top was dry and would often stand with a vertical face for some hours. In advancing the shutters, it was difficult to bring them into close contact with the face at the end of the operation. The soft material at the bottom was constantly running into the lower compartment and undermining the stiff dry material at the top. The latter gradually broke away, and, at times, the actual face was some feet in advance of the shutters. Under those circumstances, the air escaped freely through the unprotected sand face. The joints of the shutters were plastered with clay, but this did not keep the air from passing out through the lower compartments. This condition facilitated the formation of blows, which were of constant occurrence where shutters were used in the sand. In Tunnels *B* and *D*, at Manhattan, the shutters were used in the above manner clear across to the reef. In Tunnel *C*, which was considerably behind Tunnels *B* and *D*, the shutters, although placed, were never used against the face, and the excavation was carried on by poling the top and breasting the face. The change resulted in much better progress and fewer blows. The excavation through the soft material in Tunnel *C* had just been completed when Tunnel *A* was started, and the gangs of workmen were exchanged.

The work in soft ground in Tunnel *A* thus gained the benefit of the experience in Tunnel *C*. Shutters were placed only in the top compartments in this tunnel, and, as in Tunnel *C*, were never used in contact with the face. The method of work is shown by Figs. 1, 2, and 3, Plate LXXI. The result was still more rapid progress in Tunnel *A*, and although the loss of air was fully as great in this tunnel as in the other three, there was only one blow which caused any considerable loss of pressure. In Tunnels *A* and *C* the diaphragms in the rear of the center compartments of the lower tiers of working chambers were removed before the shields entered the soft ground. The change was not of as much advantage in soft ground as in rock, but it facilitated the removal of the soft wet sand in the bottom. In Tunnel *A*, after encountering gravel, a belt conveyor was suspended from the traveling stage with one end projecting through the opening into the working compartment. The use of the conveyor made it possible to continue mucking at the face while the bottom plates of the iron lining were being put in place, and resulted in a material increase in the rate of progress.

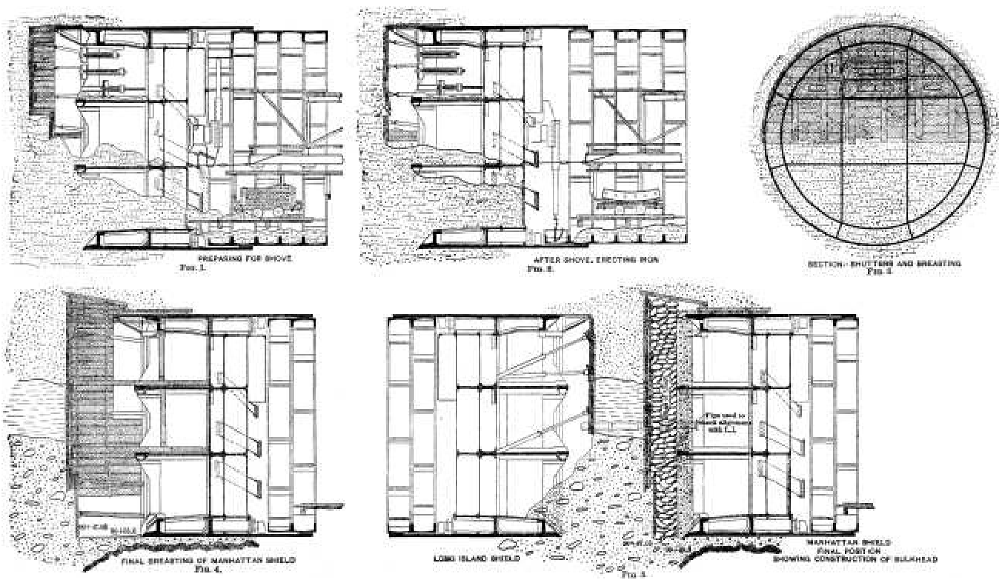

Plate LXXI

The shutters were not placed on the Long Island shields at all. Just before the shields passed into all soft ground, a fixed hood was attached to each.

The method of working in soft ground from Long Island City is illustrated by Plate LXXII. The full lines at the face of the shield show the position of the earth before a shove of the shield, and the dotted lines show the same after the shove. The face was mined out to the front of the hood and breasted down to a little below the floor of the top pockets of the shield. In the middle pocket the earth was allowed to take its natural slope back on the floor. Toward the rear of the bottom pockets it was held by stop-planks. The air pressure was always about equal to the hydrostatic head at the middle of the shield, so that the face in the upper and middle pockets was dry. In the lower pockets it was wet, and flowed under the pressure of shoving the shield. By this method 4,195 lin. ft. of tunnel was excavated by the four Long Island shields in 120 days, from November 1st, 1907, to March 1st, 1908. This was an average of 8.74 ft. per day per shield.

The rate of progress, the nature of the materials, and the methods adopted are shown in Table 2.

Preparations for Junction of Shields.—As previously mentioned, the Manhattan shields were stopped at the edge of the reef. Before making the final shove of those shields, special polings were placed with unusual care. The excavation was bell-shaped to receive the Long Island shields. The arrangement of the polings is shown by Figs. 4 and 5, Plate LXXI. After the shields were shoved into final position, as shown at the right in Fig. 5, the rear end of the polings rested over the cutting edge and allowed room for the removal of the hood. After the latter had been accomplished, the temporary bulkheads of concrete and clay bags were built as a precaution against blows when the shields were close together. An 8-in. pipe was then driven forward through the bulkhead for distances varying from 30 to 100 ft., in order to check the alignment and grade between the two workings before the shields were actually shoved together. The errors in the surveys were negligible, but here, as elsewhere, the shields were not exactly in the desired position, and it took careful handling to bring the cutting edges together. The Long Island shields were driven to meet those from Manhattan.

TABLE 2.—Rate of Progress, Nature of Materials, and Methods Adopted in Construction of East River Tunnels.

Line A, Long Island.

Material.	Method.	Station:		Date:		Number of days.	Linear Feet.	Rate of progress in feet per day.	Remarks.
		From	To	From	To				
All rock	Bottom heading	69+39.9	69+79	Aug. 2, '06	Sept 25, '06	54	39.1	0.724	
All rock	Center heading	69+79	70+64	Sept 25, '06	Nov. 21, '06	57	85	1.49	
Earth and rock	Center heading	70+64	71+34	Nov. 21, '06	Dec. 30, '06	39	70	1.79	
Earth and rock	Bottom heading	71+34	71+89	Dec. 30, '06	Feb. 13, '07	45	55	1.22	
All rock	Bottom heading	71+89	72+11	Feb. 13, '07	Feb. 21, '07	8	22	2.75	
Earth and rock	Center heading	72+11	72+67	Feb. 21, '07	Mar. 19, '07	26	56	2.15	
All rock	Center heading	72+67	76+54	Mar. 19, '07	Sept 6, '07	171	387	2.26	
Earth and rock	Going out of rock	76+54	77+24	Sept 6, '07	Oct. 4, '07	28	70	2.50	
All earth	Soft ground	77+24	90+57.3	Oct. 4, '07	Mar. 26, '08	174	1,333.3	7.66	

Line B, Long Island.

Material.	Method.	Station:		Date:		Number of days.	Linear Feet.	Rate of progress in feet per day.	Remarks.
		From	To	From	To				
All rock	Bottom heading	69+29.6	70+46	Oct. 16, '06	Nov. 20, '06	35	116.4	3.33	
Earth and rock	Bottom heading	70+46	71+95	Nov. 20, '06	Feb. 23, '07	95	149	1.57	
All rock	Bottom heading	71+95	72+25	Feb. 23, '07	Mar. 6, '07	11	30	2.73	
Earth and rock	Center heading	72+25	72+60	Mar. 6, '07	Mar. 24, '07	18	35	1.94	
All rock	Going out of rock	72+60	76+57	Mar. 24, '07	Aug. 7, '07	136	397	2.92	
Earth and rock	Soft ground	76+57	77+30	Aug. 7, '07	Sept 5, '07	29	73	2.52	
All earth	Soft ground	77+30	90+49.6	Sept 5, '07	Mar. 19, '08	196	1,319.6	6.73	

Line C, Long Island.

Material.	Method.	Station: From	Station: To	Date: From	Date: To	Number of days.	Linear Feet.	Rate of progress in feet per day.	Remarks.
All rock	Bottom heading	68+61.9	69+93	June 11, '06	Oct. 16, '06	127	131.1	1.03	
Earth and rock	Bottom heading	69+93	71+65	Oct. 16, '06	Feb. 7, '07	114	172	1.51	
All rock	Bottom heading	71+65	71+91	Feb. 7, '07	Feb. 13, '07	6	26	4.33	
All rock	Center heading	71+91	75+81	Feb. 13, '07	July 20, '07	157	390	2.48	
Earth and rock	Going out of rock	75+81	76+56	July 20, '07	Aug. 25, '07	36	75	2.08	
All earth	Soft ground	76+56	90+44.4	Aug. 25, '07	Mar. 17, '08	205	1,388.4	6.77	

Line D, Long Island.

Material.	Method.	Station: From	Station: To	Date: From	Date: To	Number of days.	Linear Feet.	Rate of progress in feet per day.	Remarks.
Rock	Bottom heading	68+50.6	69+77	June 2, '06	Oct. 24, '06	144	126.4	0.87	
Earth and rock	Bottom heading	69+77	71+22	Oct. 24, '06	Jan. 13, '06	81	145	1.79	
All rock	Bottom heading	71+23	72+00	Jan. 13, '07	Mar. 3, '07	49	78	1.59	
All rock	Center heading	72+00	75+73	Mar. 3, '07	July 10, '07	129	373	2.89	
Earth and rock	Going out of rock	75+73	77+63	July 10, '07	Sept 25, '07	77	190	2.47	
All earth	Soft ground	77+63	90+38.6	Sept 25, '07	Mar. 7. '08	164	1,275.6	7.78	

Line A, Manhattan.

Material.	Method.	Station: From	Station: To	Date: From	Date: To	Number of days.	Linear Feet.	Rate of progress in feet per day.	Remarks.
Rock	Top heading Top lift of bench Bottom lift of bench	108+43 108+43 108+43	107+74 107+74 107+74	July 20, '05 Aug. 8, '05 Aug. 30, '05	Aug. 3, '05 Aug. 23, '05 Sept 27, '05	14 15 28 } 57	69	1.21	Excavation in normal air, and before advance of shield.
Rock	Bottom heading Bottom heading	107+74 107+74	107+21 107+21	Sept 27, '05 Nov. 30, '05	Oct. 23, '05 Dec. 29, '05	26 29 } 55	53	0.96	Bottom heading timbered to avoid the possibility of a break.
Mixed	Bottom heading	107+21	106+99	Oct. 26, '06	Nov. 20, '06	25	22	0.88	Bottom heading timbered.
Mixed	Rock bench	106+99	106+34	Nov. 20, '06	Jan. 13, '07	54	65	1.20	
Earth	Poling and breasting	106+34	99+11	Jan. 13, '07	Apr. 17, '07	94	723	7.69	
Mixed	Rock cut	99+11	93+96	Apr. 17, '07	Oct. 24, '07	190	515	2.71	
Rock	Bottom heading	93+96	93+58	Oct. 24, '07	Nov. 14, '07	21	38	1.81	

Rock	Center heading	93+58	92+42	Nov. 14, '07	Dec. 27, '07	46	116	2.52	
Rock	Bottom heading	92+42	91+05	Dec. 27, '07	Feb. 24, '08	59	137	2.32	
Mixed	Rock cut	91+05	90+57	Feb. 24, '08	Mar. 20, '08	25	48	1.92	

Line B, Manhattan.

Material.	Method.	Station:		Date:		Number of days.	Linear Feet.	Rate of progress in feet per day.	Remarks.
		From	To	From	To				
Rock	Top heading Top lift of bench Bottom lift of bench Bottom lift of bench	108+35 108+35 108+35 108+15	107+87 107+87 108+15 107+87	July 6, '05 Aug. 3, '05 Aug. 26, '05 Sept 11, '05	July 27, '05 Aug. 14, '05 Aug. 30, '05 Sept 26, '05	21 11 4 15 51	48	0.94	Excavation done in normal air and before advance of shield.
Rock	Bottom heading	107+87	107+00	Oct. 23, '05	Jan. 17, '06	86	87	1.01	
Mixed	Bottom heading	107+00	106+64	Jan. 17, '06	Feb. 12, '06	26	36	1.38	
Mixed	Rock bench	106+64	106+31	Feb. 12, '06	Mar. 1, '06	17	33	1.94	
Earth	Poling and breasting	106+31	105+58	Mar. 1, '06	Apr. 3, '06	33	73	2.21	
Earth	Shutters in contact with face	105+58	99+19	Apr. 9, '06	Nov. 1, '06	206	639	3.10	
Mixed	Rock bench	99+19	98+44	Nov. 1. '06	Dec. 29, '06	58	75	1.30	
Mixed	Bottom heading	98+44	97+76	Dec, 29, '06	Feb. 12, '07	45	68	1.51	
Mixed	Rock cut	97+66	93+84	Feb. 12, '07	Aug. 6, '07	175	392	2.24	
Rock	Full face	93+84	93+21	Aug. 6, '07	Sept 2, '07	27	63	2.33	
Rock	Center Heading	93+21	92+30	Sept 2, '07	Oct. 12, '07	40	91	2.28	
Rock	Bottom heading	92+30	90+99	Oct. 12, '07	Dec. 6, '07	55	131	2.38	
Mixed	Rock cut	90+99	90+49.6	Dec. 6, '07	Jan. 3, '08	28	49.4	1.76	

[Pg 449]

Line C, Manhattan.

Material.	Method.	Station:		Date:		Number of days.	Linear Feet.	Rate of progress in feet per day.	Remarks.
		From	To	From	To				
Rock	Top heading Top heading Excavating bench Bottom heading Bottom heading	107+79.03 107+69 107+79 107+23 107+23	107+69 107+23 107+23 106+72 107+15	Dec. 20, '04 Jan. 1, '05 Jan. 21, '05 Mar. 1, '05 Oct. 12, '05	Dec. 27, '04 Jan. 15, '05 Feb. 28, '05 Mar. 11, '05 Oct. 27,	7 14 38 10 15	54	0.77	Stopped to brace portal. No work done from March 12th to October 11th, 1905, except a little trimming in September. All work up to this date done in normal air. Heading advanced to

					'05				106+70 and bulkheaded.
Rock	Bottom heading	107+15	106+62	Nov. 6, '05	Dec. 2, '05	26	53	2.04	
Mixed	Bottom heading	106+62	106+55	Dec. 2, '05	Dec. 23, '05	21	7	0.33	Heading advanced to 106 + 40. Shut down in order that Line D might have a lead.
Mixed	Bottom heading	106+55	106+17	Feb. 12, '06	Mar. 22, '06	38	38	1.00	Shut down on account of air shortage.
Mixed	Rock cut	106+17	105+85	Apr. 2, '06	Apr. 20, '06	18	32	1.78	Shut down on account of air shortage.
Mixed	Rock cut	105+85	105+55	July 27, '06	Aug. 26, '06	30	30	1.00	Shut down April 20th to July 27th, 1906.
Earth	Breasting and poling	105+55	99+40	Aug. 26, '06	Jan. 2, '07	127	615	4.84	
Mixed	Rock cut	99+40	98+70	Jan. 2, '07	Feb. 6, '07	35	70	2.00	
Rock	Full face	98+70	98+60	Feb. 6, '07	Feb. 12, '07	6	10	1.66	
Mixed	Bottom heading	98+60	98+39	Feb. 12, '07	Mar. 6, '07	22	21	0.95	
Rock	Bottom heading	98+39	98+17	Mar. 6, '07	Mar. 15, '07	9	22	2.44	
Mixed	Rock cut	98+17	95+68	Mar. 15, '07	July 30, '07	110	249	2.26	Heading advanced to 97+82.
Rock	Middle heading	95+68	94+61	July 30, '07	Aug. 21, '07	49	107	2.18	Heading advanced to 94+35.
Mixed	Rock cut	94+61	93+56	Aug. 21, '07	Oct. 3, '07	43	106	2.46	
Rock	Middle heading	93+56	92+73	Oct. 3, '07	Nov. 11, '07	39	83	2.13	
Mixed	Rock cut	92+73	90+55	Nov. 11, '07	Feb. 13, '08	94	218	2.32	Shut down until Line D shields met.
Mixed	Rock cut	90+55	90+44.4	Feb. 25, '08	Mar. 3, '08	6	11	1.83	

[Pg 450]

Line D, Manhattan.

Material.	Method.	Station:		Date:		Number of days.	Linear Feet.	Rate of progress in feet per day.	Remarks.
		From	To	From	To				
Rock	Top heading Removing bench Bottom heading Trimming	107+70.49 107+70.49 107+35 107+70 107+70	107+16 107+35 106+80 106+80 106+80	Dec. 9, '04 Jan. 1, '05 Jan. 30, '05 Mar.	Jan. 31, '05 Jan. 27, '05 Feb. 10, '05 Apr.	123	90	0.73	In normal air.

	Trimming			29, '05 Aug. 31, '05	12, '05 Sept 19, '05				
Rock	Bottom heading	106+80	106+67	Oct. 5, '05	Nov. 8, '05	34	13	0.40	Bottom heading timbered.
Mixed	Bottom heading	106+67	106+39	Nov. 8, '05	Dec. 23, '05	45	38	0.84	
Mixed	Sliding hood and breasting. Rock bench	106+29	105+70	Dec. 23, '05	Jan. 24, '06	32	59	1.84	
Earth	Poling and breasting	105+70	104+61	Jan. 24, '06	Feb. 27, '06	31	109	3.41	
Earth	Poling, breasting and shutters	104+61	103+90	Mar. 2, '06	Mar. 31, '06	29	71	2.45	Three days' delay to set shutters in top. Shut down 20 days to permit consolidation of the river bed and to repair broken plates.
Earth	Shutters	103+90	99+41	Apr. 20, '06	Sept 3, '06	136	449	3.40	Four days of 136, delay account of flood.
Mixed	Bottom bench	99+41	99+17	Sept 3, '06	Sept 23, '06	20	24	1.20	
Mixed	Bottom heading	99+17	98+50	Oct. 2, '06	Nov. 24, '06	53	67	1.27	Thirteen days' shut-down to put on hood.
Rock	Bottom heading	98+50	97+72	Nov. 24, '06	Jan. 16, '07	53	78	1.47	
Mixed	Bottom heading	97+72	97+27	Jan. 16, '07	Feb. 10, '07	25	45	1.40	
Mixed	Rock cut	97+27	95+72	Feb. 10, '07	Apr. 23, '07	72	155	2.15	
Rock	Middle heading	95+72	95+57	Apr. 23, '07	May 11, '07	18	15	0.83	
Rock	Middle heading	95+57	94+65	May 23, '07	June 17, '07	25	92	3.68	Twelve days' delay to repair cutting edge.
Mixed	Middle heading	94+65	94+41	June 17, '07	June 25, '07	8	24	3.00	
Mixed	Rock cut	94+41	94+03	June 25, '07	July 13, '07	18	38	2.11	
Rock	Middle heading	94+03	92+64	July 13, '07	Sept 12, '07	61	139	2.28	
Mixed	Middle heading	92+64	92+54	Sept 12, '07	Sept 20, '07	8	10	1.25	
	Middle			Sept 20,	Sept 21,				

Rock	heading	92+54	92+50	'07	'07	1	4	4.00
Mixed	Rock cut	92+50	90+38.66	Sept 21, '07	Jan. 8, '08	109	211.34	1.94

[Pg 451] Openings were made between the headings as follows:

Tunnel *D*, February 20th, 1908;
Tunnel *B*, March 3d, 1908;
Tunnel *C*, March 5th, 1908;
Tunnel *A*, March 18th, 1908.

It was necessary to cut away the projecting floors of the working compartments before the cutting edges could be shoved together.

Contractor's Organization.—Tunnel operations were carried on continuously for thirteen days out of fourteen, regular work being shut down for repairs on alternate Sundays. When the required pressure was more than 32 lb., four gangs of laborers were employed, each gang working two shifts of 3 hours each, with an intermission of 3 hours between the shifts. When the pressure was less than 32 lb., three gangs were employed, each gang covering 8 hours, but with an intermission of about 1/2 hour in low pressure for lunch.

Air Pressures Required.—During the greater portion of the work in soft ground, pressure was maintained which would about balance the hydrostatic head at the axis of the tunnel. This required a pressure varying from 30 to 34 lb. per sq. in. above that of the atmosphere. In Tunnels *B* and *D*, at Manhattan, during the work in soft ground, pressures as high as 37 lb. were maintained for considerable periods of time; in the firm material near the reef 28 lb. was often sufficient. While removing the broken plates, the pressure was raised for a short time to 42 lb., and was maintained between 37-1/2 and 40 lb. for a little more than one month.

Air Supply.—For regular operation the contractor furnished four compressors on each side of the river, each having a rated capacity of 5,000 cu. ft. of free air per minute delivered at 50 lb. above normal, when running at the rate of 100 rev. per min. An additional compressor of the same capacity was supplied on each side of the river, in compliance with the requirement for 25% excess capacity; the additional compressors had also high-pressure air cylinders which could be connected at will, and in which the pressure could be increased to 150 lb., and the air used to supply rock drills, grouting machines, etc. The entire combination on each side of the river, therefore, was rated at 25,000 cu. ft. of free air per minute, or a mean of 6,250 cu. ft. per
[Pg 452] heading. Its safe working capacity was not far from 20,000 cu. ft. per min.

The shields broke through rock surface in Tunnels *B*, *C*, and *D*, at Manhattan, in November and December, 1905. The consumption of air in the four tunnels soon exceeded 15,000 cu. ft. for 24 hours, and in Tunnel *D*, on several occasions, it exceeded 7,000 cu. ft. for a like period. Blows had become frequent, and it was evident that the air plant was inadequate for driving four tunnels at once in the open material east of the Manhattan rock. Work in Tunnel *A*, therefore, was not resumed, after the suspension on December 29th, for about ten months, and Tunnel *C* was also closed down for more than four months of the time between December, 1905, and July, 1906. During this period the capacity of the plant was increased from the rated 25,000 cu. ft. of free air per minute, to 35,000. In Tunnel *D* the material had gradually become firmer, with more clay and less escape of air, as the Blackwell's Island Reef was approached, and, at the end of the period, the rock surface was within 3 ft. of the top of the shield; in Tunnel *B*, the rock of the reef was still a little below the shield, but the overlying material contained a large proportion of clay and held air very well. Tunnel *C* was still in open material, but, with two lines safe and with the increased air plant, it was deemed best to resume work in Tunnel *A*, which was done on October 23d, 1906. Thenceforward work was continuous in all headings until the meeting points with the Long Island shields were reached.

This period, January to October, 1906, inclusive, was the most strenuous of the entire work, particularly the first six months. With one and, at times, two tunnels closed down, the consumption of air in the headings from Manhattan was an average of more than 20,000 cu. ft. per min. for periods of from 30 to 60 days; it was often more than 25,000 cu. ft. for 24 hours, with a maximum of nearly 29,000 cu. ft., and doubtless this was exceeded considerably for shorter periods. On several occasions the quantity supplied to a single tunnel averaged more than 15,000 cu. ft. per min. for 24 hours. The greatest averages for 24 hours were obtained later in Tunnel *A*, after the resumption of work there, and exceeded 19,000 cu. ft., but the conditions in the headings of the other lines were then so favorable that the work was carried on continuously in all.

The deficiency in the original plant at Manhattan was so marked, and the need of driving all headings from Long Island simultaneously so clear, that it was decided to increase the rated
[Pg 453] capacity of the Long Island compressor plant to 45,400 cu. ft. of free air per minute, which was 10,400 cu. ft. greater than the capacity of the Manhattan plant after the latter had been augmented.

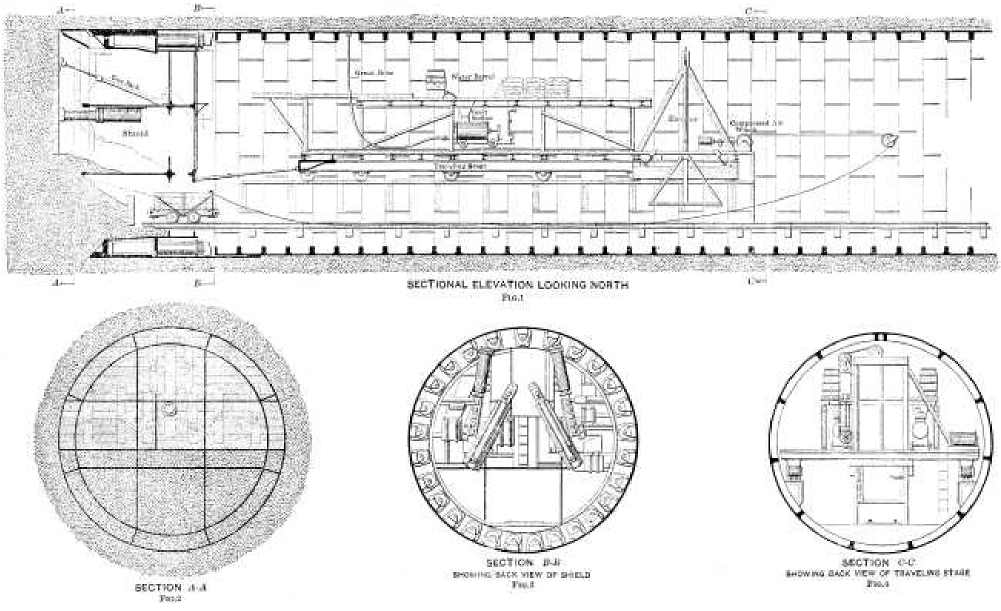

Plate LXXII

The earth encountered on emerging from rock, when driving westward from Long Island, was far more compact and less permeable to air than on the Manhattan side, but for a distance of from 400 to 600 ft. immediately east of the reef, it was a clean open sand, and, while the shields were passing through this, the quantity of air supplied to the four headings seldom fell below 20,000 cu. ft. per min.; it was usually more than 25,000 cu. ft., with a recorded maximum of 33,400 cu. ft. Although this was greater than ever used on the Manhattan side, it was more uniformly distributed among the several headings, and in none equalled the maximum observed on the Manhattan side, the largest having been 12,700 cu. ft. per min. for 24 hours; it must be remembered, however, that at one time only two tunnels were in progress in the bad material in the tunnels from Manhattan.

From the foregoing experience, it would seem that the plant finally furnished at Long Island, having a rated capacity of 45,400 cu. ft. of free air per minute, would have been a reasonable compliance with the original actual needs on the Manhattan side and *vice versa*; the plant finally developed on the Manhattan side, having a rated capacity of 35,000 cu. ft. of free air per minute, would have sufficed for the Long Island side.

The total quantity of free air compressed for the supply of the working chambers of the tunnels and the Long Island caissons was 34,109,000,000 cu. ft., and, in addition, 10,615,000,000 cu. ft. were compressed to between 80 and 125 lb. for power purposes, of which at least 80% was exhausted in the compressed-air working chambers. The total supply of free air to each heading while under pressure, therefore, averaged about 3,550 cu. ft. per min.

The quantity of air escaping during a sudden blow-out is apparently much smaller than might be supposed. Investigation of a number of cases, showing large pressure losses combined with a long stretch of tunnel supplying a relatively large reservoir of air, disclosed that a maximum loss of about 220,000 cu. ft. of free air occurred in 10 min. This averages only a little more than 19,000 cu. ft. per min., the maximum recorded supply to one tunnel for a period of 24 hours. Of [Pg 454] this quantity, however, probably from 30 to 40% escaped in the first 45 seconds, while the remainder was a more or less steady loss up to the time when the supply could be increased sufficiently to maintain the lowered pressure. Very few blows showed losses approaching this in quantity, but the inherent inaccuracy of the observations make the foregoing figures only roughly approximate.

Special Difficulties.

The most serious difficulties of the work came near the start. In Tunnel *D* blows and falls of sand from the face were frequent after soft ground was met in the top. About six weeks after entering the full sand face, and before the shutters had been installed, the shield showed a decided tendency to settle, carrying the tunnel lining down with it and resulting in a number of badly broken plates in the bottom of the rings. Notwithstanding the use of extremely high vertical leads,[D] the sand was so soft that the settlement of the shield continued for about fifteen rings, the maximum being nearly 9 in. below grade. The hydrostatic head at mid-height of the tunnel was 32-1/2 lb., and the raising of the air pressure to 37 lb., as was done at this time, was attended with grave danger of serious blows, on account of the recent disturbance of the natural cover by the pulling and re-driving of piles in the reconstruction of the Long Island ferry slips directly above. It dried the face materially, however, and the shield began to rise again, and had practically regained the grade when the anticipated blow-outs occurred, culminating with the entrance of rip-rap from the river bed into the shield and the flooding of the tunnel with 4 ft. of sand and water at the forward end. The escape of air was very great, and, as a pressure of more than 28 lb. could not be maintained, the face was bulkheaded and the tunnel was shut down for three weeks in order to permit the river bed to consolidate.

This was the most serious difficulty encountered on any part of the work, and, coming at the very start, was exceedingly discouraging. During the shut-down the broken plates were reinforced temporarily with steel ribs and reinforced concrete (Fig. 1, Plate LXXIII) which, on completion of the work, were replaced by cast-steel segments, as described elsewhere. Practically, no further movement of iron took place, and the loss of grade caused by the settlement of the shield, which was by far the largest that ever occurred in this work, was not sufficient to require a change in the designed grade or alignment of the track. Work was resumed with the shutters in use at the face as an aid to excavation. The features of extreme seriousness did not recur, but for two months the escape of air continued to be extremely large, an average of 15,000 cu. ft. per min. being required on many days during this period.

Plate LXXIII, Fig. 1.—Temporary Reinforcement of Broken Plates And Removal of a Plate in Sections.

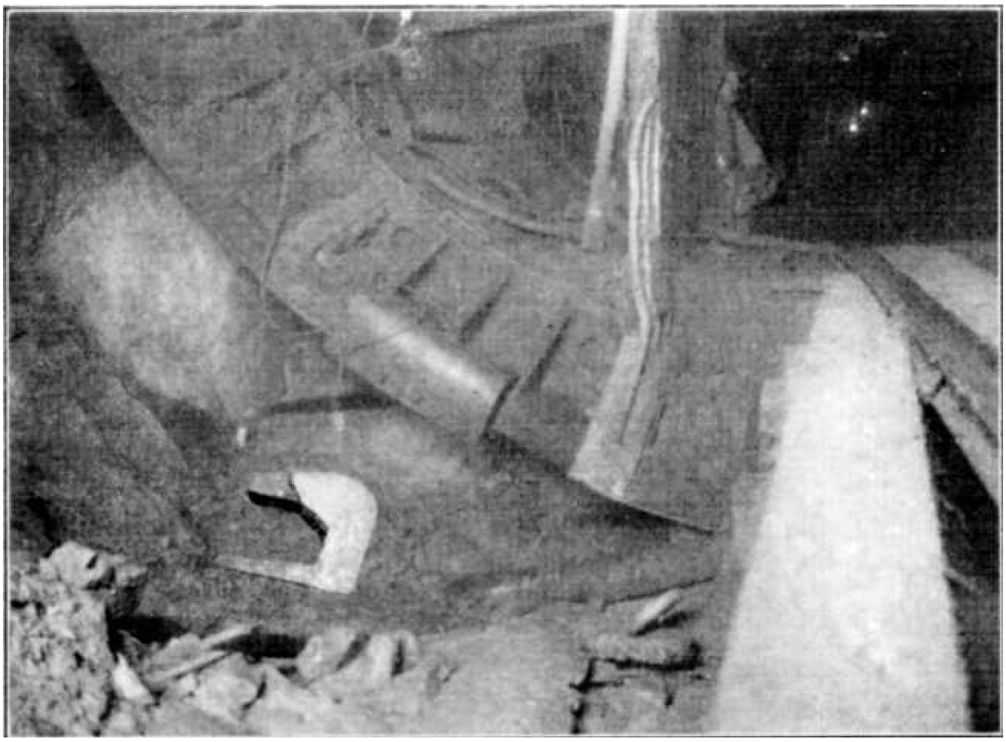

Plate LXXIII, Fig. 2.—Heavy Cast-Steel Patch Attached to Bent Segment of Cutting Edge.

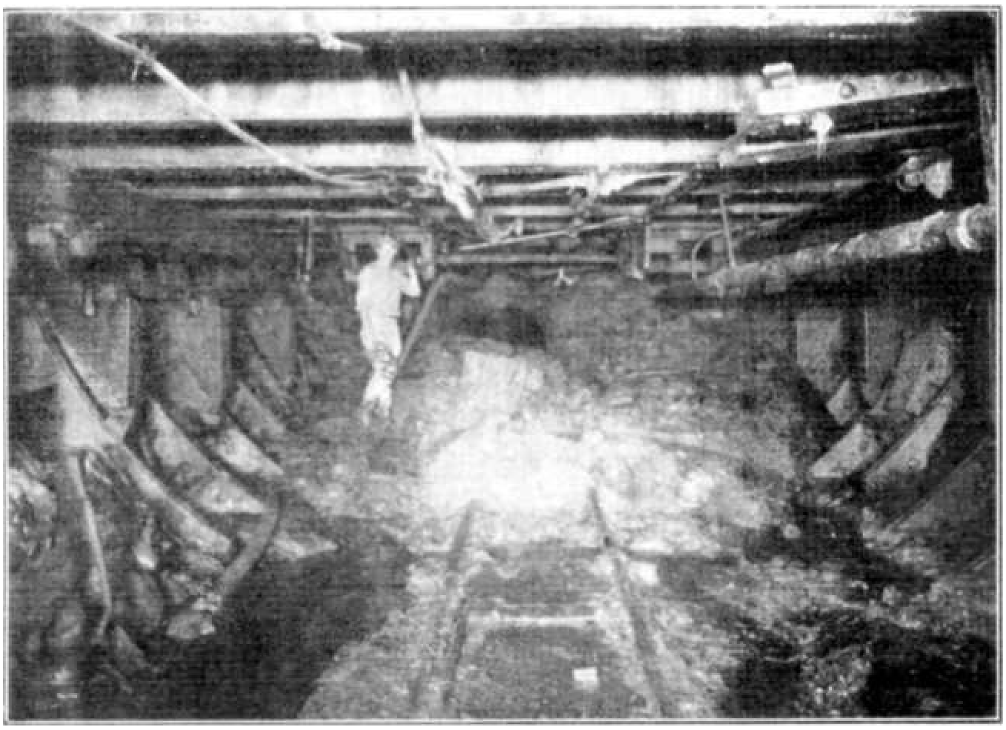

Plate LXXIII, Fig. 3.—Inflow of Soft Clay Through Shield.

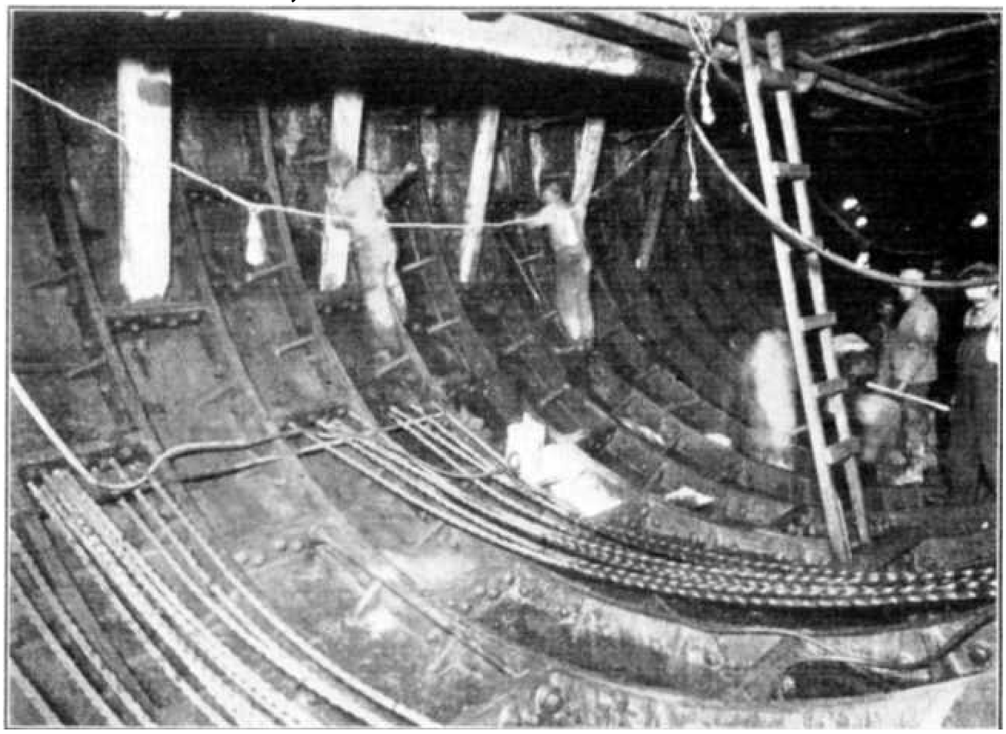

Plate LXXIII, Fig. 4.—Reinforcement of Broken Plate with Long Polt and Twisted Steel Rods.

In Tunnel *B*, after passing out from under the bulkhead line, in April, 1906, the loss of air became very great, and blow-outs were of almost daily occurrence until the end of June. At the time of the blows the pressure in the tunnel would drop from 2 to 8 lb., and it generally took some hours to raise the pressure to what it was before the blow. During that time regular operations were interrupted. In the latter part of June a permit was obtained allowing the clay blanket to be increased in thickness up to a depth of water of 27 ft. at mean low tide. The additional blanket was deposited during the latter part of June and early in July, and almost entirely stopped the blows.

By the end of the month the natural clay, previously described, formed the greater portion of the face, and, from that time forward, played an important part in reducing the quantity of air required. During April and the early part of May the work was under the ferry racks of the Long Island Railroad. The blanket had to be placed by dumping the clay from wheel-barrows through holes in the decking.

In Tunnel *A* a bottom heading had been driven 23 ft. in advance of the face at the time work was stopped at the end of 1905. During the ten months of inactivity the seams in the rock above opened. The rock surface was only from 2 to 4 ft. below the top of the cutting edge for a distance of about 60 ft. Over the rock there were large boulders embedded in sharp sand. It was an exceedingly difficult operation to remove the boulders and place the polings without starting a run. The open seams over the bottom heading also frequently caused trouble, as there were numerous slides of rock from the face which broke up the breasting and allowed the soft material from above to run into the shield. There were two runs of from 50 to 75 cu. yd. and many smaller ones.

Guiding the Shields.

Little difficulty was experienced at any time in driving the shield close to the desired line, but it was much harder to keep it on grade. In rock section, where the cradle could be set far enough in [Pg 456] advance to become hard before the shield was shoved over it, there was no trouble whatever. Where the cradle could be placed only a very short time before it had to take the weight of the shield, the case was quite different. The shield had a tendency to settle at the cutting edge, and when once pointed downward it was extremely difficult to change its direction. It was generally accomplished by embedding railroad rails or heavy oak plank in the cradle on solid foundation. This often had to be repeated several times before it was successful. In soft ground it was much easier to change the direction of the shield, but, owing to the varying nature of the material, it was sometimes impossible to determine in advance how the shield should be pointed. It was found by experience at Manhattan that the iron lining remained in the best position in relation to grade when the underside of the bottom of the shield at the rear end was driven on grade of the bottom of the iron, but if the rate of progress was slow, it was better to drive the shield a little higher.

In the headings from Long Island, which, as a rule, were in soft ground, the cutting edges of the shields were kept from 4 to 8 in. higher, with respect to the grade line, than the rails. The shields would then usually move parallel to the grade line, though this was modified considerably by the way the mucking was done and by the stiffness of the ground at the bottom of the shield.

On the average, the shields were shoved by from ten to twelve of the bottom jacks, with a pressure of about 4,000 lb. per sq. in. The jacks had 9-in. plungers, which made the average total force required to shove the shield 2,800,000 lb. In the soft ground, where shutters were used, all of the twenty-seven jacks were frequently used, and on several occasions the pressure exceeded 6,000 lb. per sq. in. With a unit pressure of 6,000 lb. per sq. in., the total pressure on the shield with all twenty-seven jacks in operation was 5,154 tons.

Injuries to Shields.

There were only two instances of damage to the essential structural features of the shields. The most serious was in Tunnel *D* where the cutting edge at the bottom of the shield was forced up a slightly sloping ledge of rock. A bow was formed in the steel casting which was markedly increased with the next few shoves. Work was suspended, and a heavy cast-steel patch, filling out [Pg 457] the bow, was attached to the bent segments, as shown in Fig. 2, Plate LXXIII. No further trouble was experienced with the deformed portion. The other instance was in Tunnel *B*, from Long Island, where a somewhat similar but less serious accident occurred and was treated in a like manner.

Bulkheads.—At Manhattan, bulkheads had to be built near the shafts before the tunnels could be put under pressure. After 500 ft. of tunnel had been built on each line, the second bulkheads were constructed. The air pressure between the first and second bulkheads was then reduced to between 15 and 20 lb. When the shields had been advanced for 1,500 ft., the third set of bulkheads was built. Nearly all the broken plates which were removed were located between the first and third bulkheads at Manhattan. Before undertaking this operation, the doors of the locks in the No. 3 bulkheads were reversed to take pressure from the west. By this means it was possible to carry on the work of dismantling the shields under comparatively low pressure simultaneously with the removal of the broken plates.

At Long Island City the roofs of the caissons served the purpose of the No. 1 bulkheads. Two other sets of bulkheads were erected, the first about 500 ft. and the second about 1,500 ft. from the shafts.

Settlement at Surface of Ground.

The driving of such portions of the river tunnels, with earth top, as were under the land section, caused a settlement at the surface varying usually from 3 to 6 in. The three-story brick building at No. 412 East 34th Street required extensive repairs. This building stood over the section of part earth and part rock excavation where the tunnels broke out from the Manhattan ledge and where there were a number of runs of sand into the shield. In fact, the voids made by those runs eventually worked up to the surface and caused the pavement of the alley between the buildings to drop 4 or 5 ft. over a considerable area. The tunnels also passed directly under the ferry bridges and racks of the Long Island Railroad at East 34th Street. Tunnels *B* and *D* were constantly blowing at the time, and, where progress was slow, caused so much settlement that one of the racks had to be rebuilt. Tunnel *A*, on the other hand, where progress was rapid, caused practically no settlement in the racks.

Clay Blanket.

As previously mentioned, clay was dumped over the tunnels in varying depths at different times. [Pg 458] A material was required which would pack into a compact mass and would not readily erode under the influence of the tidal currents of the river and the escape of the great volumes of air which often kept the water in the vicinity of the shields in violent motion. Suitable clay could not be found in the immediate vicinity of the work. Materials from Shooter's Island and from Haverstraw were tried for the purpose. The Government authorities did not approve of the former, and the greater portion of that used came from the latter point. Although a number of different permits governing the work were granted, there were three important ones. The first permit allowed a blanket which roughly followed the profile of the tunnels, with an average thickness of 10 ft. on the Manhattan side and somewhat less on the Long Island City side. The second general permit allowed the blanket to be built up to a plane 27 ft. below low water. This proved effective in checking the tendency to blow, but allowed considerable loss of air. Finally, dumping was allowed over limited and marked areas up to a plane of 20 ft. below low water. Wherever advantage was taken of this last authority, the excessive loss of air was almost entirely stopped. After all the shields had been well advanced out into the river, the blanket behind them was dredged up, and the clay used over again in advance of the shield.

Soundings were taken daily over the shields, and, if marked erosion was found, clay was dumped into the hole. Whenever a serious blow occurred, a scowload of clay was dumped over it as soon as possible and without waiting to make soundings. For the latter purposes a considerable quantity of clay was placed in storage in the Pidgeon Street slip at Long Island City, and one or two bottom-dump scows were kept filled ready for emergencies. Mr. Robert Chalmers, who had charge of the soundings for the contractor, states that "the depressions in the blanket caused by erosion due to the escape of air were, as a rule, roughly circular in plan and of a curved section somewhat flat in the center." Satisfactory soundings were never obtained in the center of a violent blow, but the following instance illustrates in a measure what occurred. Over Tunnel *B*, at Station 102+80, there was normally 36 ft. of water, 7 ft. of clay blanket, and 20 ft. of natural cover. Air was escaping at the rate of about 10,000 cu. ft. per min., and small blows were occurring once or twice daily. On June 22d, soundings showed 54 ft. of water. A depth of 18 ft. of
[Pg 459] the river bottom had been eroded in about two days. On the next day there were taken out of the shield boulders which had almost certainly been deposited on the natural river bed. Clay from the blanket also came into the shields on a number of occasions during or after blows. The most notable occasion was in September, 1907, when the top of the shield in Tunnel *D* was emerging from the east side of Blackwell's Island Reef. The sand in the top was very coarse and loose, and allowed the air to escape very freely. The fall of a piece of loose rock from under the breast precipitated a run of sand which was followed by clay from the blanket, which, in this locality, was largely the softer redredged material. Mucking out the shield was in progress when the soft clay started flowing again and forced its way back into the tunnel for a distance of 20 ft., as shown in Fig. 3, Plate LXXIII. Ten days of careful and arduous work were required to regain control of the face and complete the shove, on account of the heavy pressure of the plastic clay.

The clay blanket was of the utmost importance to the work throughout, and it is difficult to see how the tunnels could have been driven through the soft material on the Manhattan side without it.

The new material used in the blanket amounted to 283,412 cu. yd., of which 117,846 cu. yd. were removed from over the completed tunnels and redeposited in the blanket in advance of the shields. A total of 88,059 cu. yd. of clay was dumped over blows. The total cost of placing and removing the blanket was $304,056.

Iron Lining.

The standard cast-iron tunnel lining was of the usual tube type, 23 ft. in outside diameter. The rings were 30 in. wide, and were composed of eleven segments and a key. The webs of the segments were 1-1/2 in. thick in the central portion, increasing to 2-3/8 in. at the roots of the flanges, which were 11 in. deep, 2-1/4 in. thick at the root, and 1-1/2 in. at the edge, and were machined on all contact faces. Recesses were cast in the edge of the flanges, forming a groove, when the lining was in place, 1-1/2 in. deep and about 3/8 in. wide, to receive the caulking. The bolt holes were cored in the flanges, and the bosses facing the holes were not machined. The customary grout hole was tapped in the center of each plate for a standard 1-1/4-in. pipe. In this work, experience indicated that the standard pipe thread was too fine, and that the taper was objectionable. Each segment weighed, approximately, 2,020 lb., and the key weighed 520 lb., the
[Pg 460] total weight being 9,102 lb. per lin. ft. of tunnel. Fig. 1 shows the details of the standard heavy lining.

In addition to the standard cast-iron lining, cast-steel rings of the same dimensions were provided for use in a short stretch of the tunnel, when passing from a rock to a soft ground foundation, where it was anticipated that unequal settlement and consequent distortion and increase in stress might occur, but, aside from the small regular drop of the lining as it passed out of the tail of the shield, no such settlement was observed.

Two classes of lighter iron, one with 1-in. web and 8-in. flanges and the other with 1-1/4-in. web and 9-in. flanges—the former weighing 5,166 lb. per lin. ft. of tunnel and the latter, 6,776 lb.—were provided for use in the land sections between East Avenue and the Long Island City shafts. Two weights of extra heavy segments for use at the bottom of the rings were also furnished. The so-called *XX* plates had webs and flanges 1/4 in. thicker than the standard segment and the *YY* plates were similarly 1/2 in. heavier. The conditions under which they were used will be referred to later. All the castings were of the same general type as shown by Fig. 1.

Rings tapering 3/4 in. and 1-1/2 in. in width were used for changes in alignment and grade, the former being used approximately at every fourth ring on the 1° 30' curves. The 1-1/2-in. tapers were largely used for changes in grade where it was desired to free the iron from binding on the tail of the shield. Still wider tapers would have been advantageous for quick results in this respect.

No lug was cast on the segments for attachment to the erector, but in its place the gadget shown on Fig. 4, Plate LXX, was inserted in one of the pairs of bolt holes near the center of the plate, and was held in position by the running nut at one end.

In the beginning it was expected that the natural shape of the rings would not show more than 1 in. of shortening of the vertical diameter; this was slightly exceeded, however, the average distortion throughout the tunnels being 1-7/16 in. The erectors were attached to the shield and in such a position that they were in the plane of the center of the ring to be erected when the shove was made without lead and just far enough to permit placing the segments. If the shield were shoved too far, a rare occurrence, the erection was inconvenienced. In driving with high vertical [Pg 462] leads, which occurred more frequently, the disadvantage of placing the erector on the shield was more apparent. Under such conditions the plane of the erector's motion was acutely inclined to the plane of the ring, and, after placing the lower portion of the ring, it was usually necessary to shove the shield a few inches farther in order to place the upper plates. The practical effect of this action is referred to later.

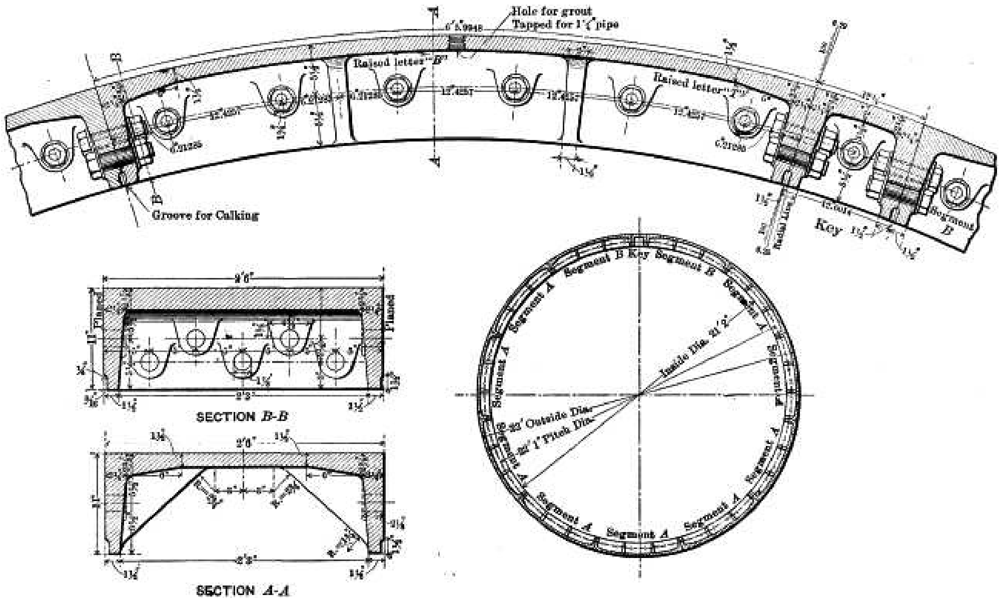

Fig. 1.

At first the erection of the iron in the river tunnels interfered somewhat with the mucking operations, but the length of time required to complete the latter was ample for the completion of the former; and the starting of a shove was seldom postponed by reason of the non-completion of a ring. After the removal of the bottom of the diaphragms, permitting the muck cars to be run into the shield and beyond, the two operations were carried on simultaneously without serious interference. The installation of the belt conveyor for handling the soft ground spoil in Tunnel *A* was of special benefit in this respect.

Preparatory to the final bolt tightening of each ring as erected, a 15-ton draw-jack, consisting of a small pulling-jack inserted in a light eye-bar chain, was placed on the horizontal diameter, and frequently the erectors were also used to boost the crown of the iron, the object being to erect the ring truly circular. Before shoving, a 1-1/4-in. turn-buckle was also placed on the horizontal diameter in order to prevent the spreading of the iron, previous to filling the void outside with grout. The approach of the supports for the upper floor of the trailing platform necessitated the removal of these turnbuckles from all but the three leading rings, but if the iron showed a tendency to continue distortion, they were re-inserted after the passage of the trailing platform and remained until the arch of the concrete lining was placed.

The cost of handling and erecting the iron varied greatly at different times, averaging, for the river tunnels, $3.32 per ton for the directly chargeable labor of handling and erecting, to which must be added $7.54 for "top charges." The cost of repairing broken plates is included in this figure.

Broken Plates.—During the construction of the river section of the tunnels, a number of segments were found to have been broken while shoving the shield. The breaks, which with few exceptions were confined to the three or four bottom plates, almost invariably occurred on the advanced [Pg 463] face of the ring, and rarely extended beyond the bottom of the flange. A careful study of the breaks and of the shoving records disclosed several distinct types of fracture and three principal known causes of breakage by the shield.

In the first case, the accidental intrusion of foreign material between the jack head and the iron caused the jack to take its bearings on the flange above its normal position opposite the web of the ring, and resulted usually in the breaking out of a piece of the flange or in several radiating cracks with or without a depression of the flange. These breaks were very characteristic, and the cause was readily recognizable, even though the intruding substance was not actually observed.

In the second case, the working of a hard piece of metal, such as a small tool, into the annular space between the iron and the tail of the shield, where it was caught on the bead and dragged along as the shield advanced, was the known cause of a number of broken segments. Such breaks had no particular characteristic, but were usually close above the line of travel of the lost tool or metal. Their cause was determined by the finding of a heavy score on the underside of the segment or the discovery of the tool wedged in the tail of the shield or lying under the broken plate when it was removed. It is probable that a number of breaks ascribed to unknown causes should be placed in this class.

The third cause includes the largest number of breaks, and, while difficult to define closely, is the most interesting. Broadly speaking, the breaks resulted from the movements of the shield in relation to the position of the tunnel lining. While shoving through soft ground, it was frequently difficult to apply sufficient power to the lower jacks to complete the full shove of 30 in. on the desired alignment. The shield, therefore, was driven upward at the beginning of the shove, and, as the sand packed in front of the shield and more power was required, it was furnished by applying the upper jacks. The top of the shield was slowly pushed over, and, at the close of the shove, the desired position had been obtained; but the shield had been given a rocking motion with a decided lifting of the tail toward the close of the shove. A similar lifting of the tail occurred when, with high vertical leads, the top of the shield was pushed over in order to place the upper plates of the ring. Again, when the shield was driven above grade and it was desired to descend, [Pg 464] the passage of the shield over the summit produced a like effect. In all these movements, with the space between the tail of the shield and the iron packed tight with pugging, the upward thrust of the shield tended to flatten the iron in the bottom and occasional broken plates were the result. The free use of the taper rings, placed so as to relieve the binding of the lining on the tail of the shield, forces the tunnel to follow the variations in the grade of the shield, but reduces greatly the injuries to the rings from this action.

In Tunnel *D*, where very high vertical leads were required through the soft sand, combined with a marked tendency of the shield to settle, the shield was badly cramped on the iron and dragged along it at the top. The bearing of the iron on its soft foundation tended to thrust up the bottom in this case also, as shown by the opening of the bottom cross-joints when the bolts were slackened to relieve the strain during a shove. The anticipated cracks in the crown plates, which have been more frequently observed in other tunnels, did not occur here, and were not found elsewhere except in one place in Tunnel *B* where they were traced to a similar action of the shield. The cracks resulting from the movements of the shield, as briefly described above, in this third case were not confined to any particular type, but occurred more frequently at the extreme end of the circumferential flange than at any other point.

The number of broken plates occurring in the river tunnels was 319, or 0.42% of the total number erected. Of these, 52 were found and removed, either before or immediately after a shove, by far the greater number being broken in handling before or during erection. The remaining 267 are considered below.

Repair of Broken Plates.—On the completion of a shove, the tail of the shield lacked about 5 in. of covering the full width of the last ring, and the removal of a plate broken during the shove, therefore, would have exposed the ground at the tail of the shield. With a firm material in the bottom, this introduced no particular difficulties, and, under such conditions, a broken plate was usually removed at once. In the sand, however, and especially on the Manhattan side where it was quick and flowing, the removal of a plate was attended with some danger, and such plates were usually left to be removed on the completion of the tunnel. Many of these had been reinforced by the use of *XX*, *YY*, and steel segments placed adjacent to the break in the following rings.

[Pg 465] After the meeting of the shields, the postponed replacement of the broken segments was taken up. The pressure was raised sufficiently to dry thoroughly the sand outside the segments, which were drilled and broken out usually in quarters as shown on Fig. 1, Plate LXXIII. A steel segment was then inserted in the ring and drawn into place by turnbuckles. The application of the draw-jack, with a pull of about 30 tons to each end successively, brought the plate to a firm bearing on the radial joints at the ends.

Where the broken plate was isolated and was reinforced by steel or extra heavy segments in the adjacent ring, the crack, if slight, was simply caulked to insure water-tightness. If, however, the crack was opened or extended to the web of the plate, the cross-flanges were tied together by a 1-1/2-in. by 7-ft. bolt, inserted through the bolt holes nearest the broken flange. The long bolt acted in the nature of a bow string, and was provided at its ends with two nuts set on opposite sides of the cross-joints to replace the standard bolts removed for its insertion. Fig. 4, Plate LXXIII shows one of these bolts in place. In addition, all broken plates remaining in the tunnel were reinforced with 1-in. twisted-steel rods in the concrete lining, also shown in Fig. 4, Plate LXXIII.

Special Construction at River Shield Junctions.—Dismantling the shields was started as soon as they came to rest in their final position with the cutting edges together. The plans contemplated their entire removal, with the exception of the cylindrical skins and cast-steel cutting edges. Inside the former the standard tunnel lining was erected to within 4 ft. of the heels of the cutting edges. Spanning the latter, and forming the continuous metal tunnel lining, the special construction shown by Fig. 2 was built. This consisted of a 1-1/4 in. rolled-steel ring, 7 ft. long, erected inside the cutting edges, with an annular clearance of 1 in., and two special cast-iron rings shaped to connect the rolled-steel ring with the normal lining. One flange of the special cast-iron rings was of the standard type, the other was returned 9 in. in the form of a ring, the inside diameter of which was the same as the outside diameter of the rolled-steel ring to which it was bolted.

The space between the standard and special construction was of varying width at the various shields, and was filled with a closure ring cast to the lengths determined in the field. Fig. 2 shows
[Pg 466] the completed construction.

Hook-bolts, screwed through threaded holes and buried in 1 to 1 Portland cement grout ejected through similar holes, reinforced the rolled-steel ring against external water pressure. In two of the tunnels the concrete lining was carried completely through the junction, and covered the whole construction, while in the remaining two tunnels it was omitted at the rolled-steel ring, leaving the latter exposed and set back about 3 in. from the face of the concrete.

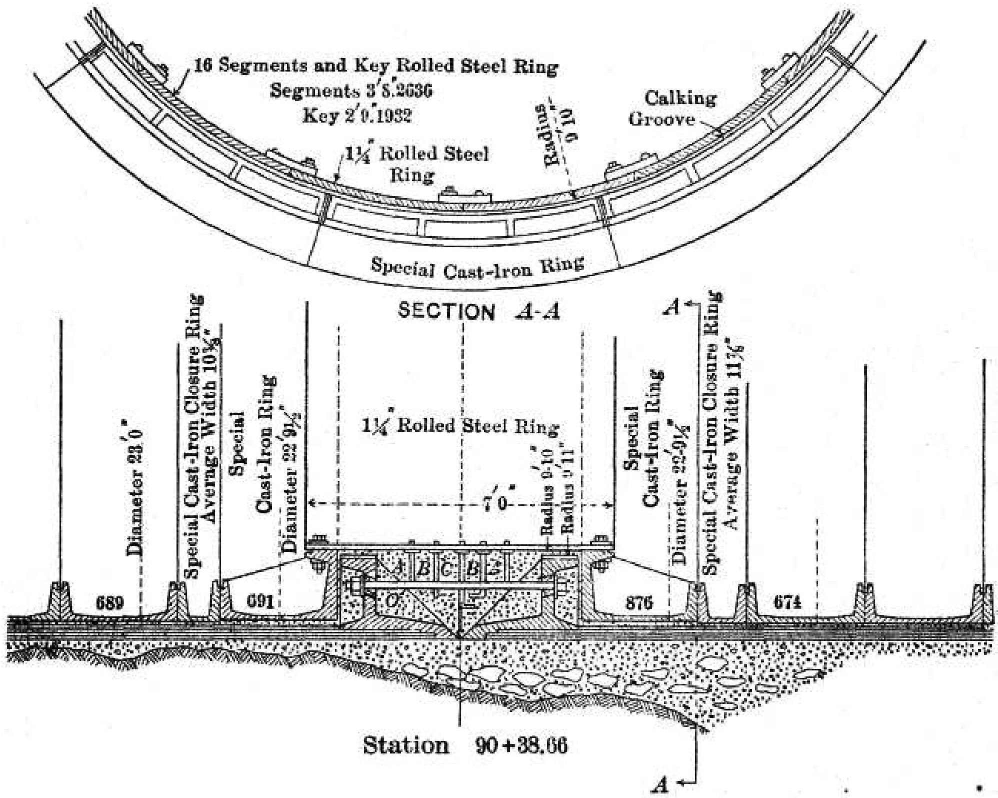

Fig. 2.

Grouting.

Except as previously noted, the voids outside of the tunnel lining were filled with grout ejected through the grout holes in each segment. The possibility was always present that Portland cement, if used for grout in the shield-driven tunnels, would flow forward around the shield and set hard, "freezing" the shield to the rock or the iron lining, or at least forming excrescences upon it, which would render its control difficult. With this in mind, the contractors proposed to substitute an English Blue Lias lime as a grouting material. Grout of fresh English lime containing a moderate quantity of water set very rapidly in air to the consistency of chalk. Its
[Pg 467] hydraulic properties, however, were feeble, and in the presence of an excess of water it remained at the consistency of soft mud. It was not suitable, therefore, as a supporting material for the tunnel.

An American lime, made in imitation of the Lias lime, but having greater hydraulic properties, was tried, but proved unsatisfactory. Two brands of natural cement were also tried and rejected, but a modified quick-setting natural cement, manufactured especially for this work, was eventually made satisfactory, and by far the largest part of the river-tunnel grouting was done with this material mixed 1 to 1 by volume. East of the Long Island shafts the work which was built without shields was grouted principally with Portland cement and sand mixed 1 to 1 by volume.

In the river tunnels large quantities of the English lime were used neat as grout over the top of the tunnel in attempts to stop losses of air through the soft ground. It was not of great efficiency, however, in this respect until the voids outside of the lining had been filled above the crown. Its properties of swelling and quick setting in the dry sand at that point then became of value. The use of dry lime in the face, where the escaping air would carry it into the voids of the sand and choke them, was much more promptly efficacious in checking the loss.

With the exception of the English lime, all grout was mixed 1 to 1 with sand in a Cockburn continuous-stirring machine operated by a 3-cylinder air engine. The grout machine was placed on the lower floor of the trailing platform shown on Plate LXXII, while the materials were placed on the upper platform, and, together with the water, were fed into the machine through a hole in the upper floor. The sand was bagged in the yard, and the cars on which the materials were sent into the tunnels were lifted by an elevator to the level of the upper floor of the trailing platform before unloading.

Great difficulty was experienced in preventing the waste of the fluid grout ahead of the shield and into the tail through the space between it and the iron lining. In a full soft ground section, the first condition did not usually arise. In the full-rock sections the most efficient method of checking the waste was found to be the construction of dams or bulkheads outside the lining between it and the rock surface. For this purpose, at intervals of about 30 ft., the leading ring and the upper half of the preceding one were disconnected and pulled forward sufficiently to give [Pg 468] access to the exterior. A rough dam of rubble, or bags of mortar or clay, was then constructed outside the iron, and the rings were shoved back and connected up. In sections containing both rock and soft ground, grout dams were built at the cutting edge at intervals, and were carried up as high as circumstances permitted.

The annular space at the tail of the shield was at all times supposed to be packed tight with clay and empty bags, but the pugging was difficult to maintain against the pressure of the grout. For a time, 1/2-in. segmental steel plates, slipped down between the jackets and the iron, were used to retain the pugging, but their displacement resulted in a number of broken flanges, and their use was abandoned. In their place, 2-in. segmental plates attached to the jack heads were substituted with more satisfactory results. Notwithstanding these devices, the waste of grout at the tail was very great.

The soft ground material on various portions of the work acted very differently. The clay and "bull's liver" did not cave in upon the iron lining for several hours after the shield had passed, sometimes not for a day or more, which permitted the space between it and the iron to be grouted. The fine gray or beach sand and the quicksand closed in almost at once. The quicksand has a tendency to fill in under the iron from the sides and in places to leave a cavity at about the horizontal diameter which was not filled from above, as the sand, being dried out by the air, stood up fairly well and did not cave against the iron, except where nearly horizontal at the top.

The total quantity of grout used on the work was equivalent in set volume to 249,647 bbl. of 1 to 1 Portland cement grout, of which 233,647 bbl. were ejected through the iron lining, an average of 14.93 bbl. per lin. ft. The cost of grout ejected outside of the river tunnels was 93 cents per bbl. for labor and $2.77 for "top charges." East of the Long Island shaft the corresponding costs were $0.68 and $1.63, the difference being partly due to the large percentages of work done in the normal air at the latter place.

Caulking and Leakage.

Up to August, 1907, the joints between the segments of the cast-iron lining were caulked with iron filings and sal ammoniac, mixed in the proportion of 400 to 1 by weight. With the air pressure balancing the hydrostatic head near the tunnel axis, it was difficult to make the rust- [Pg 469] joint caulking tight below the axis against the opposing water pressure; this form of caulking was also injured in many places by water dripping from service pipes attached to the tunnel lining. A few trials of lead wire caulked cold gave such satisfactory results that it was adopted as a substitute. Pneumatic hammers were used successfully on the lead caulking, but were only used to a small extent on the rust borings, which were mostly hand caulked. Immediately before placing the concrete lining, all leaks, whether in the rust borings or lead, were repaired with lead, and the remainder of the groove was filled with 1 to 1 Portland cement mortar, leaving the joints absolutely water-tight at that time. The subsequent development of small seepages through the concrete would seem to indicate that the repair work should have been carried on far enough in advance of the concreting to permit the detection of secondary leaks which might develop slowly. The average labor cost chargeable against the caulking was 12 cents per lin. ft., to which should be added 21.8 cents for "top charges."

Unfortunately, it was necessary to place the greater part of the concrete lining in the river tunnels during the summer months when the temperature at the point of work frequently exceeded 85°; and the temperature of the concrete while setting was much higher. This abnormal heat, due to chemical action in the cement, soon passed away, and, with the approach of winter, the contraction of the concrete resulted in transverse cracks. By the middle of the winter these had developed quite uniformly at the ends of each 30-ft. section of concrete arch as placed, and frequently finer cracks showed at about the center of each 30-ft. section.

While the temperature of the concrete was falling, a like change was taking place in the cast-iron lining, with resulting contraction. The lining had been erected in compressed air, the temperature of which averaged about 70° in winter and higher in summer. Compressed air having been taken off in the summer of 1908, the tunnels then acquired the lower temperature of the surrounding earth, slowly falling until mid-winter. The contraction of the concrete, firmly bedded around the flanges of the iron, and showing cracks at fairly uniform intervals, probably localized the small corresponding movements of the iron near the concrete cracks, and resulted in a loosening of the caulking at these points. With the advent of cold weather, damp spots appeared in numerous places on the concrete, and small seepages showed through quite [Pg 470] regularly at the temperature cracks, in some cases developing sufficiently to be called leaks. Only a few, however, were measurable in amount.

Early in January small brass plugs were firmly set on opposite sides of a large number of cracks, and caliper readings and air temperature observations were taken regularly throughout the winter and spring. The widths of the cracks and the amount of leakage at them increased with each drop in temperature and decreased as the temperature rose again, but until spring the width of the cracks did not return to the same point with each return of temperature.

The leakage was similar in all four tunnels, but was largest in amount in Tunnel *D*, where, at the beginning of February, the ordinary flow was about 0.0097 cu. ft. per sec., equivalent to 0.00000347 cu. ft. per sec. per lin. ft. of tunnel. Of this amount 0.0065 cu. ft. per sec. could be accounted for at eight of the cracks showing measurable leakage, leaving 0.0032 cu. ft. per sec. or 0.00000081 cu. ft. per sec. per lin. ft. of tunnel to be accounted for as general seepage distributed over the whole length.

It was not feasible to stop every leak in the tunnel, most of which were indicated simply by damp spots on the concrete; a rather simple method was devised, however, for stopping the leaks at the eight or ten places in each tunnel where water dripped from the arch or flowed down the face of the concrete. The worst leak in any tunnel flowed about 0.0023 cu. ft. per sec. To stop these leaks, rows of 1-in. holes, at about 4-in. centers, were drilled with jap drills through the concrete to the flange of the iron. These rows were from 3 to 18 ft. long, extending 1 ft. or more beyond the limits of the leak. The bottoms of the holes were directly on the caulking groove and the pounding of the drill usually drove the caulking back, so that the leak became dry or nearly so after the holes were drilled. If left alone the leaks would gradually break out again in a few hours or a few days and flow more water than before. They were allowed to do this, however, in only a few cases as experiments. After the holes were drilled, the bottom 4 in. next the flange was filled with soft neat cement mortar. Immediately on top of this was placed two plugs of neat cement about 2-1/2 in. long, which were 5 or 6 hours old and rather hard. Each was tamped in with a round caulking tool of the size of the hole driven with a sledge hammer. On top of this were [Pg 471] driven in the same way two more plugs of neat cement of the same size, which were hard set. These broke up under the blows of the hammer, and caulked the hole tight. When finished, the tamping tool would ring as though it was in solid rock. Great pressure was exerted on the plastic mortar in the bottom of the hole, which resulted in the re-caulking of the joint of the iron. No further measurable leakage developed in the repaired cracks, during a period of four months, and the total leakage has been reduced to about 0.002 cu. ft. per sec. in each tunnel, an average of 0.00000051 cu. ft. per sec. per lin. ft.

Sump and Pump Chambers.

To take care of the drainage of the tunnels, a sump with a pump chamber above it was provided for each pair of tunnels. The sumps were really short tunnels underneath the main ones and extending approximately between the center lines of the latter. They were 10 ft. 9-1/2 in. in outside diameter and 44 ft. long. The water drops directly from the drains in the center lines of the tunnels into the sumps. Above the sumps and between the tunnels, a pump chamber 19 ft. 5 in. long was built. Above the end of the latter, opposite the sump, a cross-passage was constructed between the bench walls of the two tunnels. This passage gives access from either tunnel through an opening in the floor to the pump chamber and through the latter to the sump.

From the preliminary borings it was thought that the sumps were located so that the entire construction would be in rock. This proved to be the case on Tunnels *C* and *D*, but not on Tunnels *A* and *B*. The position of the rock surface in the latter is shown by Fig. 3. After the excavation was completed in Tunnel *B*, January 1st, 1908, the plates were removed from the side of the tunnel at the cross-passage, and a drift was driven through the earth above the rock surface across to the lining of Tunnel *A*. The heading was timbered as shown by Fig. 3. There was practically no loss of air from the drift, but the clay blanket had been removed from over this locality and the situation caused some anxiety. In order to make the heading as secure as possible, the 24-in. I-beams, shown on Fig. 3, were attached to the lining of the two tunnels. The beams formed a support for the permanent concrete roof arch of the passage, which was placed at once. At the same time plates were removed from the bottom in Tunnel *B* over the site of the sump, and a heading was [Pg 472] started on the line of the sump toward Tunnel *A*. As soon as the heading had been driven beyond the center line of the pump chamber, a bottom heading was driven from a break-up westward in the pump chamber and a connection was made with the cross-passage. The iron lining of the pump chamber was next placed, from the cross-passage eastward. The soft ground was excavated directly in advance of the lining, and the ground was supported by polings in much the same manner as described for shield work. On account of bad ground and seams of sand encountered in the rock below the level of the cross-beams, the entire west wall of the pump chamber was placed before enlarging the sump to full size. This was also judicious, in order to support as far as possible the iron lining of the tunnels. The sump was then excavated to full size. The iron lining of the sump and the east wall of the pump chamber were placed as soon as possible. The voids outside the iron lining of the sump and the pump chamber were filled as completely as possible with concrete, and then thoroughly grouted. Finally, the concrete lining was put in place inside of the iron.

As shown by Fig. 3, the excavation of these chambers left a considerable portion of the iron lining of the tunnels temporarily unsupported on the lower inner quarter. To guard against distortion, a system of diagonals and struts was placed as shown.

The floor of the pump chamber was water-proofed with felt and pitch in a manner similar to that described for the caissons at Long Island City. It was not possible to make the felt stick to the vertical walls with soft pitch, which was the only kind that could be used in compressed air, and, therefore, the surfaces were water-proofed by a wall of asphalt brick laid in pitch melting at 60° Fahr. Forms were erected on the neat line, and the space to the rock was filled with concrete making a so-called sand-wall similar to that commonly used for water-proofing with felt and pitch. The bricks were then laid to a height of four or five courses. The joints were filled with pitch instead of mortar. Sheets of tin were then placed against the face of the wall and braced from the concrete forms. As much pitch as possible was then slushed between the brick and the sand-wall, after which the concrete in the main wall was filled up to the top of the water-proofing course. The tin was then withdrawn and the operation repeated. This method was slow and expensive, but gave good results. Ordinary pitch could not be used on account of the fumes, [Pg 474] which are particularly objectionable in compressed air. The 60° pitch was slightly heated in the open air before using.

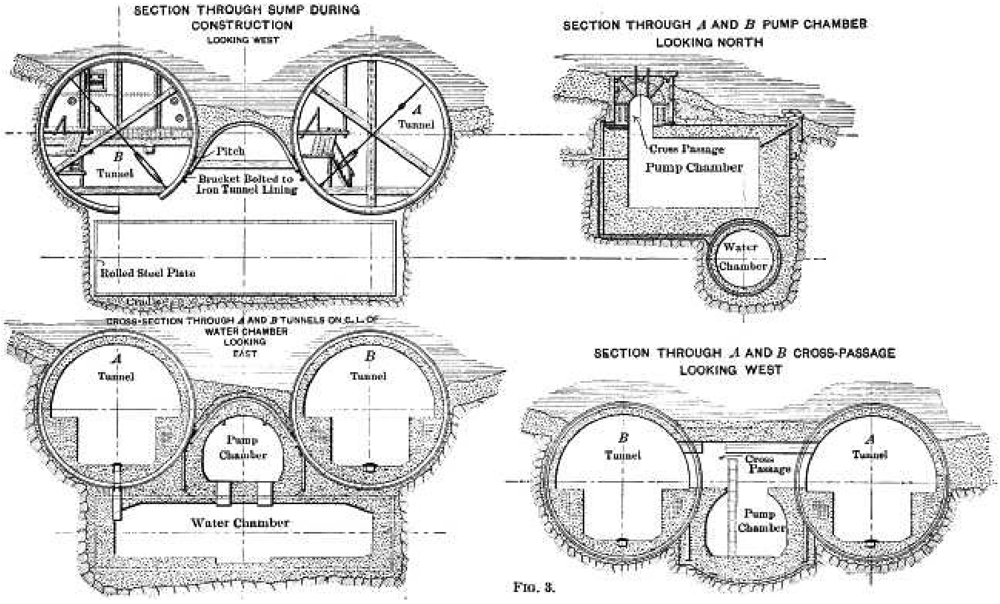

Fig. 3.

The sump and pump chamber on Tunnels *C* and *D* differed from the one described only in minor details; but, being wholly constructed in rock, presented fewer difficulties and permitted a complete envelope of water-proofing to be placed in the top.

Concrete Lining.

The placing of concrete inside the iron tube was done by an organization entirely separate from the tunneling force. A mixing plant was placed in each of the five shafts. The stone and sand bins discharged directly into mixers below, which, in turn, discharged into steel side-dump concrete cars. All concrete was placed in normal air.

The first step, after the iron lining was scraped clean and washed down and all leaks were stopped, was the placing of biats, marked *B* on Plate LXXIV. These were made up of a 6 by 12-in. yellow pine timber, 17 ft. long, with two short lengths of the same size spliced to its ends by pieces of 12-in. channels, 3 ft. 9 in. long, clamped upon the sides. These biats were placed every 5 ft. along the tunnel in rings having side keys. Next, a floor, 13 ft. wide, was laid on the biats and two tracks, of 30-in. gauge and 6-1/2-ft. centers, were laid upon the floor. There were three stages in the concreting. Fig. 2, Plate LXXIV, shows the concrete in place at the end of the first, and Fig. 3, Plate LXXIV, at the end of the second stage. The complete arch above the bench walls was done in the last operation.

Two 3 by 10-in. soldiers (*SS* in Figs. 1 and 2, Plate LXXIV) were fastened to each biat and braced across by two horizontal and two diagonal braces. To each pair of soldiers a floor template, *T*, was then nailed. The form for the center drain was then suspended as shown in Fig. 1, Plate LXXIV. Three pieces of shuttering, *FFF*, 20 ft. long, were then nailed to the bottom of the soldiers. One is all that would have been needed for the first concrete placed, but it was easier to place them at this stage than later, when there was less room. Three rough shutters were also nailed to the curved portion for the floor template. Opposite each biat, a bracket, *bb*, was then nailed, which carries a set of rough boards which formed the risers for the duct steps. Everything [Pg 475] was then ready for concreting except that, where refuge niches occurred, a form for the portion of the niche below the seat was nailed to the shuttering. This form is shown at *R* in Fig. 1, Plate LXXIV.

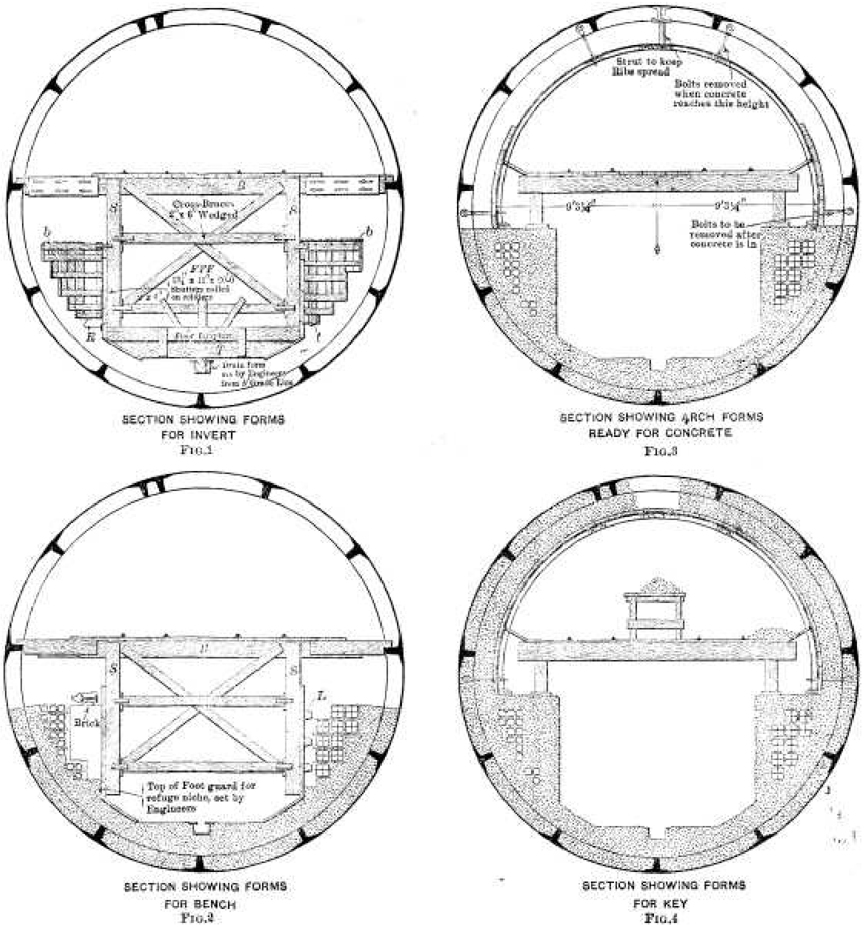

Plate LXXIV

The concrete was dumped down on each side from side-dump cars standing on the track, and, falling between the risers for the duct steps, ran or was shoveled under the forms and down into the bottom. The horizontal surface on each side the center drain was smoothed off with a shovel. The workmen became very skillful at this, and got a fairly smooth surface. This concrete was usually placed in lengths of 45 or 60 ft. After setting for about 24 hours, the brackets, *bb*, were removed, together with the shuttering on the steps. The triangular pieces, *t* in Fig. 1, Plate LXXIV, were not removed until later. Instead, a board was laid upon this lower step on which the duct layers could work. This and the triangular piece were not removed until just before the bench concrete was placed. This was important, as otherwise the bond between the old and new concrete would be much impaired by dirt ground into the surface of the old concrete. The ducts were then laid, as shown in Fig. 2, Plate LXXIV.

The remaining shutters for the face of the bench walls were then placed. The remainder of the forms for the refuge niches, *RR*, in Fig. 1, Plate LXXIV, were nailed to the shutters, the steel beam over the niche was laid in place, the forms for the ladders, *L* in Fig. 2, Plate LXXIV, which occur every 25 ft., were tacked to the shutters, the shutters and forms were given a coat of creosote oil, and then all was ready for placing the bench concrete.

The specifications required a 2-in. mortar face to be placed on all exposed surfaces and the remainder to be smoothed with a trowel and straight-edge. After about 48 hours, the biats were blocked up on the bench, and all forms between the bench walls below the working floor were removed.

The centering for the arch concrete consisted of simple 5 by 3-1/2 by 5/16-in. steel-angle arch ribs, curved to the proper radius, spaced at 5-ft. intervals. Each rib was made up of two pieces spliced together at the top. Two men easily handled one of these pieces. After splicing, the rib was supported by four hanger-bolts fastened to the iron lining as shown in Fig. 3, Plate LXXIV.

In the early part of the work, two additional bolts were used about half way up on the side between the upper and lower hanger-bolts. It was soon found that by placing the strut between the tunnel lining and the crown of the rib, these hanger-bolts could be dispensed with. The lagging was of 3-in. dressed yellow pine, 12 in. wide, and in 15-ft. lengths. Each piece had three saw cuts on the back, from end to end, allowing it to be bent to the curve of the arch; it was kept curved by an iron strap screwed to the back. The arches were put in, either in 15, 30 or 45-ft. lengths, depending on what was ready for concrete and what could be done in one continuous working. The rule was that when an arch was begun, the work must not stop until it was finished. An arch length always ended in the middle of a ring. The lagging was placed to a height of about 6 ft. above the bench before any concreting was done. When the concrete had been brought up to that point, lagging was added, one piece at a time, just ahead of the concrete, up to the crown, where a space of about 18 in. was left. When the lagging had reached the upper hanger-bolts, they were removed, which left only the two bottom bolts fixed in the concrete. Most of these were unscrewed from the eye and saved, as tin sleeves were placed around them before concreting. Two cast-iron eyes were lost for every 5 ft. of tunnel. To place the key concrete, a stage was set up in the middle of the floor, and, beginning at one end, about 2 ft. of block lagging was placed. Over this, concrete was packed, filling the key as completely as possible. This was done partly by shoveling and using a short rammer, and partly by packing with the hands by the workmen, who wore rubber gloves for the purpose. Another 2 ft. of lagging was then placed, and the operation was repeated, and thus working backward, foot by foot, the key was completed. This is the usual way of keying a concrete arch, but in this case the difficulty was increased by the flanges of the iron lining. It was practically impossible to fill all parts of the pockets formed by these flanges. To meet this difficulty, provision was made for grouting any unfilled space. As the concrete was being put in, tin pipes were placed with their tops nearly touching the iron lining, and their bottoms resting on the lagging. Each pocket was intended to have two of these pipes, one to grout through and the other to act as a vent for the escape of air. Each center key ring had six pipes, and each side key had eight. The bottoms of the pipes were held by a single nail driven half way into the lagging. This served to keep the pipes in position and to locate them after the lagging was taken down.

[Pg 477] The cost of labor in the tunnels directly chargeable to concrete was $1.80 per cu. yd. The top charges, exclusive of the cost of materials (cement, sand, and stone), amounted to $3.92.

Electric Conduits.

In one bench wall of each tunnel there were fifteen openings for power cables and in the other, between the river shafts, there were forty openings for telephone, telegraph, and signal cables. East of the Long Island shaft, the number of the latter was reduced to twenty-four. The telephone ducts were all of the four-way type. The specifications required that the power ducts should have an opening of not less than 3-1/2 in., nor more than 3-7/8 in., and that after laying they should pass a 4-ft. mandrel, 3-3/8 in. at the leading end and 2-5/8 in. at the other. The outside dimension was limited between 5 and 5-3/8 in. The openings of the four-way ducts were required to be not less than 3-3/8 in., nor more than 3-5/8 in., and after laying to pass a 5-ft. mandrel, 3-1/4 in. at the leading end and 2-1/2 in. at the other. The outside dimensions were limited between 9 and 9-1/2 in. All were to be laid in 1/4-in. beds of mortar. The specifications were not definite as to the shape of the opening, but those used were square with corners rounded to a radius of 3/8 in. The four-ways were 3 ft. long, and the singles, 18 in.

A study of the foregoing dimensions will show that the working limits were narrow. Such narrow limits would not pay for the ordinary conduit line in a street, where there is more room. In the tunnel greater liberality meant either reducing the number of conduits or encroaching on the strength of the concrete tunnel lining. The small difference of only 1/8 in. in the size of the mandrel, or a clearance of only 1/16 in. on each side, no doubt did increase the cost of laying somewhat, though not as much as might at first be supposed. All bottom courses were laid to a string, in practically perfect line and grade, and all joints were tested with mandrels which were in all openings, and pulled forward as each piece of conduit was laid. As the workmen became skillful, the progress was excellent.

All costs of labor in the tunnel chargeable to duct laying amounted to $0.039 per ft. of duct; top charges brought this up to $0.083.

The serious problem was to guard against grout and mortar running into the duct opening through the joints from the concrete, which was a rather wet mixture. Each joint was wrapped,
[Pg 478] when laid, with canvas, weighing 10 oz. per sq. yd., dipped in cement grout immediately before using. These wraps were 6 in. wide, and were cut long enough to go around the lap about the middle of the duct. As soon as all the ducts were laid, the entire bank was plastered over with fairly stiff mortar, which, when properly done, closed all openings. The plastering was not required by the specifications, but was found by the contractor to result in a saving in ultimate cost.

The concrete on the two sides of the bank of ducts was bonded together by 2 by 1/8-in. steel bonds between the ducts, laid across in horizontal joints. Both ends were split into two pieces, 1 in. long, one of which was turned up and the other down. These bonds projected 1-1/2 in. into the concrete on either side. Where the bond came opposite the risers of the duct step, against which the ducts were laid, recesses were provided for the projecting bond. This was done by nailing to the rough shutters for the steps a form which when removed left a dove-tailed vertical groove. This form was made in two pieces, one tapering inward and the other with more taper outward. As the bonds were placed, these grooves were filled with mortar.

The ducts usually received their final rodding with the specification mandrel a month or more after they were laid, after which all openings into splicing chambers were stopped by wooden plugs, 8 in. long tapering from 3-3/4 in. at one end to 2-3/4 in. at the other end, and shaped to fit the opening tightly. At first the plugs were paraffined, to keep them from swelling and breaking the ducts, but were not successful, as the paraffin lubricated them so that they would not stay in place. They were expensive, and there was some swelling in the best that were obtained. A better plug was made by using no paraffin, but by making six saw cuts, three horizontal and three vertical, in the larger end, cutting to within about 2 in. of the smaller end. The swelling of the wood was then taken up by the saw cuts and the spring of the wood.

The splicing chambers are at 400-ft. intervals. They are 6 ft. long, 4 ft. 9 in. high, with a width varying from 3 ft. 2 in. at the top to 1 ft. 2 in. at the bottom.

FOOTNOTES:

[A] Presented at the meeting of December 15th, 1909.

[B] *Transactions*, Am. Soc. C. E., Vol. LXIX. p. 1.

[C] *Minutes of Proceedings*, Inst. C. E., Vol. CXXX, p. 50.

[D] The lead of the shield is the angular divergence of its axis from the axis of the tunnel and, in this tunnel, was measured as the offset in 23 ft. It was called + when the shield was pointed upward from grade, and - when pointed downward.

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