AMERICAN SOCIETY OF CIVIL ENGINEERS

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Paper No. 1359

THE ASTORIA TUNNEL UNDER THE EAST RIVER FOR GAS DISTRIBUTION IN NEW YORK CITY*

By John Vipond Davies, M. Am. Soc. C. E.

With Discussion by Messrs. F. Lavis, Milton H. Freeman, W. H. Bradley, James F. Sanborn, Edward Wegmann, R. C. Kellogg, W. W. Brush, Thomas H. Wiggin, William Cullen Morris, and John Vipond Davies.

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SYNOPSIS.

The object of this paper is to describe in general the design and construction of a tunnel of large magnitude, but generally simple in character, and to treat more particularly certain difficulties due to physical conditions encountered and methods used in overcoming them.

The work described consisted of sinking two shafts, 242 and 277 ft. deep, respectively, and driving a tunnel, 18 ft. on the vertical and 19 ft. on the horizontal axis, between these shafts, a distance of 4 662 ft., through rock under a river with a depth of water of 100 ft. The main problem was to drive through a zone of decomposed rock extending on the line of the tunnel for a distance of 450 ft.

The paper is divided into fifteen parts, as follows:

1.—History of project and economic reasons for removal of gas plants from Borough of Manhattan to remote districts, by providing transmission of gas through a tunnel under the East River.

2.—General description of the construction.

3.—Description of the plant.

* Presented at the meeting of October 6th, 1915.

4.—Sinking of the shafts, 30 and 42 ft. external diameter, respectively.

5.—Tunnel driving through various rocks under normal conditions. Geology of line of tunnel. Details of work accomplished, and rates of progress.

6.—Tunneling through decomposed rocks under heavy water pressure, together with a geological description of the sheared contacts and conditions as actually found. In this part is described the method of thorough exploration of the rock formation by test drilling in advance and the consolidation of decomposed material by cement grouting to produce a rock formation through which the tunnel could be safely advanced by ordinary blasting. It also describes the methods of drilling, both with percussion and diamond drills, in preparation for grouting; the practical application and extent of the grouting operations; the use of buttresses to face rotten rock to permit of grouting; and the use of emergency bulkheads to secure the safety of the work and the employees.

7.—Flooding of entire work by breaking out of seam before it was securely grouted and controlled.

8.—Unwatering the tunnel and finally plugging and securing the source of water inlet and solidifying the rock; the methods considered and those adopted; the use of the air lift; the condition of the Portland cement after grouting; and the final completion of the tunnel excavation.

9.—Cast-steel lining used through the bad rock section. Assumptions as to the design of the lining, the details, and the erection.

10.—Drainage of the tunnel.

11.—Ventilation of the tunnel.

12.—Lighting of the tunnel.

13.—Triangulation and alignment; methods used and results obtained.

14.—Quantities of items making up the work; and details of costs of all work executed under normal conditions.

15.—The laying of the gas mains in the tunnel. Two lines of 72-in. cast-iron pipe, each pipe length weighing 26 000 lb. Heaviest cast-iron pipe ever manufactured. Special machinery designed and used for laying pipe. Special machine designed and made for testing joints of pipes as laid. Jointing and caulking of pipe mains.

The writer has endeavored to give a comprehensive description of the work as a whole, and to emphasize the portion of the paper covering the operation of passing through the zone of bad rock. It is hoped that the photographs and drawings which accompany the paper will assist in making clear the actual conditions encountered in the field.

1.—Historical.

About 35 years ago, before the general introduction of electricity, the production of gas for illuminating and heating purposes within the City of New York had reached such a point, with reference to the occupation of lands for manufacturing plants and local interference with city development, as to have made it desirable to consider the removal of these industries from the densely populated sections of the city.

Consequently, on June 21st, 1886, at the request of Mr. James W. Smith, then President of the Consolidated Gas Company, a report outlining the future policy of the Company was presented by Mr. William H. Bradley, then Engineer of the 44th Street Station of the Company, now Chief Engineer, in which the removal of the gas plants from Manhattan Island was strongly advocated. Following this report, the question was thoroughly ventilated in the public press, with strong advocacy of the suggestion that all companies then manufacturing gas on the Island of Manhattan should remove to sites outside the city, and that a great central manufacturing plant should be created on the Flushing Meadows, from which gas should be piped to a convenient point whence it might be conveyed by tunnel under the East River to Manhattan. For several years, however, nothing was done with this proposition. At that time the Ravenswood Gas Company, having a small manufacturing plant at the foot of Webster Avenue, East River, supplied gas locally in Long Island City. About 1891, this company was reorganized by Mr. Emerson McMillin, its corporate title was changed to East River Gas Company, and it obtained from the Legislature of the State of New York the necessary franchise rights to supply gas to New York City by a tunnel to be constructed under the East River.

In 1892 and 1893 the writer's firm constructed, for this new corporation, a small tunnel (internal diameter 10 ft. 2 in. in the portions which were iron lined and a rectangular section 10 by 8 ft. in the portions in solid rock) under the East River, crossing the two channels and Blackwell's Island. This tunnel (shown on Plate XXIV) extends from the foot of East 71st Street, Manhattan, to the Ravenswood works of the Company at the foot of Webster Avenue, Long Island City. Borings and soundings were made at close intervals across the channels, and as far as information could be obtained (with the extremely rapid current running in the East and West Channels of the East River), there was every reason to believe that the construction of a tunnel on that line would be through a practically continuous bed of rock, although the geological information indicated clearly the intrusion of a seam of dolomitic limestone under each channel.

The work on this tunnel was let out by contract, and proceeded very slowly for a considerable time, when, having sunk both shafts and having turned the tunnel on the Manhattan side of the river, decomposed rock was encountered at the contact between the gneiss and dolomite under the West Channel. The contractors immediately abandoned the work, and it was then carried on by the writer's firm, as Constructing Engineers, for account, and on behalf, of the Gas Company.

This tunnel was at a depth of nearly 100 ft. below mean low water. The depth of the water in the West Channel was 65 ft., but that in the East Channel was only about 30 ft. Under the West Channel two comparatively narrow sheared contacts in the dolomite rock were badly decomposed; under the East Channel the contacts between the Fordham gneiss, the mica schist, and the dolomitic formation were also extensively distorted, and, to some extent, decomposed, but the whole of this tunnel was completed successfully with the use of air pressure, the depth not being too great to prohibit this method of construction.

After the completion of this tunnel the East River Gas Company passed into the ownership of the Consolidated Gas Company, and thereafter, the Astoria Light, Heat and Power Company was organized to construct a great central gas manufacturing plant to supply gas to all the constituent companies. This plant was established on a large tract of property at Lawrence Point, Long Island, at the northerly end of the channel known as Hell Gate.

For several years gas from both the Astoria and Ravenswood Plants, for the supply of Manhattan and The Bronx, had been carried through a large pipe line to Ravenswood and thence to Manhattan through the 71st Street tunnel in two 36-in. mains. The supply for The Bronx had been conducted in pipes laid in open coffer-dam construction across the Harlem River, involving a devious detour.

About 1903 it became necessary to consider an independent means of conducting to Manhattan the gas manufactured at the Astoria Plant, as at that time the center of gravity of the gas consumption of the Boroughs of Manhattan and The Bronx combined was at a point south of the Harlem River.

Long legal proceedings, to obtain an easement for a right of way for a tunnel or other means of communication, delayed procedure with this undertaking for several years.

The line of this tunnel was definitely fixed by the necessities of the commercial situation, regardless of geological considerations, as the New York terminus had to be at 111th Street and Pleasant Avenue, where the Gas Company had a distributing station, and the Long Island terminus had to be on the property of the Company at Astoria, just north of Winthrop Avenue. The line, therefore, was laid out between these two points, the Astoria end being kept as close as possible to Winthrop Avenue, in order to conform to the final layout planned for the gas holders of the Company. This line passes under Ward's Island, where it was intended to sink an intermediate shaft for construction purposes, and from this shaft it was contemplated to drive a branch tunnel to a point in The Bronx. Borings were made at the sites of the entrance, outlet and intermediate shafts, and the geological features were studied carefully.

As the depth of the water in the channels on this line was somewhat in excess of 100 ft., and was so great that it was impossible to use air pressure, and as the known geological conditions made it certain that the contacts between the gneiss and dolomite formations would give more or less trouble, it was considered desirable to place the tunnel deep in the rock, in order to minimize trouble from open seams. On the other hand, the necessity (in event of a deeper location) for lengthening vertically the pipes for carrying the gas made it undesirable that these shafts should be deeper than was reasonably

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necessary to assure that the tunnel would pass below any serious difficulties of geological contact. Ultimately, the depth for the tunnel was decided on as 186½ ft. below mean sea level at the Manhattan Shaft descending to 218 ft. below that level at the Long Island Shaft. Within a prism on this line and grade, easements for right of way were acquired, and all legal proceedings were completed.

As before stated, these legal proceedings consumed considerable time, and in the interim the center of gravity of gas consumption had moved north of the Harlem River, with every indication that it would extend still farther north; and, by the time the Gas Company was ready to proceed with the work, it had become desirable to discontinue, for the time being, the plan for constructing the tunnel on the original line to 111th Street, and, instead, to proceed with that of delivering gas directly from the Astoria Plant to the Borough of The Bronx. At the same time, the Company did not desire, by any means, to abandon its rights to construct at a later date the tunnel from Astoria to East 111th Street, as originally laid out. This rearrangement necessitated the retention of the shaft near Winthrop Avenue, Astoria, and the purchase of land at Port Morris, at the foot of 132d Street, fronting on the East River, on which to construct a shaft as the northerly outlet of the tunnel, near to, and suitable for a connection with, the distribution system of the Central Union Gas Works, at the foot of 138th Street and Locust Avenue, The Bronx.

The location of the underground prism for the easement for construction of the proposed future tunnel to 111th Street determined the depth of the Astoria Shaft for the tunnel to 132d Street, and an allowance for the necessary drainage gradient toward Astoria determined the limitations of depth at the Bronx Shaft. At the same time, the grade of the tunnel was lowered to the utmost limit permissible within the prism forming the subterranean easement, as it was recognized that on this line the axis of the tunnel would be nearly parallel to the line of strike of the rock, and consequently to the planes of contact between the different geological formations to be penetrated, and therefore, in all probability, would involve more difficulties than the previously projected tunnel to 111th Street, which passed almost at right angles across these contacts. However, the

Gas Company considered that, notwithstanding this, it would be simpler and wiser to face the constructive difficulties than to be under the necessity of adopting a new location which would involve a revival of the entire legal proceedings; and, on this basis, the work hereinafter described was designed and carried out. Plate XXV is a profile of the tunnel and the river bottom.

On account of the uncertainties which might arise in construction, as well as for various other reasons, the Company decided not to invite bids from contractors on this undertaking, but to carry out the work departmentally by its own forces, and the writer's firm was retained as Constructing Engineers in respect to the design and construction.

The following description records for the most part a work of tunnel construction of large magnitude, but comparatively simple in character, excepting only that the general location was at a deep level, with access only at vertical terminal shafts nearly a mile apart, and practically entirely below navigable waterways.

The intention, therefore, in the following presentation, is to describe, in outline only, the work of normal character involved in this construction, and to emphasize more particularly the difficulties encountered, and the methods by which they were overcome.

2.—Construction.

The construction involved in this undertaking consisted of a vertical shaft, 277 ft. deep, on the property of the Astoria Light, Heat and Power Company, at Astoria, a vertical shaft, 242 ft. deep, on private property in The Bronx, and a tunnel connecting these shafts.

Anticipating the future construction of the previously planned tunnel direct to 111th Street, Manhattan, the shaft at Astoria was made larger than the one at The Bronx, in order to accommodate the future shaft installation necessary for the two tunnels; and a short portion of the tunnel on the line to 111th Street, Borough of Manhattan, was constructed, so that, as future necessities arose, this tunnel could be extended without disturbing the Astoria-Bronx service.

The necessities for the gas distribution involved the provision of two 72-in. cast-iron mains from Astoria to The Bronx, with space in the upper portion of the tunnel for future developments and utilities.

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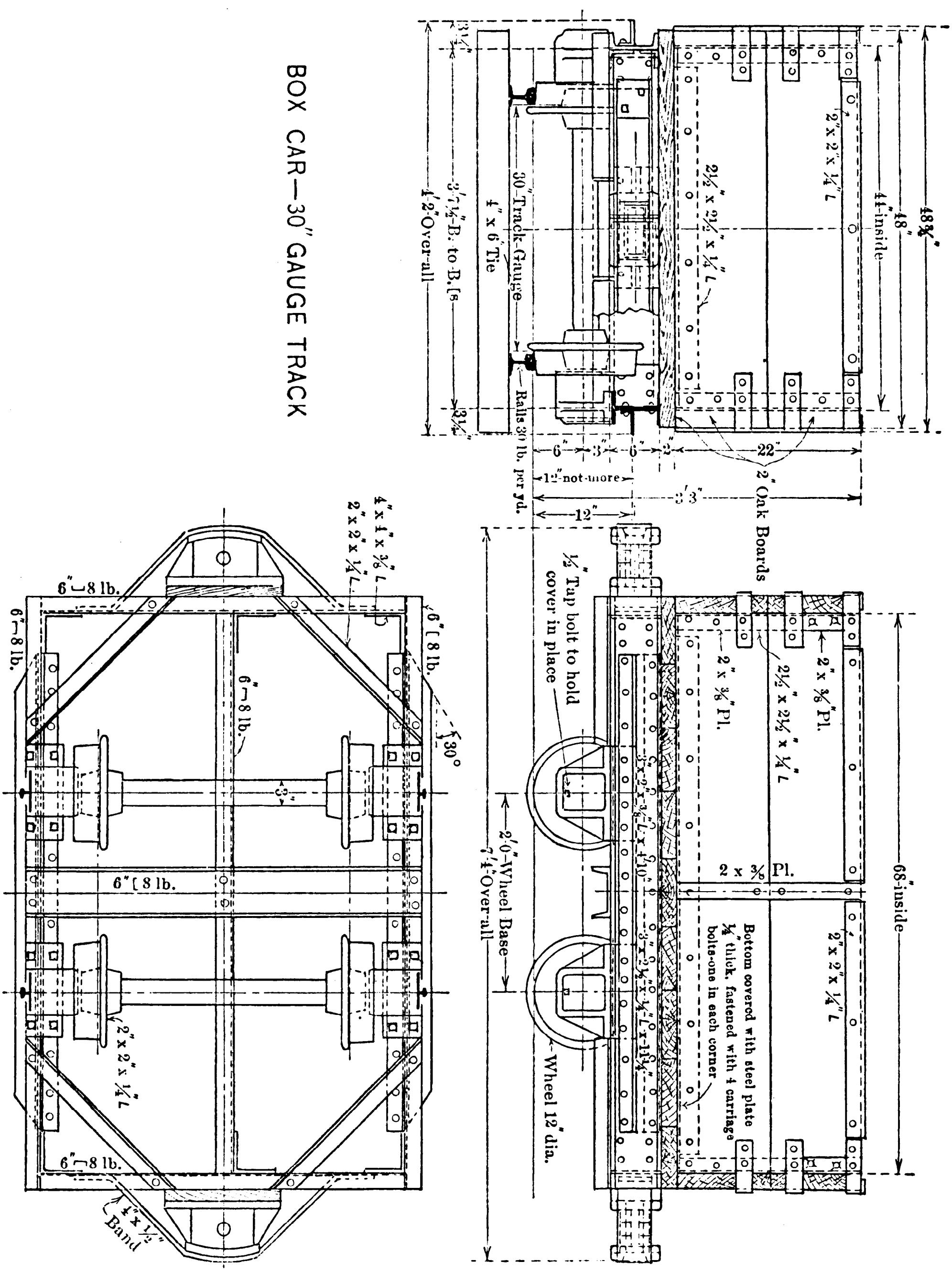
This caused the adoption of a tunnel cross-section 18 ft. on the vertical axis and 19 ft. on the horizontal axis. The vertical pipe risers, elevator frames, etc., made it necessary that the shaft should be 26 ft. in internal diameter at the Bronx terminal, and, though the original plan for an Astoria-Manhattan tunnel required a shaft at Astoria of only this same size, the modification, to provide for both a Bronx and a Manhattan tunnel, made it necessary to increase the internal diameter of the Astoria Shaft to 34½ ft.

Borings at the shaft sites showed that on the Astoria side there was a solid rock floor approximately 50 ft. below the surface of the ground, or about 40 ft. below mean sea level, the overlying material being a natural deposit of sand, gravel, and boulders, which, so near the East River, practically assured considerable water inflow in excavation. At the Bronx Shaft the rock floor was only some 13 ft. below the surface of the ground, and was overlaid with boulders, beach sand, and gravel. Soundings along the line of the tunnel indicated two river channels, each having a water depth of approximately 100 ft., with a high reef lying between them. The geologic survey maps indicated certain changes in the geological formation, with Stockbridge dolomite lying between the Fordham gneiss, which exists at the locations of the two shafts and extends for a considerable distance from each. The two deep-water channels clearly define the contacts at each end between the gneiss and dolomite.

3.—Plant.

The properties for plant use, which were fenced in for the exclusive use of the Tunnel Department, consisted of a plot 255 by 230 ft., aggregating 1.35 acres, at the Astoria Shaft, and a plot 394 by 100 ft., aggregating 0.96 acre, at the Bronx Shaft. For the transportation of men and materials between the two plants, a strong, gasoline, motor-driven boat, commonly called an "oyster boat", was purchased. The hull was of wood, 51 ft. long and 14½ ft. beam. The boat was equipped with an excellent, 25-h.p., direct-driven engine, with screw propeller.

In laying out the plant, careful consideration was given the question of water transportation for excavated material, involving the use of scows and the utilization of the excavated material to fill other lands owned by the Company. A dock existed at the Astoria plant, but there was only a broken rock shore with extremely steep slopes



BOX CAR—30" GAUGE TRACK

FIG. 1.

at the Bronx plant, at which site a crib dock had to be built. At the Astoria dock, 230 ft. frontage was allotted to the Tunnel Department, and this provided berths for two scows; at the Bronx dock only one scow could be docked on the frontage of 108 ft.

As the tunnel was to be entirely in rock, it was desirable to use a car of as large a capacity as possible, with its body so low that a man could readily load it. For handling rock excavation the writer has found that a car having a wooden body is more convenient and economical in operation and maintenance than a steel car. Figs. 1 and 3 illustrate the car designed for this purpose; it consisted of a substantial steel underframe with an oak box body. Dumping arrangements were avoided, as they would have introduced additional height and an increase in mechanism subject to damage.

The dumps, which were placed directly over the scows at the docks, consisted of a revolving tipple, Fig. 2, such as used in coal-mining practice, operated with a 3-cylinder air engine, and the cars were turned completely over in discharging into the chutes.

In order to discharge excavated material into the scows, an elevated deck was built at each shaft, extending from the shaft to the dock. Having ample space at the Astoria Shaft, a trestle loop was built entirely around the shaft location, so that the cars could be operated around the loop, with an extension to the dock, as well as a connection to the rock crusher which was used during part of the tunnel construction. Electric locomotives were used for operating the cars on these trestles between the shafts and the docks. Although there were two such locomotives at each shaft, only one was in service at any given time. These were 3-ton mine locomotives, manufactured by the Westinghouse Electric Company, equipped with two 8-h.p. 250-volt, direct-current motors, with a drawbar pull of 900 lb. at 6.6 miles per hour. Power for the locomotives was supplied by third-rail contact from the tunnel lighting circuit.

The mechanical plant at each shaft was planned with the expectation that considerable water (and consequent pumping) would be encountered in the tunnel driving, and that a full complement of rock drills and labor-saving devices would be necessary, and with the intention of constructing half the length of the tunnel from each shaft. The following plant was used.

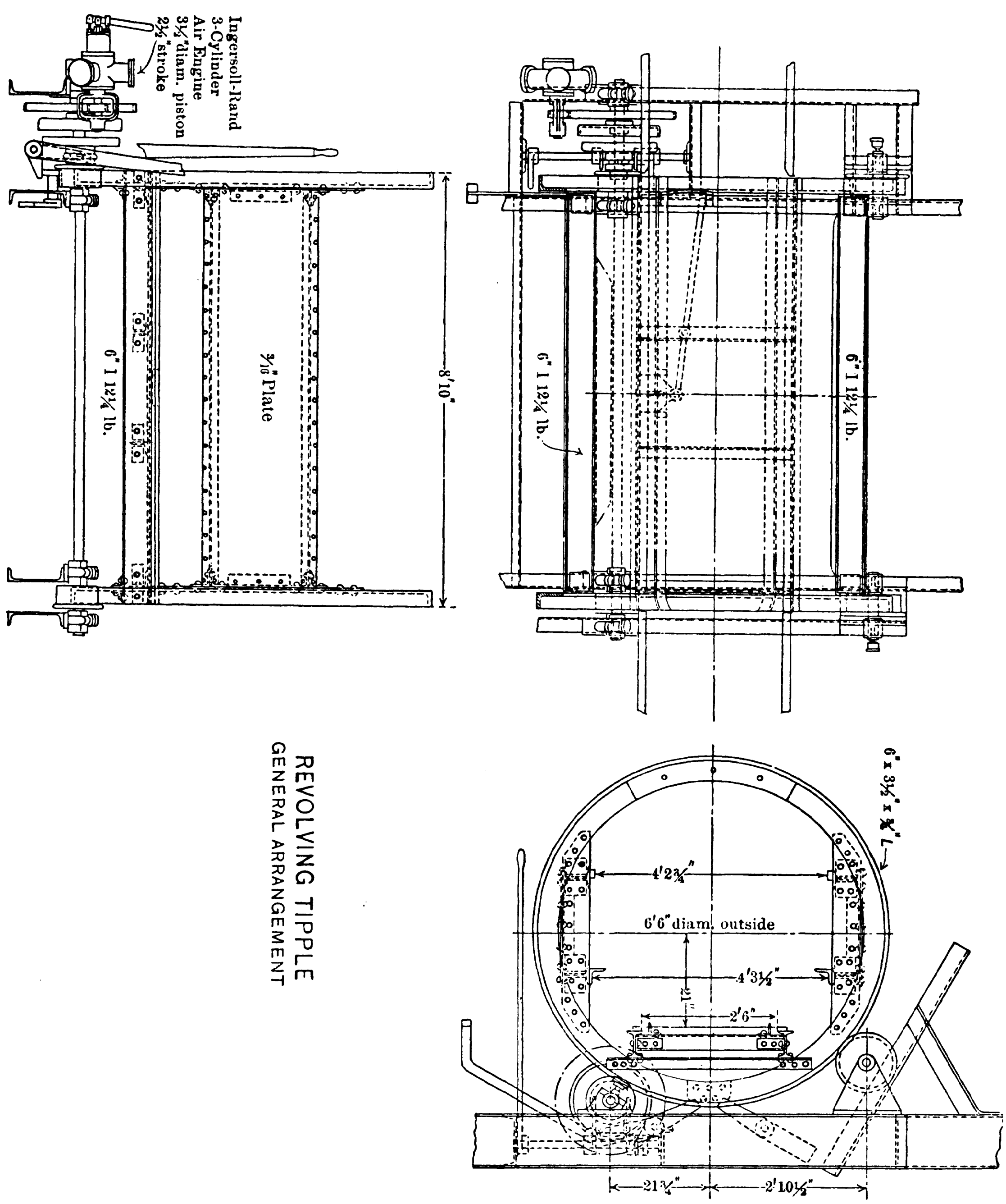

Ingersoll-Rand
3-Cylinder
Air Engine
3½"diam. piston
2½"stroke
6" I 12¼ lb.
⁵⁄₁₆" Plate
8'10"
6" I 12¼ lb.
6" I 12¼ lb.
REVOLVING TIPPLE
GENERAL ARRANGEMENT
6" x 3½" x ⅜" L
4'2¾"
6'6" diam. outside
4'3½"
21"
2'6"
21¾"
2'10½"

FIG. 2.

Astoria Plant.

Boiler-Room.—

Four 302-h.p. Heine water-tube boilers, } 1 840 total boiler h.p.
Two 316-h.p. " " " " }

Six 20-in. Typhoon turbine blowers—L. J. Wing Manufacturing Company.

Engine-Room.—

Two 100-lb. pressure, Ingersoll-Rand air compressors; total capacity, 3 200 cu. ft. per min.

Two 42-in. Ingersoll-Rand after-coolers.

Two 54 by 120-in. Ingersoll-Rand air receivers.

One hot-well tank, 48 in. diameter, 96 in. high—G. Stuebner.

Two 50-kw., 200-ampere, 250-volt, General Electric generators.

Two 75-h.p. Harrisburg Foundry and Machine Company, horizontal engines.

One Walker Electric Company switch-board for 250-kw. generators.

Two 1 200-boiler h.p. Worthington boiler feed pumps.

One 250-gal. per min. Worthington duplex pump.

One surface condenser and feed-water heater combined—12 600 lb. of steam per hour—Wheeler Condenser and Engineering Company.

One vacuum oil separator and simplex pump—12 000 lb. steam per hour—Warren Webster Company and Warren Steam Pump Company.

Two closed water-tube feed-water heaters—800 h.p. to raise 24 000 lb. of water per hour from 60 to 200° Fahr.—F. L. Patterson and Company.

One 30-gal. oil filter—Hall Manufacturing Company.

Surface.—

One 45-ft. derrick.

Two 50-ft. derricks.

Three Lidgerwood Manufacturing Company hoisting engines for derricks.

One 1-cu. yd. Smith concrete mixer and engine.

One No. 4 gyratory stone crusher—Allis-Chalmers Company.

One 8 by 12-in. Buckeye vertical engine.

One 42-in. Ingersoll-Rand air reheater.

Two 3-ton electric mine locomotives—Westinghouse Electric and Baldwin Company.

Blacksmith-Shop.—

One Ingersoll-Rand Ajax drill sharpener.

One Ingersoll-Rand furnace.

Two 36 by 36-in. air forges—Buffalo Forge Company.

Two hand forges—Buffalo Forge Company.

Machine-Shop.—

One 18-in. horizontal lathe—Niles Bement Pond Company.

One 16-in. shaper " " " "

One 24-in. drill press " " " "

One $\frac{3}{4}$ to $1\frac{1}{2}$-in. bolt-threading machine—Wells Brothers.

One $2\frac{1}{2}$ to 8-in. pipe-threading machine—Curtis and Curtis.

One power hack-saw—Frevert Machine Company.

One 12-in. emery wheel—Niles Bement Pond Company.

One 6 by 6-in. vertical engine—B. F. Sturtevant.

Carpenter-Shop.—

One 16 to 20-in. wood-frame rip-saw, $7\frac{1}{2}$ to 15 h.p.—American Woodworking Machine Company.

One swing-saw.

One band-saw, 1-in. saw, 33-in. band wheels—H. B. Smith and Company.

Two Fairbanks grindstones.

One 6 by 6-in. vertical engine—B. F. Sturtevant.

Shaft Hoisting Equipment.—

One 10 by 12-in. reversible, compound-geared, elevator engine—Lidgerwood Manufacturing Company.

One $12\frac{1}{4}$ by 15-in. reversible, link-motion, single-geared, elevator engine—Lidgerwood Manufacturing Company.

One 66 by 72-in. passenger elevator cage.

Two 66 by 96-in. material elevator cages.

Four $1\frac{1}{2}$-yd. shaft buckets—G. Stuebner.

Three $\frac{3}{4}$-yd. tip buckets—G. Stuebner.

Bronx Plant.

Boiler-Room.—

Three 375-h.p., Babcock and Wilcox boilers—1 125 total boiler h.p.

One induced-draft fan and engine.

Engine-Room.—

Two 100-lb. pressure, Ingersoll-Rand air compressors; total capacity, 3 200 cu. ft. per min.

Two 42-in. Ingersoll-Rand after-coolers.

Two 54 by 120-in. Ingersoll-Rand air receivers.

One hot-well tank, 48-in. diameter, 96 in. high—G. Stuebner.

Two 50-kw., 200-ampere, 250-volt, General Electric generators.

Two 75-h.p. Harrisburg Foundry and Machine Company, horizontal engines.

One Walker Electric Company switch-board for 250-kw. generators.

Two 1 200-boiler h.p. Worthington boiler feed pumps.

One 250-gal. per min. Worthington duplex pump.

One surface condenser and feed-water heater combined—12 600 lb. of steam per hour—Wheeler Condenser and Engineering Company.

One vacuum oil separator and simplex pump—12 000 lb. steam per hour—Warren Webster Company and Warren Steam Pump Company.

One 30-gal. oil filter.

Surface.—

Two 50-ft. derricks.

Two 8¼ by 10-in. non-reversible engines for derrick—Lidgerwood Manufacturing Company.

One 1-cu. yd. Smith concrete mixer and engine.

One 42-in. Ingersoll-Rand air reheater.

One 60-h.p. vertical boiler—Wickes Brothers.

Two 3-ton electric mine locomotives—Westinghouse and Baldwin Companies.

Shaft Hoisting Equipment.—

One 10 by 12-in., reversible, compound-geared, elevator engine—Lidgerwood Manufacturing Company.

One 12¼ by 15-in., reversible, link-motion, single-geared elevator engine—Lidgerwood Manufacturing Company.

One 66 by 72-in. passenger elevator cage.

Two 66 by 96-in. material elevator cages.

Four 1½-yd. shaft buckets—G. Stuebner.

Three ¾-yd. tip buckets—G. Stuebner.

Tunnel Equipment.

Rock-Drilling Equipment.—

Six Ingersoll-Rand rock drills, $2\frac{1}{4}$-in. pistons.

Thirty Ingersoll-Rand rock drills, $3\frac{1}{4}$-in. pistons.

Six Ingersoll-Rand rock drills, $3\frac{5}{8}$-in. pistons.

Twenty-three Ingersoll-Rand hand hammer drills.

Sixteen Ingersoll-Rand $5\frac{1}{2}$ by 96-in. drill columns.

Twenty-eight Ingersoll-Rand drill tripods.

Concrete Equipment.—

Two Blaw steel arch and side-wall forms.

Two " " side-wall forms.

Twelve bottom-dump buckets—G. Stuebner.

Grouting Equipment.—

Two 200-lb. pressure, Ingersoll-Rand, straight-line, air compressors. One 500-lb. pressure, Ingersoll-Rand, straight-line, air compressors. Two 36 by 96-in. air receivers—Logan Iron Works.	Total capacity 900 cu. ft. per min. In Engine-room.

Two 500-lb. pressure, cast-steel, grout pans, without engines.

Eight 200-lb. pressure, grout machines and engines—Cockburn Barrow and Machine Company.

Pumping Plant.—

Two	Cameron	piston	pumps,	115	gal.	per	min.
One	"	sinking	"	200	"	"	"
Five	"	piston	"	330	"	"	"
Nineteen	"	"	"	600	"	"	"
One	"	"	"	800	"	"	"
One	"	"	"	1 000	"	"	"

Rolling Stock and Haulage.—

Two 8 by 10-in. endless-cable, haulage engines—Lidgerwood Manufacturing Company.

Four 5 by 6-in. single-drum, hoisting engines—Lidgerwood Manufacturing Company.

One hundred $1\frac{1}{2}$-yd. wooden mine cars.

Thirty "V" steel, side-dump cars.

Ventilating Plant.—

Two 12-in. Sirocco fans with motors—American Blower Company.

One 30-in. ventilating fan and engine—B. F. Sturtevant.

One 42-in. centrifugal blower and engine—B. F. Sturtevant.

4.—Shaft Sinking.

Shaft Sinking in Earth.

Astoria Shaft.—The sinking of the Astoria Shaft began on September 12th, 1910. Steel sheet-piling of United States Steel Company section was used for the exterior sheeting through the earth section, for a depth of 52 ft., and was braced with 16-sided timber frames, 4 ft. apart, strapped at the joints with steel plates, to which were attached turnbuckle tie-rods extending across the shaft for use in maintaining the circular form. (Fig. 4.) The dump trestle having been constructed to circular form at a height of 15 ft. above the ground, and the excavation being removed to 8 ft. below the ground, a frame was prepared to the correct circular form, plumbed accurately below the trestle form, and served as a guide for driving the sheet-piling. The piling was cut in two lengths for the total depth, with joints staggered, and was driven with an Arnott 2 000-lb. steam pile-hammer suspended from a derrick.

Excavation was removed as the sheet-piling was driven, in order to avoid any distortion by over-driving against boulders or rock.

Having sunk the shaft to rock level, excavation was carried down into the rock about 4 ft. below the point of the piling, and concrete was placed to half the ultimate thickness for the full depth of the excavation, in order to secure the sheet-piling and timber frames from injury during the further extension of the shaft construction.

Bronx Shaft.—At the Bronx Shaft, the shallow depth of the overlying soil and material, as well as its character, made it unnecessary to use steel sheet-piling. Wooden sheeting of 4-in. tongued and grooved stuff, supported by 12-sided timber frames, 4 ft. apart, was used through the 13 ft. of earth to rock level; the permanent lining inside this sheeting was concreted on reaching the rock floor.

Shaft Sinking in Rock.

Shaft sinking in rock was carried out by the ordinary methods, the usual practice being to line up with concrete every 30 ft., as the rock was of treacherous character, and the introduction of the lining insured the employees against accidents.

For hoisting and removing the rock excavated from the shafts, and to avoid the danger of using a swinging bucket operated from the boom of a derrick, the permanent head-frame, Fig. 5, to be equipped later for the use of elevator cages, was erected, with overhead hoisting sheaves and the regular elevator hoisting engines. One of these elevator wells was then fitted with guide-framing below the landing, and at the level of the landing a broad-gauge track crossed the elevator opening, with trap-doors fitted to insure safety. The spoil buckets were hoisted through this trap and landed on a flatcar run through the elevator opening before the hoisting rope was detached.

Water entered from numerous rock joints at various points in sinking the shafts, but not in such volume as to retard the progress of the work, except by the time lost in the removal by the derrick of the pumps and hose when blasting. This shaft water was readily handled in each shaft by one 350-gal. per min. steam-driven pump.

Two water rings were placed in each shaft as the sinking proceeded, in order to intercept the water seepage and prevent it from pouring on the men working below. Each ring was simply a 6-in. wooden shelf with gutter board sheathed with zinc, and a 3-in. pipe extending to the shaft bottom for drainage. Later, these leaks were stopped by grouting, while the driving of the tunnel was in progress.

Astoria Shaft.—At the bottom of the Astoria Shaft the design provided for an enlargement, about 41 ft. high, 34½ ft. wide, and extending some 19 ft. beyond the neat shaft lines. This was to be used ultimately as an operating chamber for the distribution of gas, but it, as well as the short length of 100 ft. of tunnel in the direction of the future Manhattan Shaft at 111th Street, was utilized, during the construction of the tunnel, as a pump chamber and store-room. This enlargement extended 16 ft. below the tunnel invert, and, in addition, contained a 5-ft. circular sump 8 ft. deep, so that ample provision was afforded for the accumulation of the expected water flows and for settling any solid matter carried with the water.

Bronx Shaft Sump.—As the tunnel drained southward toward Astoria, a similar sump was not required in the Bronx Shaft, but ample precautions were taken by the construction of a rectangular sump, 21 ft. long, 12 ft. wide, and 8½ ft. deep.

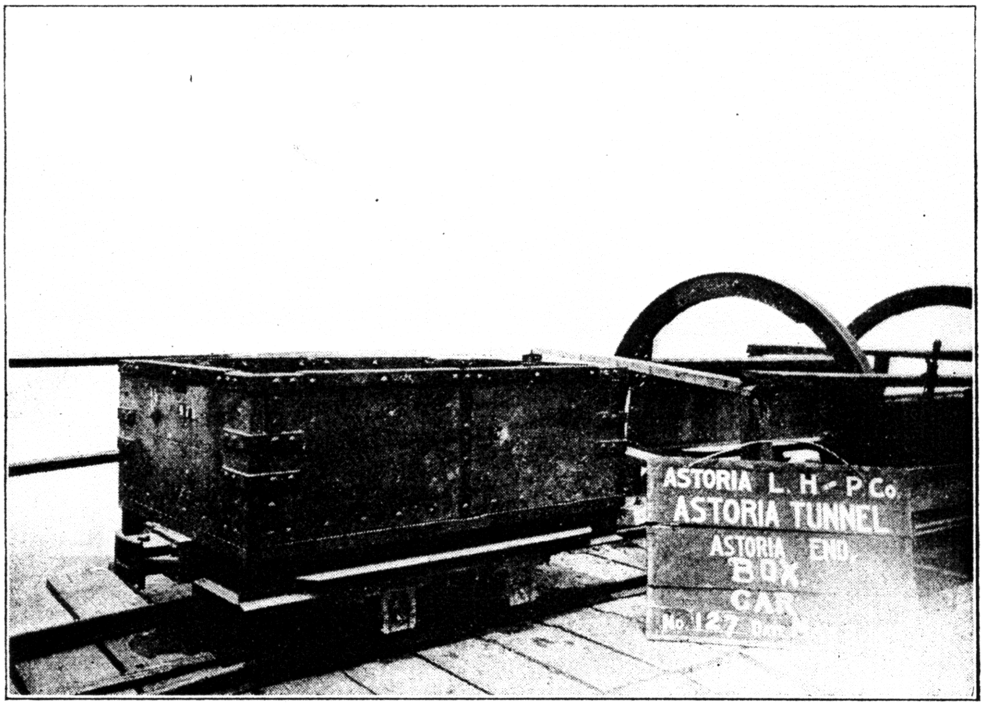


FIG. 3.—BOX CAR FOR EXCAVATION FROM ASTORIA TUNNEL.

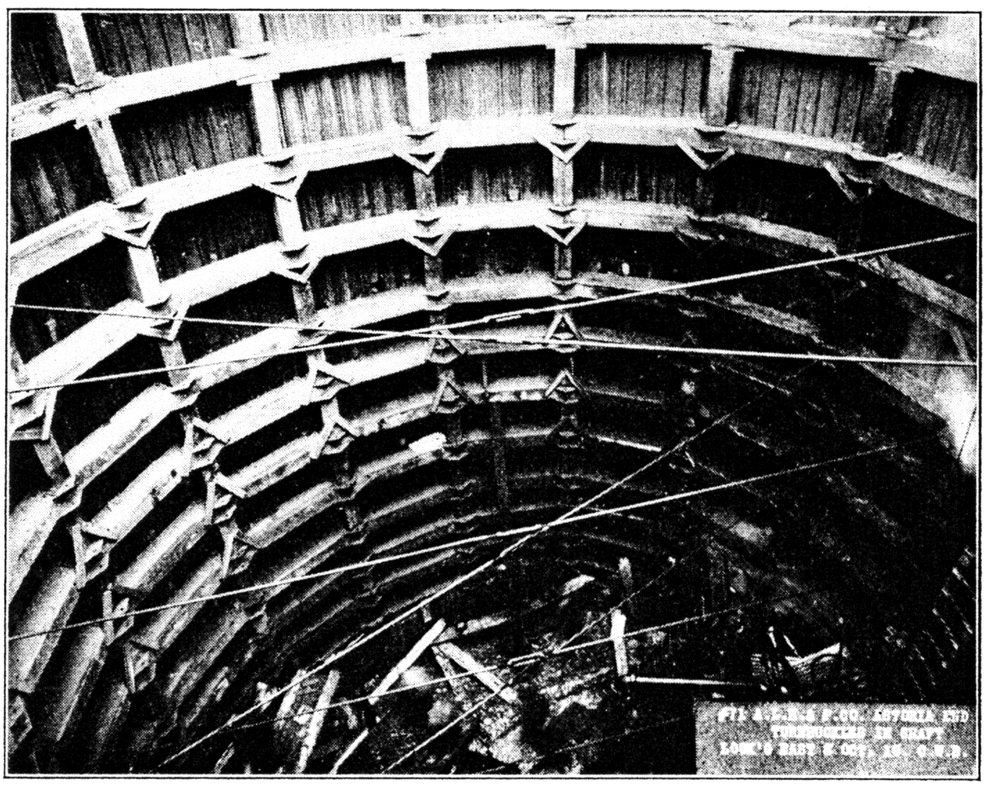


FIG. 4.—LOOKING DOWN THE ASTORIA SHAFT.

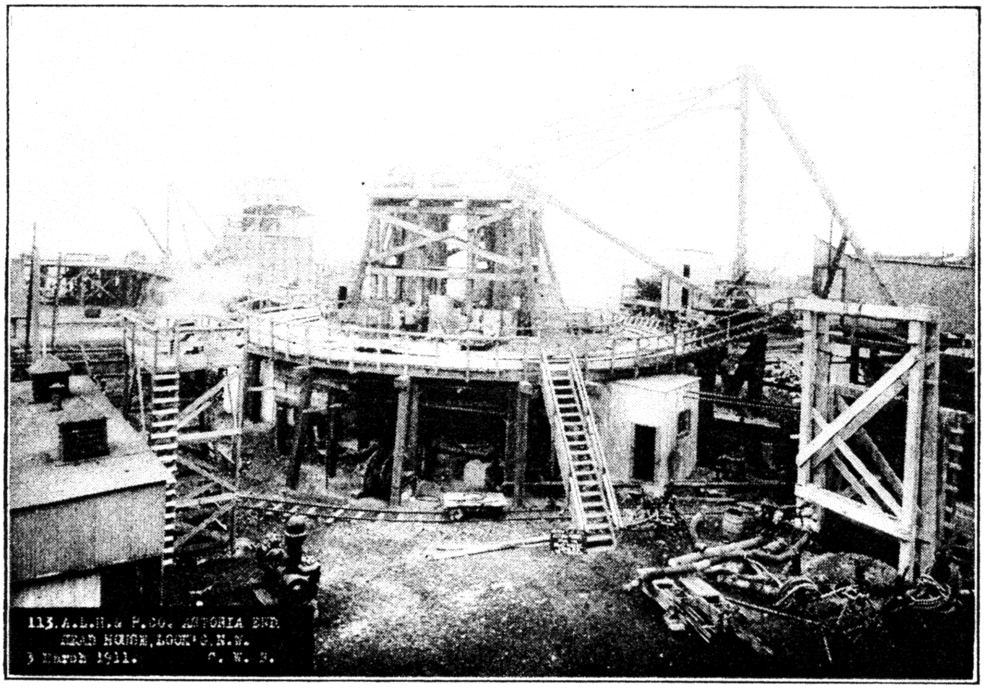


FIG. 5.—HEAD-HOUSE, ASTORIA END OF TUNNEL.

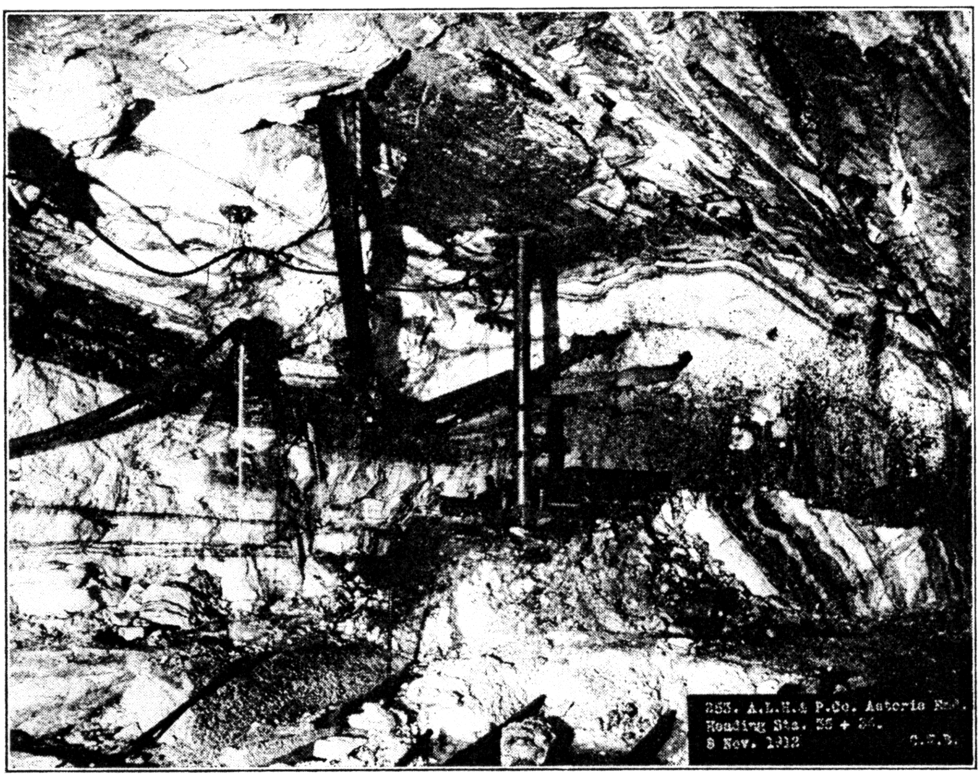


FIG. 6.—HEADING AT STATION 35 + 36.

Quantities.—The following tabulation presents the unit quantities relating to the shaft sinking in rock:

Drilling and Blasting.	Astoria Shaft.	Bronx Shaft.
Feet drilled per actual cubic yard............	3.9	3.3
Linear feet of drill steel used per cubic yard..	0.174	0.172
Pounds of 60% Forcite used per cubic yard....	1.2	1.1

Progress and Unit Costs.—Excellent progress was attained in the shaft construction at both ends. This, together with the unit costs of shaft construction, is shown in Table 1. The dimensions of the shaft are given in Table 2. The total unit costs of the shafts are given in Table 3.

TABLE 1.—UNIT COSTS OF SHAFT CONSTRUCTION.

	ACTUAL CUBIC YARDS.		WORKING DAYS OF 24 HOURS EACH.		DAILY AVERAGE. IN ACTUAL CUBIC YARDS.	
	Astoria Shaft.	Bronx Shaft.	Astoria Shaft.	Bronx Shaft.	Astoria Shaft.	Bronx Shaft.
Excavating earth...	2 687	367	16.8	2.9	159.7	126.6
Excavating rock....	11 542	5 939	123.4	97.9	93.5	60 7
Placing concrete....	3 178	1 621	37.2	23.3	85.5	69.6
Total construction..	......	......	177.4	124.1	......	......

TABLE 2.—DIMENSIONS OF SHAFTS.

	Astoria Shaft.	Bronx Shaft.
External diameter, earth section..................	42 ft.	30 ft.
External diameter, rock section..............................	38½ ft.	28½ ft.
Internal diameter..	34½ ft.	26 ft.
Depth...	276½ ft.	242 ft.

TABLE 3.—UNIT TOTAL COSTS OF SHAFTS.

	PER ACTUAL CUBIC YARD.		PER LINEAR FOOT.	
	Astoria Shaft.	Bronx Shaft.	Astoria Shaft.	Bronx Shaft.
Earth excavation.......................	$7.05	$2.67	$365.81	$75.39
Rock excavation..............................	10.43	11.22	535.84	275.44
Concrete lining..............................	14.21	13.76	163.28	92.16

5.—Tunnel Driving Under Normal Conditions.

Bronx Heading.—The Bronx Shaft reached a sufficient depth for turning the heading on February 12th, 1911, and the latter was driven for a short length before completing the shaft and sump, so that tunnel driving really began on March 8th, 1911, and continued under normal conditions through sound, close-grained gneiss until August 29th, 1911. At that time the first appreciable delay occurred when the heading entered the expected contact seam of decomposed, water-bearing dolomite, 771 ft. from the shaft center, at which point the water depth in the river is 80 ft. below mean sea level, and the deep river channel corresponds in location to this dolomitic intrusion.

Astoria Heading.—At the Astoria end, work on the main tunnel did not begin until April 8th, 1911, when the headings of both the Bronx and Manhattan Tunnels were already turned. As in The Bronx, the headings were turned when the shaft reached the level of the floor of the top heading, and prior to completing the shaft sinking; the advance toward The Bronx continued until April 23d, 1911, during which time about 80 ft. of the Manhattan Branch Tunnel were driven. Owing to the large chamber arrangements necessary at the bottom of the Astoria Shaft, work on the main tunnel was not resumed from this end until June 23d, 1911, and it continued without incident until November 7th, 1912, a distance of 3 536 ft. from the shaft center.

Geology.—For the first 1 200 ft. from Astoria the tunnel was driven through a hard, compact, and tough granitic gneiss, requiring heavy drilling and large consumption of powder. For the next 2 336 ft. the tunnel passed through the dolomite, and the passage through the easterly contact between the gneiss and the dolomite was made without any apparent disturbance or shear of the geological structure, a condition quite different from the contact encountered in the Bronx heading, where the geological change was featured by violent shear, accompanied by innumerable water fissures and excessive disintegration. At a point 3 536 ft. from the Astoria Shaft, this heading met the first indications of the water-bearing disintegration of the westerly contact between the gneiss and the dolomite. (Fig. 6.) The final results developed the fact that the entire width of this decomposed contact normal to the strike was some 150 ft., whereas the angle of crossing made by the tunnel involved a total distance of 350 ft., measured on the axis of the tunnel, or 450 ft. between points of contact on the two side lines.

Excavation.—For the tunnel excavation, the top-heading-and-bench method was adopted, maintaining the bench some 50 ft. behind the heading. During the early part of the work the arch lining was not placed as the excavation advanced, these exposed sections being concreted later by using steel forms, and work was performed simultaneously with, and without hindrance to, the driving of the heading and bench. On deciding to place the arch lining along with the tunnel advance, a system of alternate excavating and concreting was adopted, with excellent results as to progress attained. This method consisted of excavating both the heading and bench from 8 A. M. Monday to 8 P. M. the following Friday, the remainder of the 6-day week (until 8 A. M. Sunday) being occupied in placing the concrete arch. By this method the maximum monthly progress was made, being 269 ft. of full tunnel section excavated and arch lined. The average progress maintained by this method was 53 ft. of heading, bench, and concrete arch per 6-day week, which, in volumetric measure, equalled 675 cu. yd. of neat-line excavation and 81 cu. yd. of neat-line concrete arch.

The average unit drilling and blasting quantities incidental to driving the tunnel 4 274 lin. ft., or 92% of the total length, under normal conditions, are presented in Table 4.

TABLE 4.—AVERAGE UNIT DRILLING AND BLASTING QUANTITIES FOR TUNNEL.

	Average per Actual Cubic Yard.					
	Fordham Gneiss.			Stockbridge Dolomite.		
	Heading.	Bench.	Total.	Heading.	Bench.	Total.
Drilling, in feet	5.64	3.04	4.22	5.09	2.03	3.42
Pounds of powder used	4.20	1.35	2.65	4.35	1.08	2.57
Number of exploders	0.79	0.38	0.57	0.71	0.26	0.46

Overbreakage.—Notwithstanding numerous experiments in the placing of drill holes for face of heading and bench, it was found that neither the gneiss nor the dolomite rock could be blasted without great irregularity in cross-section. The large quantities of blasting gelatine needed to pull the rock caused considerable overbreakage. Careful and repeated cross-section measurements, checked by the volume of concrete used to complete the lining, indicated that, notwithstanding the particular care taken, overbreakage outside of the neat line of minimum lining section in the sound sections of good rock amounted to 18% in the gneiss and 12½% in the dolomite.

Drilling and Firing.—The typical arrangement and length of drill holes for blasting, for both heading and bench, are given in the diagram, Fig. 7, as applicable to both the gneiss and dolomite, under normal conditions. In all cases holes were started with 3-in. drills, which were reduced ¼-in. in diameter with each 2-ft. advance, to a final diameter of 1¾-in. for the 12-ft. holes.

Fig. 7 also indicates graphically the arrangement of wiring, and the order of shooting, the holes.

Two double-strength "Victor" fuses were always used in regular course to insure the proper explosion of charges.

All firing was done by magneto batteries maintained about 500 ft. back of the heading, the wire connections to the heading always being strung on the side of the tunnel opposite that on which electric light wires were placed.

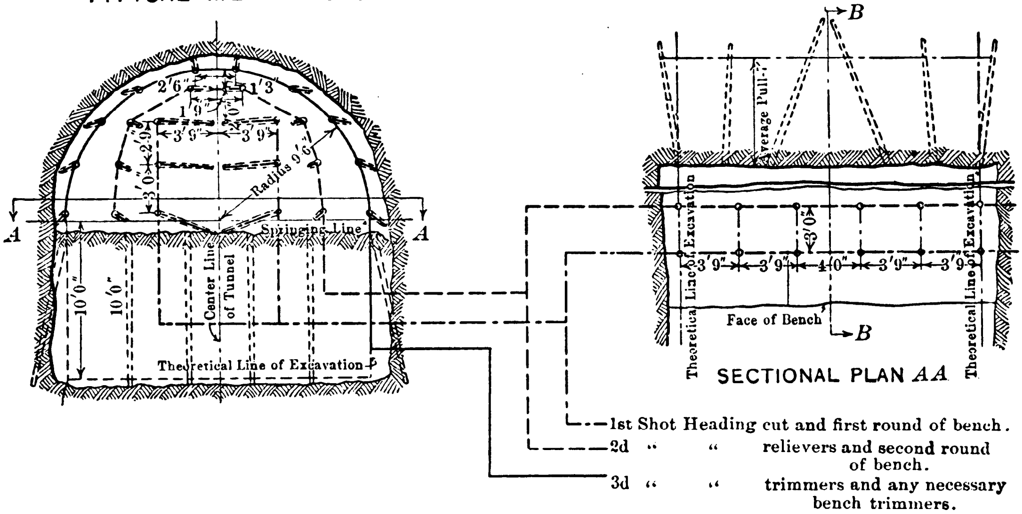
Both for heading and bench excavation ⅜-in. steel shoveling plates were used on the floors for facilitating the mucking operations.

In the varied classes of rock throughout the tunnel headings the speed of drilling was 9.9 lin. ft. per hour per percussion machine. The bench drilling was easily maintained at the equivalent rate of progress.

Practically all the best known brands of drill steel furnished in the New York market were tried out on the work, resulting in the adoption of "ABC non-tempering" steel, which, in these rocks and under the conditions, was found more durable and showed less breakage in dressing and drilling than the others.

The average progress of excavation attained during the tunnel driving under normal conditions, consisting of 4 274 lin. ft., or 92% of the ultimate length, and, based on the advance of one heading only, is given in Table 5. In this tabulation only the total accumulative time chargeable to excavation is considered, with a 24-hour actual working day as the unit.

TYPICAL METHODS OF DRILLING HEADING AND BENCH IN GNEISS



Item	Astoria Heading	Bronx Heading	Astoria Bench	Bronx Bench
Astoria End	Period from June 22d, 1911, to January 24th, 1912. From Sta. 1+00.7 to Sta. 14 +44.8, or 1344.1 ft. Gneiss = 1100 ft. ± Limestone = 244 ft. ±			
Bronx End	Period from April 10th, 1911, to July 22d, 1911 From Sta. 46 + 66.5 to Sta. + 39.50.5, or 616 ft. Gneiss = 616 ft.			
Strength and Size of Powder used	60% 1½-in. Forcite			
Quantity of Powder per Hole	Cut 6 Sticks Reliever 5 " Trimming 4 "		5 Sticks	
Size of Starting and Ending Bits	3-in and 1¾-in.			
Drills Used	E-44 Ing. Rand. 3⅝-in. cylinders. Mounted on Columns. E-94 Ing. Rand. 4½-in. cylinders. Mounted on Columns.		E-44 Ing. Rand. 3⅝-in. cylinders. Mounted on Tripods	
Average number of Drills used at one time	5		4	
Average time drilling a Complete Round Average elapsed time for removal of Round	44.1 man-hr. 15.1 hr.	56.5 man-hr. 21.3 hr.		
Average quantity of Powder per cubic yard	4.9 lb.		1.25 lb.	
Average feet of hole drilled per cubic yard	5.3 ft.	5.7 ft.		
Average feet of hole drilled per hour	5.3 ft. per man includes setting up.	4.6 ft. per man includes setting up.		

In Driving through Dolomitic Formation, the Heading Holes were all lengthened 1 ft.

FIG. 7.

TABLE 5.—PROGRESS OF ROCK EXCAVATION IN TUNNEL UNDER NORMAL CONDITIONS.

	Linear feet of full tunnel section.	AVERAGE DAILY PROGRESS.	
		Linear feet.	Actual cubic yards.
Fordham Gneiss:			
Astoria end	1 195	8.72	127.7
Bronx end	757	6.62	94.9
Mean	1 952	7.79	113.0
Stockbridge Dolomite:			
Astoria end, in dolomite	2 322	11.68	164.4
Mean Astoria end, in gneiss and dolomite	3 517	10.43	148.8
Mean result for both ends of tunnel, in gneiss and dolomite	4 274	9.46	135.1

Based on the results in Table 5, the average monthly (30-day) advance of completed tunnel, excavation only, was 284 lin. ft., or 4 054 actual cu. yd., in one heading.

Although the rate of progress was not as great as in other tunnels, of which reports have been published, the results obtained are thought to be very satisfactory, considering the general conditions of hoisting from a deep level, particularly as at no time was it considered by the management desirable to enter into the system of bonusing men to obtain record results. The entire work was carried out on a normal wage basis, without any attempt to offer other or special inducements to the labor to accomplish records. The progress of the work was perfectly regular and remarkably uniform, both at the Bronx and Astoria Shafts, up to the time of meeting the contact of decomposed rock at each end.

Concrete Arch.—The portion of sound rock tunnel driven from both the Bronx and Astoria Shafts was a hard, solid structure, but the rock indicated extensive jointing, with a tendency to scale away and for blocks of rock to fall without warning, a condition due to the character of the rock and also to the heavy blasting operations. Therefore what had been anticipated to be an untimbered tunnel, necessitated early the consideration either of timbering or of carrying the lining along with the tunnel operations, in order to insure the safety of the workmen. After careful consideration of the advantages and disadvantages of these two methods, it was decided to construct the arch lining, and, on account of the original cross-section adopted, to finish this arch lining to a skewback intended for the bottom concrete in which the permanent cast-iron gas mains were to be solidly embedded; this arch lining, hanging to the arch, was supported only on the irregularly jointed section of the rock walls.

Change of Design.—From the commencement of this work it had been contemplated to embed the cast-iron gas pipes solidly and permanently in concrete, and to make a floor above them, but, after 2 867 ft. had been lined in this way, the design was reconsidered and a revision made, whereby the pipes would be left exposed and a deck would be inserted above them. The tunnel has been left completed according to this plan (Fig. 8). This obviously necessitated, subsequent to the completion of other parts of the tunnel lining, cutting out portions of the arch lining and skewback which had previously been constructed. In the remaining length of the tunnel, the arch concrete was supported by timber sills on posts, the side-walls and invert not being placed until the complete excavation of the tunnel from end to end, when the sills and posts were removed as the wall lining proceeded.

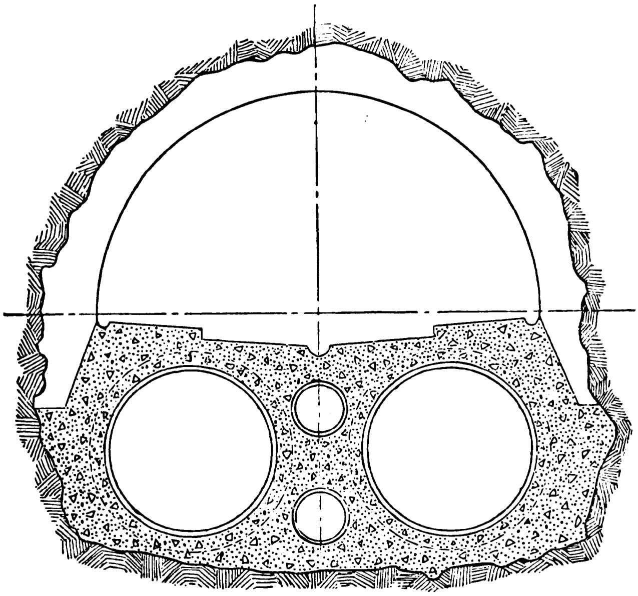
This method of procedure was peculiar, in that, for the entire job, the arch lining was first executed. Then, when the tunnel was holed through, and the steel lining, hereinafter described, was being erected in the decomposed section, the invert was put in place by trimming the rock floor, in lengths ahead of concreting and laying the invert, to accurately placed side-forms. The forward end of each length of invert was laid out with a curved cross-form which gave accurately the section of the concrete to be laid; this was swept with straight-edges, using the last completed length of invert for the rear sweep and a wooden form for the forward end. The joints at the side-forms, as well as the cross-joints, were designed so as to lock thoroughly with the abutting concrete to be placed later. On the completed invert, after it had come to strength, was laid a track of 60-in. gauge, on which were operated two complete collapsible steel forms, each 50 ft. long; and these were used for the construction of the intervening side-walls, the two side-walls being concreted simultaneously. These forms, Fig. 9, were set up 100 ft. apart, and were advanced 100 ft. at each move, so that each form was used for alternate lengths of side-wall lining, thus permitting the setting up of one form while the concreting was proceeding in the other; this enabled continuous working operations.

Although these forms ran on the 60-in. track laid on the tunnel invert, they had on the bottom frame a standard tunnel-gauge track, with a short incline at each end, so that other operations in the tunnel could proceed by running the tunnel cars through the lower portion of the steel frame. There was an elevator at each end of each form to raise the concrete cars to the upper level, so that they could be run to any point for dumping. The collapsible feature of the steel forms was obtained by using jacks and turnbuckles, and the upper platform of the forms, which was the dumping platform, was practically at the springing line of the arch where the joint was made between the side-walls and the arch already in place.

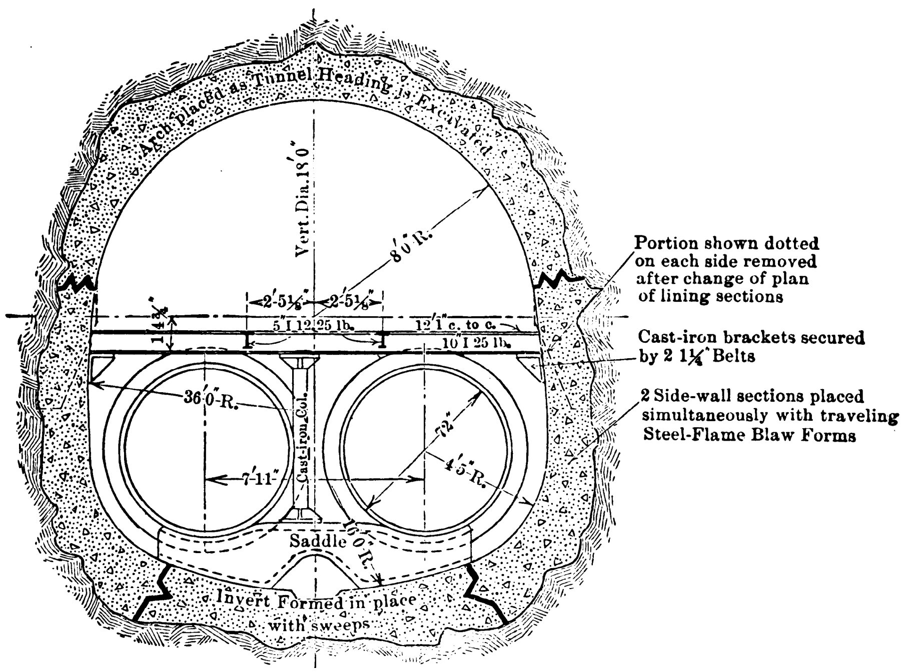
Before placing the forms the surfaces were well oiled. The moving was done by a small air-driven engine on the dumping platform. This engine was also used to operate the elevator. These forms worked admirably after they had been reconstructed, to some extent, to meet the conditions. The progress obtained with their use was one 50-ft. section each working day, and this rate was maintained with almost perfect regularity for a length of 3 310 ft. of tunnel.

The proper keying of the side-wall concrete to the arch skewback was accomplished, after a number of experimental methods were tested, by forming a wooden chute at the base of the joint and to a level of about 1 ft. above it, through which wet concrete was filled in and rammed into the joint with rods, in order to work the concrete into close contact with the arch skewback and enable the air bubbles to escape. This left a projecting lump of concrete at the joint, but, just prior to moving the forms forward, these chutes were removed and the projecting concrete was chipped off to the neat lines while the concrete was still green. The results of this method were quite satisfactory.

Throughout the work of placing the concrete lining in the arch, side-walls, and inverts, it was considered, owing to the heavy pressures which would come on the lining by any seepage of water, that all voids between the arch section and the solid rock should be entirely filled with concrete. Plums of broken stone, however, were used freely where the concrete exceeded in thickness the neat section. Consequently, no loose packing of rock behind the arch or walls was done in any portion of the work, and, throughout the tunnel, on the com-



ARRANGEMENT OF CONCRETE ARCH
FOR ORIGINAL CROSS-SECTION



SEQUENCE OF OPERATIONS IN PLACING CONCRETE
LINING FOR FINAL CROSS-SECTION

FIG. 8.

pletion of the entire lining from end to end, grouting was carried out by the use of grout pipes which had previously been left projecting from the lining so as to insure absolute solidity of the lining.

6.—Tunneling Under Adverse Conditions Through Decomposed Water-Bearing Dolomite.

As stated previously, no evidence of any shear or disintegration was disclosed at the eastern contact between the gneiss and the dolomite; but the western contact, as encountered from the Astoria end, was featured by some 354 ft. (along the tunnel center line) of highly decomposed dolomite with a heavy flow of water. It is interesting to note that, of this 354-ft. belt, the eastern side was advanced to a farther state of decomposition than the western, the rock mass containing countless seams of decomposed material and pockets of residual clay, all so disintegrated and distorted that the cleavage planes were not distinguishable, and though the strike maintained regularity, the dip was most irregular; in fact, at numerous points it was indeterminable.

The seams were so extremely decomposed that the material consisted only of a micaceous greensand, so porous that, on exposure, water quickly formed a free passage. Usually, these seams were little better than loose sand, although at times they choked the rock seam to such an extent as to yield practically no flow of water.

The first contact with the decomposed rock (which was met in driving the Bronx heading) seemed to indicate the likelihood of getting through the contact without serious difficulties, as the tunnel, after careful grouting, was advanced a considerable distance in rock, which, though excessively distorted and water-bearing, had sufficient strength to carry the pressures without danger. At the same time, it was desirable to protect this heading as it advanced, and the arch was carried on heavy timbering in order to guard against falling rock. Having extended this length on timbering, it was thought that the insertion of cast-iron lining for this section might enable the work to advance successfully, particularly as the rock appeared to be getting stronger and harder beyond the first point of contact. As immediate delivery could be obtained of cast-iron segments made from the patterns from which the Pennsylvania North River Tunnel segments were constructed, a short length of 50 lin. ft. was cast, delivered, and promptly

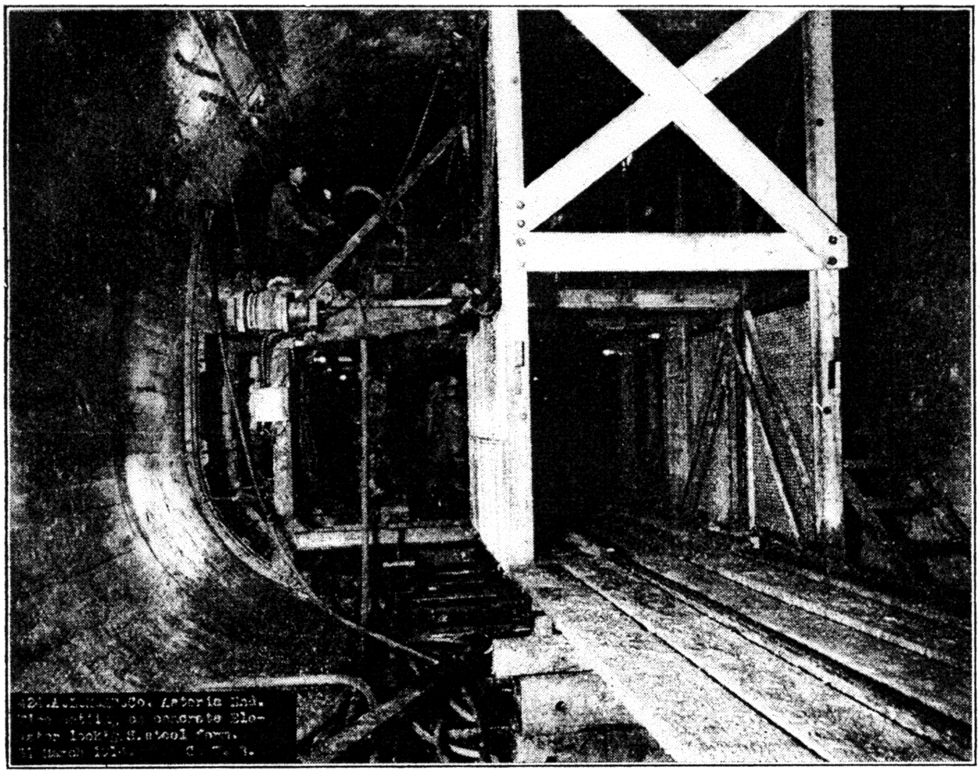


FIG. 9.—STEEL FORM FOR PLACING CONCRETE LINING.

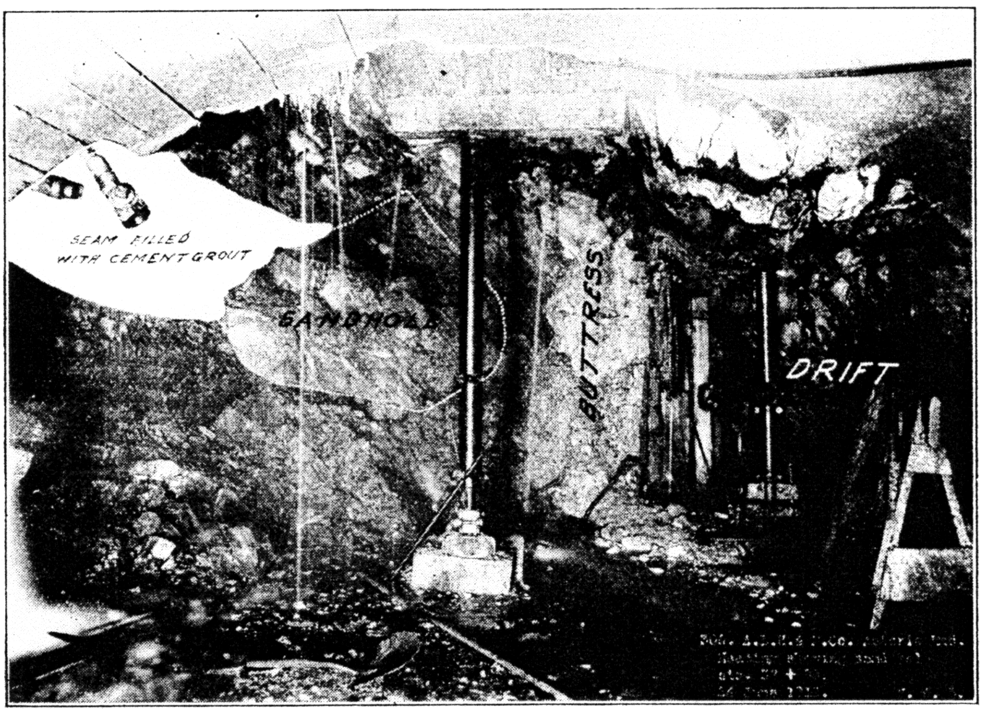


FIG. 10.—HEADING AT STATION 37 + 00, SHOWING SAND HOLE.

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erected in this wet, water-bearing, rock section. Then, inside the iron lining, concrete was inserted to the neat finished section adopted for the tunnel. This lined section remained in place in the finished work as an intermediate portion between two sections of cast-steel internal lining subsequently erected, which the following record describes.

The seams of greensand developed a maximum width of about 6 ft. at 3 750 ft. from the Astoria Shaft (Fig. 10). In this vicinity also, various pockets in the greensand seams were disclosed; one in particular being 4 ft. square and 20 ft. long, from which the previous water flows had evidently washed the sandy material.

On Plate XXIV, taken from the published Geological Survey, which presents the historical geology surrounding the Astoria Tunnel, it will be observed that there is a non-conformity in the plan defining the positions of the lines of contact as between the north and south sides of the Bronx Kills. This has been accounted for by assuming the existence of a cross-fault between Randall's Island and The Bronx, marking the course of the Bronx Kills. Although no conclusive evidence of the existence of such a cross-fault was observed during the driving of the tunnel, indications of its possible existence and proximity were observed. The material encountered in the vicinity of the assumed cross-fault was so disintegrated and decomposed, and the conditions for observations were so unfavorable, that it is doubtful if such a fault would be readily recognized in passing through it.

It has been assumed, however, that the tunnel passed through this hypothetical cross-fault, as shown on Plate XXVI, this assumption being based on two important facts:

1.—The distortion of the line of contact; and

2.—The rock structure encountered.

(1) It is quite natural that a cross-fault should have a limit of length, so that, in the case of this particular one, though it may extend through the Bronx Kills, as assumed, it may not necessarily extend to the path of the Astoria Tunnel. Such being the case, it seems possible that the actual fault at its eastern end terminates very close to the tunnel path, and that this end, instead of consisting of an abrupt fracture, is a gradual bend or distortion of the rock mass. That such a distortion was passed through is clearly shown on Plate XXVI. This distortion of the actual line of contact between the

hard micaceous gneiss on the west and the badly decomposed dolomite on the east, was encountered by an abrupt bend, 858 ft. from the center of the Bronx Shaft, and extended along the tunnel line some 70 ft. The maximum distortion was 10 ft., at a point midway along its length, at which point the hypothetical cross-fault has been assumed.

(2) The rock structure encountered at this point (893 ft. from the center of the Bronx Shaft), in addition to being extremely porous, was greatly shattered, more so than at any other point in the tunnel. The dolomite, especially, appeared like a mosaic of inlaid tile slabs, quite small (3 to 4 sq. in.), and readily removed by hand, although the individual pieces were moderately hard. It was at this place (Fig. 11) that three large water-flows burst forth at various times. One was an average single flow of 1 000 gal. per min., and in addition to this water, it carried in sediment large quantities of greensand and countless hard rock fragments. Here, too, it was necessary to terminate two heading drifts from the Bronx end. To the north of the assumed cross-fault, the actual contact between the gneiss and dolomite consisted of a continuous small seam, ¼ in. wide, of soft brown mud, and to the south of this point the contact plane was featured by a 3 to 4-ft. seam of hard, firm, bluish-green clay.

In this section of New York City, observation has established the existence of cross-faults, one at 138th Street and St. Nicholas Avenue, and one parallel to it, south of Hell Gate, and crossing the East River north of Blackwell's Island.

Water Flows.—The water-bearing fissures in the 354 ft. of decomposed dolomite were quite numerous, sixteen appreciable streams, each averaging from 300 to 10 000 gal. per min., under a full pressure head of 95 lb., having been encountered. These flows were usually quite sudden, and were accompanied by an inrush of greensand, the maximum flow of 10 000 gal. alone washing in 400 cu. yd. of sand, coal, etc., and, during a period of 6 weeks, some 1 700 cu. yd. of sand were washed into the Astoria heading. The establishment of a direct connection to the river bed was proved by the appearance of air bubbles on the river surface during grouting operations in the headings, as well as by the quantities of coal, wood, shells, bricks, etc., washed in at various times.

Method of Attack.—On account of the great depth of the tunnel and the resultant pressure head (95 lb. per sq. in.), any compressed-air methods of attack were out of the question, and, on account of the

FIG. 11.—WATER FLOW IN DRIFT AT STATION 37 + 71.

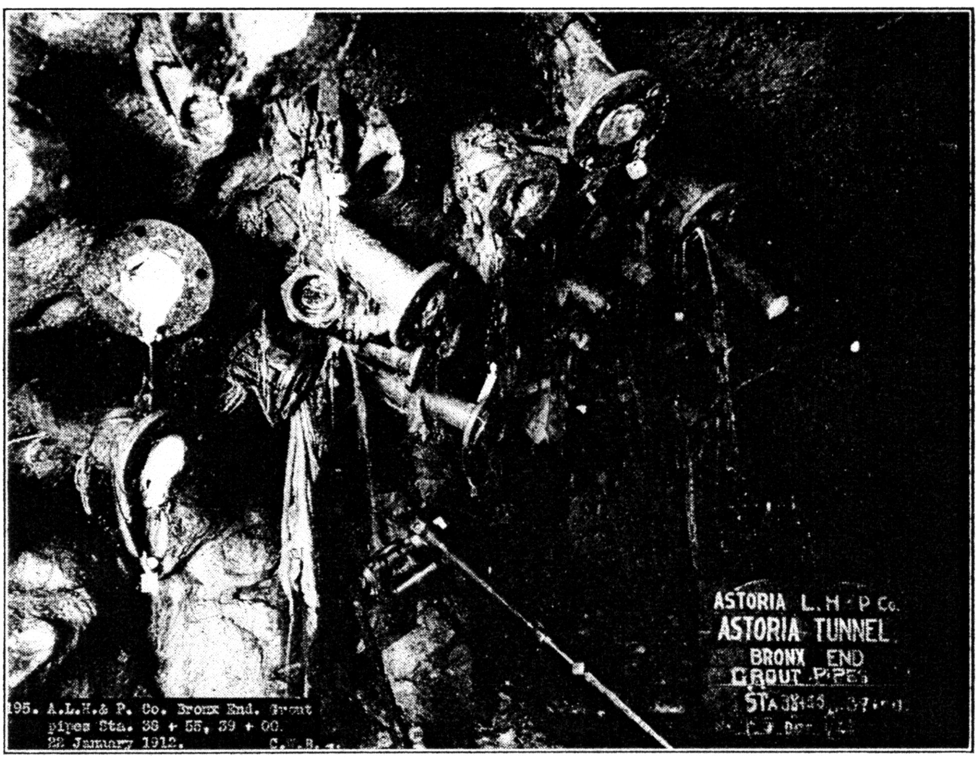


FIG. 12.—GROUT PIPES, STATION 38 + 55 TO STATION 39 + 00.

necessities of the gas supply, it was not desired to go to any lower level in an attempt to pass under the disintegrated bed of dolomite. It was consequently necessary to drive the tunnel at the original depth and alignment, so that the proposition presented was a difficult one.

The theory on which tunneling operations were executed through the decomposed rock formation was the thorough exploration of the formations ahead by test holes and the consolidation of the rock by grouting. It was very obvious, in working in a narrow top heading, even by drilling numerous holes in the form of a fan, that a very limited area could be reached for consolidation, and as the percussion drill, working on more or less horizontal or dry holes, is only capable of extending to a depth of about 20 ft., the tunnel section which it is possible to consolidate is very short, particularly in view of the fact that there is a definite limit to the number of grout holes which can be drilled into the face of such a small heading (Fig. 12), and that considerable time must be allowed for cement grout to attain strength to permit of blasting safely. It was obvious, therefore, that a greater area of attack must be provided, and this was done on the theory of diverting the heading from the straight line to lines external to the final side lines of the tunnel, following the line of the strike of the sound rock as far as possible to permit of cross access to the decomposed strata. By doing this a long face could be exposed from which the drilling could proceed. Further, whenever the rock was sound and reasonably hard, a full and adequate anchorage for the grout pipes was naturally provided, but, if the rock was decomposed, seamy, and water-bearing, it was usually found to be so soft that proper anchorage could not be obtained for the grout pipes. In such cases it became necessary to construct buttress faces to the soft rock after exposure, before grout pipe holes could be drilled and pipes inserted. The work was carried out on the further theory that grouting above the extrados of the arch and outside the side-walls, within the limit of the top heading, would in all reasonable probability cut off the direct access of heavy water flow and consequent danger of breaks occurring in the bottom. This was carried out to the end of the work and proved successful, as was illustrated by the fact that it was found unnecessary to do any grouting of considerable extent in order to take out the later bench excavation, the water-bearing seams having evidently been plugged at the higher level and the resistance of the decomposed material in the seams being adequate to resist any indirect access or flow.

Reference has been made to the necessity for buttressing the face of soft rock to provide anchorage for grout pipes, in the event of the rock being unsound and not giving adequate security for the insertion of such pipes. In such cases, owing to the high pressures involved, these concrete buttresses were allowed to set for practically two weeks on each occasion before they could be utilized.

When such buttresses were set and thoroughly hard, or when sound rock existed, the process of preparing the grout pipes for use, as indicated by Fig. 13, was generally as follows:

The drilling was commenced with 6-in. percussion drills, and entered from 3 to 4 ft. deep into the concrete buttress or hard rock. A piece

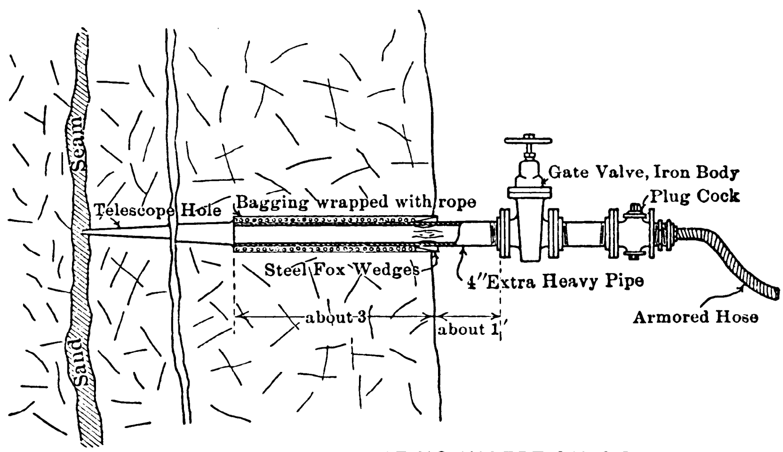


DIAGRAM ILLUSTRATING INSERTION OF GROUT PIPES IN ROCK FOR HIGH-PRESSURE GROUTING.

FIG. 13.

of 4-in. pipe, about 1 ft. longer that the depth of the hole, was then wrapped tightly with bagging and wound around with marline to secure it tightly to the pipe, the quantity of bagging being put on up to practically the dimensions of the 6-in. hole. The wrapped pipe was then inserted in the hole, and driven to its extreme end, no thread, flange, or other protector being put on the inner end of this first length of pipe. When thus inserted the wrapping was caulked back into the hole, and steel wedges were inserted and driven tightly between the 6-in. hole in the rock and the body of the 4-in. pipe. These wedges were driven so hard as to indent the 4-in. pipe and secure it rigidly. A screwed flange was then put on the outer end of this 4-in. nipple and an open gate-valve was attached to the flange, in order to provide a clear opening equal to the diameter of the pipe. Drilling then proceeded through the gate-valve, commencing with 3-in. percussion drills and telescoping if necessary, as the drilling advanced. The length of the test holes rarely exceeded 20 ft. Of course, it will be understood that where the drilling was carried out from narrow cross-headings, and the holes were drilled at an angle with the strike, the effective length was reduced on account of the lack of clearance to insert long drills.

Reference is made in the following pages to the use of the diamond drill. On first meeting the decomposed rock at the Bronx end, a $1\frac{7}{8}$-in. diamond drill was set up in the heading and holes were driven, one at the elevation of the heading, horizontally at right angles to the strike of the rock, in order to intercept the seams at right angles to the general strike; and two holes straight ahead on the axis of the tunnel, one horizontally and one pointing downward. The hole at right angles to the strike of the rock was extended in only some 50 ft., but the long holes ahead were extended for about 200 ft., and these drill holes gave an excellent idea regarding the conditions to be met, as far as drilling could be accomplished with the small machine used. At a later date, a heavier diamond drill, capable of drilling 3-in. holes, was used, and gave much more satisfactory results. The use of the diamond drill for long holes was extended considerably, previous to and after the flooding of the tunnel, giving long penetration and providing a means for grouting at considerable distances. The later diamond drill outfit was of the Sullivan type, of heavy construction, and proved to be admirably adapted to work of this character. In the entire construction through this decomposed rock section, some 3 300 test holes were drilled, aggregating a length of about 43 300 ft. by percussion drills, in addition to seventeen diamond drill borings aggregating a length of 1 500 ft.

Grouting in the Astoria Tunnel has probably exceeded very greatly that in any other work executed, in consolidating soft fissured rock, and in stopping extensive and large leaks at high pressure. Grouting at a higher pressure was done on the Catskill Aqueduct, though the volume of inflow was probably very much less. In the case of the Astoria Tunnel, the grouting was a continuous operation for consolidating and cementing decomposed rock throughout the entire length of the sheared contact between the gneiss and dolomite, and as such served the purpose, a result which has not, it is thought, been approached or attempted in other work. The work involved was the conversion of a rotted and decomposed rock filled with fissures into a solid and substantial substance through which the tunnel could be driven and, incidentally, at the same time, stop the influx of water. In the grouting operations it was found to be almost impossible to grout into a seam of decomposed dolomite sand. This would apply equally to any other sand or material filling seams, which is likely to be scoured out by a flow of water. On meeting a seam filled with decomposed rock sand, the indications on this work were, that the sand was practically impervious, but, after a short exposure to water flow, the soft rock abutting on the seam became water-loaded and softened; then the passage of small quantities of water loosened and demoralized the sand filling the seams, following which the sand was scoured out, thus forming an open water channel. Therefore, it was found particularly desirable, after drilling grout holes into a seam filled with sand, to rake the sand out with rods, as far as was feasible, and then to allow these test holes to flow freely, by blowing with high-pressure air or in any other way, the idea being to get the sand to flow with the water and thus empty the seam, after which the grouting operation was much more thorough, successful, and permanent. When these seams were emptied of the sand and grouted at high pressure the result was practically a solid rock formation, and the tunnel could be built by blasting operations with security; whereas a seam not so clear of sand would resist the flow of grout and be a menace to the future advance of the tunneling operations.

Glass Tunnel Model.—In order to present clearly the actual geological information, disclosed both by direct observations and test-hole exploration, so as to determine the most advantageous direction of drift attack, an unusual method was designed by the field engineers and applied to this work. This consisted of a glass plate tunnel model. As the general strike of the rock containing the numerous seams of disintegration was nearly parallel to the tunnel line, and the dip was decidedly irregular, it was impracticable to plot the geological data on drawings and still have them clear and of working value, as they could not conveniently be superimposed. This condition was admirably simplified by this glass plate model, constructed at the tunnel works. This method of geological plotting proved quite successful, as the conditions of the explored rock structure were clearly presented at a glance, proving an important factor in the determination of the various methods of attack adopted.

This model consisted of a series of glass plates, 16 in. square, placed upright in a skeleton frame, 12 ft. long, and arranged to scale corresponding to the 5-ft. tunnel stationing. As the tunnel driving proceeded, the actual lines, drifts, bulkheads, timbers, iron rings, etc., together with the exposed disintegrated seams and the test-hole information, were all painted with oil colors on the plates, this work being always maintained up to date, so that the conditions actually existing were always visible.

Blasting was naturally performed with very light charges, necessitated by the unsound strata, as water flows were easily started, not only by the shattering of the rock in their immediate vicinity, but by the concussions from blasting in sound rock at a considerable distance from the dangerous strata. In one instance, at the Astoria end, a 50-ft. length of drift was temporarily lost by this latter condition. The caution and care with which the rock was thoroughly sounded and scaled immediately following blasting is shown by the fact that no serious injuries or fatalities occurred, which is regarded as unusual, in view of the extremely unsound condition of the rock.

Grouting.—During the early stages of adverse tunneling, the grouting of the water-bearing fissures was performed with ordinary grout machines, using a neat Portland cement mortar at a pressure varying from 100 to 200 lb. per sq. in. This made it necessary, in September, 1911, to put in a steam-driven, straight-line booster at each plant. Grouting continued with this pressure for some months, but it became apparent as the work proceeded that an air pressure of even 200 lb. was insufficient to insure success.

For successful grouting into narrow seams it is essential to obtain a high initial velocity of grout flow, in order to overcome the frictional resistance; consequently, to grout against a water head of approximately 100 lb. per sq. in., more than 100 lb. additional pressure was found to be necessary. The increase of the starting pressure insured the initial flow, and the expansion of the air, even down to 200 lb. or less, was adequate to maintain the continuity of the flow. The use of the high pressure also insured that the seam would be packed more tightly and that the grout would be more dense when it had taken its ultimate set and attained strength.

Consequently, an additional steam-driven straight-line booster was erected at the Astoria end in November, 1912, this machine being capable of developing an air pressure of 500 lb. per sq. in., for which special grout machines were constructed. The injection of cement into the water-bearing fissures at this pressure (500 lb.) was exceptionally effective, and was undoubtedly a valuable factor in the ultimate success in driving through the unsound water-bearing rock.

The disintegrated rock structure (Fig. 14) frequently necessitated the construction of concrete wall buttresses, in order to withstand the high grouting pressures used, and considerable difficulty was experienced during the early stages of the work in preventing the injected cement from washing out of the water-bearing crevices. Unsuccessful efforts were made to prevent this by mixing oats and bran with the cement mortar, as used in other subaqueous tunnels.

Another method introduced, which proved of great benefit and aided in securing the injected cement, consisted of the addition of a handful of fine-cut cotton waste to each batch of grout, which by fibrous reinforcement of the cement held it in place while it was setting. During lengthy grouting periods, two machines were used alternately in series, thereby maintaining a continuous injected flow.

The special machines for grouting with 500 lb. air pressure were designed and assembled at the tunnel works. The general arrangement and capacity were identical with the riveted pans for 200 lb. pressure, with the exception of some details designed to resist the higher pressure. The entire pan and the cover were made of cast steel, carefully annealed and tested, and having no joints other than that of the cover. The heads were made in convex form; one end was cast in one piece with the body, and the other was a cast-steel removable cover with male and female bolted flanged joints. In operation these pans were very reliable, and, when required, one pan was operated 25 hours without a stop, and discharged 4 500 bags of cement at pressures varying from 350 to 500 lb. Extra heavy 2-in. screwed pipe was used for the transmission of the high-pressure air from the engine-room to the heading, with the exception of the first 600 ft., where extra heavy 4-in. pipe was used to give greater storage capacity. Special 1-in. hose was used to make the connection between the air line

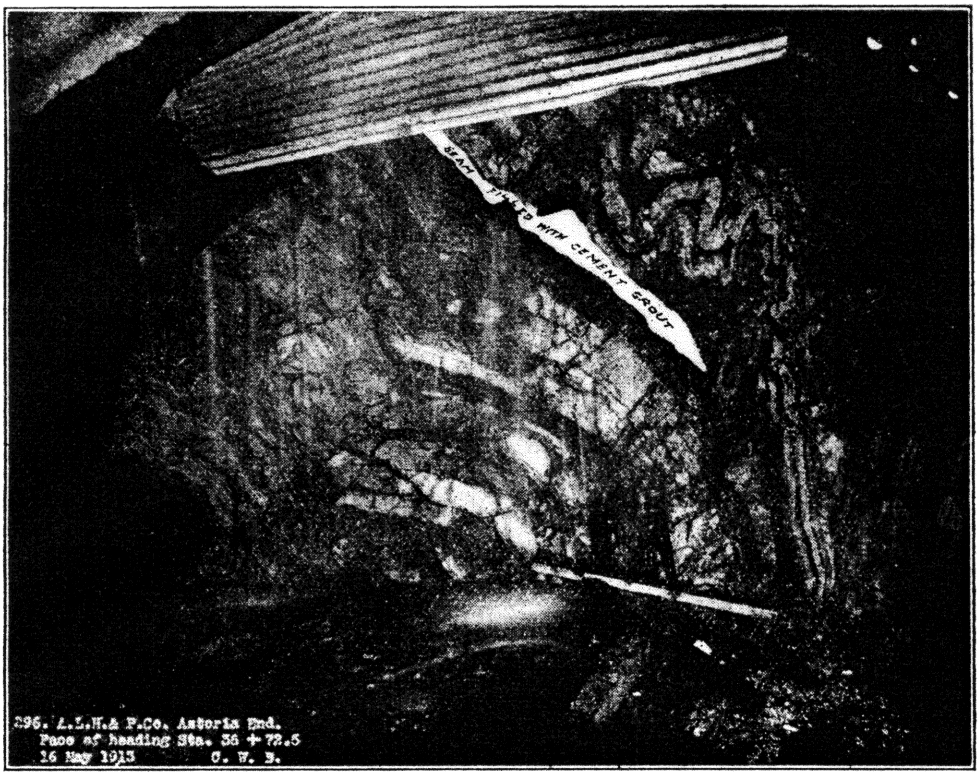


FIG. 14.—FACE OF HEADING AT STATION 36 + 72.5.

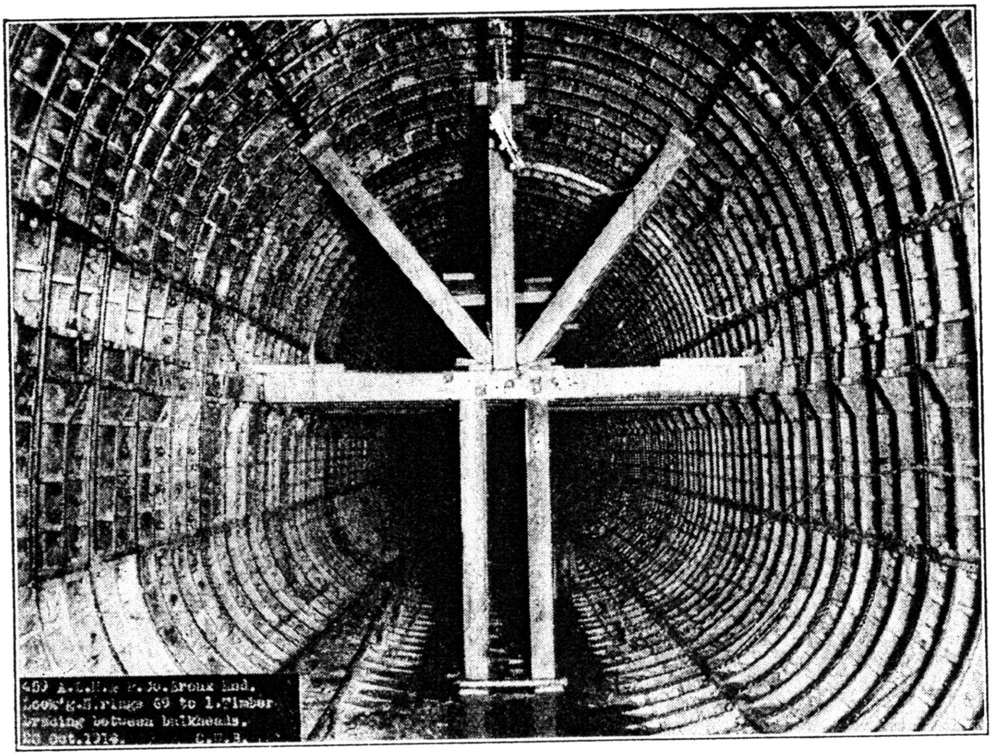


FIG. 15.—TIMBER BRACING BETWEEN BULKHEADS.

and the grout pan. This was a 6-ply rubber and canvas hose, with a marline woven cover, wound with $\frac{3}{16}$-in., half-round, steel wire, $\frac{4}{10}$-in. pitch. Knox standard couplings were fitted to each end. A special 2-in. grout hose was used, this also being of 6-ply rubber and canvas, wound with $\frac{3}{16}$-in., half-round wire, $\frac{1}{2}$-in. pitch.

Bulkheads.—Prior to entering the belt of disintegration at each end, adequate precaution was taken to guard against flooding, by the construction of full tunnel section emergency bulkheads, well back from the point of attack. As the headings proceeded, additional emergency bulkheads were built as close to the heading as the work permitted. These were to the heading size only, as the bench was not removed through this soft-ground section until after the meeting of the headings.

The first emergency bulkhead of full tunnel section, built at the Bronx end, was of a concrete buttress type, fitted with two guillotine doors and not reinforced. A guillotine type of door was considered in the first design to be the most certain in action. The clear openings of these doors were about 5 ft. square, of such size as to permit a tunnel car to pass through. These doors were never actually closed or used, but in constructing later doors it was considered preferable to adopt a simpler form of top-hinged flap, so that, in case of necessity, by cutting away the wire rope supports, they would drop readily into position, this type being not only cheaper to build but simpler in operation, and throughout the remainder of the work such doors were used. Some of the full tunnel section bulkheads, as well as the emergency bulkheads, were reinforced and some were not, the design being modified for each individual case. These doors were used only occasionally, and, as hereinafter stated, gave excellent results in operation. Owing to the necessity for knowing that these doors were always in working order, and for trying them out from time to time, they were equipped on the outer side with tripping devices and rams operated by compressed air from the tunnel line for raising them when they were desired to be opened. Valve arrangements were provided so that the door could be operated from inside or outside; thus, in the event of any one being accidentally left on the wrong side, it was possible for him to open the door and release himself.

Numerous solid heading and wall buttresses were constructed from time to time, for the reasons previously stated. This concreting, of course, necessitated frequent and unusual delays, the accumulated lost time incurred by this work accounting for at least 50% of the time required to tunnel the 354 ft. of unsound rock, as generally from 10 to 14 days were allowed for the concrete to set sufficiently for 500 lb. grouting pressure.

During the bench removal, after holing through the headings, full section tunnel emergency bulkheads were necessary, these being generally about 14 ft. thick. As the bench excavation proceeded, these bulkheads were kept fairly close to the point of work, in order to facilitate transportation. The continual construction of heavy timber runways was necessitated by the fact that it was desirable to place the emergency bulkhead doors well above the invert, in order to prevent them from becoming clogged by the sandy sediment in the inflowing water. Drainage through the bulkheads was provided by 6 and 8-in. pipes, passing below the doorways, but at a sufficient height from the bottom to prevent them from being clogged by the sand. These drains were equipped on the shaft side with standard gate-valves to permit of their being closed.

Bench Excavation.—After the meeting of the headings, on July 17th, 1913, efforts were concentrated on the removal of the remaining bench, which, at that time, amounted to 474 lin. ft. This length of excavation was attacked simultaneously from the Astoria and Bronx sides. In the first 237 ft. on the Astoria side only good sound dolomite was encountered, no trouble was experienced, and the immediate lining of this excavation was not necessary. On the Bronx side the lower west portion of the bench face consisted of hard sound gneiss with intrusions of clay at its contact with the dolomite on the east. The dolomite was both porous and disintegrated, but no serious difficulties were encountered, although it was essential to place the concrete lining immediately after each short advance of excavation.

In this bench excavation the advance was thoroughly explored with long test holes ranging well outside the necessary excavation lines, and the material was displaced by light blasting. This arrangement was due, not only to the character of the rock, but on account of the existence of the overlying concrete arch.

The work proceeded in this manner until exploratory test holes disclosed the presence of excessive water at the Astoria side of the remaining bench. This water was located by four test holes, 3 ft.

apart, along the west side of the bench top. The nearest hole was 24 ft. from the bench face, and the total flow at high pressure was about 1 500 gal. per min. These holes were piped for grouting, and encased in an inclined concrete buttress, 20 ft. long and extending from the arch haunch to the rock bench.

The water was allowed to flow freely through these holes for one week, while the concrete buttress was attaining strength. The valves of the drains through the inclined buttress were then closed in preparation for grouting, and water broke through the top of the bench at the toe of the buttress. It was then decided to place a full-section emergency bulkhead at each end of this remaining 122-ft. section of bench, so that any water that might overcome working operations could be confined between the bulkheads.

On the completion of these emergency bulkheads, on September 16th, the work of preparing to consolidate the rock previous to excavation was resumed. The inclined buttress was removed and a much heavier and more massive one was constructed. This extended along 34 ft. of the bench top from the recently constructed emergency bulkhead on the Astoria side, was about 6 ft. high and 12 ft. thick, and was completed on September 25th.

At the same time, the western side of the bench top, at the Bronx side, was covered with a 23-ft. length of inclined buttress against the concrete arch and extending from the recently constructed Bronx emergency bulkhead to a heading emergency bulkhead on top of the bench placed during the driving of the Astoria heading. A similar inclined buttress, 13 ft. long, was placed against the west side of the arch. Thus, the entire 122 ft. of exposed bench was covered on the west side by a series of concrete bulkheads and buttresses.

After allowing these structures to set until October 1st, grouting through them into the rock fissures began, and 139 bags of cement were successfully injected into the last two mentioned buttresses. The grouting of the massive 34-ft. buttress was not successful, as the reactive pressure developed by the closing of the drain valves fractured this concrete structure very badly and rendered it useless for the purpose for which it was intended.

It was then decided to remove this fractured buttress entirely and replace it with one in the form of an inverted arch, and of more massive proportions, the inverted arch to react against the permanent roof arch already in place. In the removal of this buttress blasting was done with extremely light charges, and every care was taken not to disturb the underlying rock bench. The removal of this buttress was completed about 8 A. M., on Sunday, October 5th, 1913.

7.—Flooding of Tunnel.

Shortly after 8 A. M. a large flow of water, carrying greensand, burst forth under high pressure from the top of the rock bench about 15 ft. from the Astoria emergency bulkhead. After flowing 30 min. the flow abruptly ceased, only to burst forth again a few minutes later with renewed vigor, yielding a volume of approximately 10 000 gal. per min., which eventually overcame the capacity of the pumps at the Astoria end. The bulkhead doors were promptly closed. On the Bronx side the force of the water was broken by the intervening heading bulkhead still in place, and the workmen were able to close the drains; but, on the Astoria side, owing to the rush of water and sand, they were able to close only two of the three drain valves in the bulkhead. It was found later that a small piece of 1-in. board, floating in the water, had become wedged between the door and the door frame of the bulkhead on the Astoria side. Through the small opening thus caused, and through the drain pipe which the men had been unable to close, the water poured into the tunnel, carrying with it a large volume of dolomitic sand and débris. The water in the Astoria Shaft rose steadily until, at 3.15 P. M., it had completely submerged the pumps, which soon thereafter ceased working, and the water reached tidal elevation at 8.15 P. M., on Monday, October 6th. At this time the pumping plant at the Astoria Shaft consisted of 12 pumps with a rated capacity of 7 500 gal. per min., but, on account of the sandy water continually handled, it had previously been found that the actual discharges were about 70% of the rated capacity; thus the actual capacity probably did not exceed 5 500 gal. per min.

Immediately following the flooding of the Astoria end, the Bronx emergency bulkhead was strengthened as a further measure of safety by a reinforced central buttress. On the completion of this buttress, an additional emergency bulkhead was built about 105 ft. nearer the Bronx Shaft. The actual need of this bulkhead never arose, as the first one withstood the full hydrostatic pressure, but it was desired to take every possible precaution against the flooding of the remaining protected tunnel, as the unwatering of an entirely flooded tunnel would have been a much more difficult and costly proposition.

It was also considered advisable to increase immediately the Bronx pumping plant, which at this time consisted of five pumps with a rated capacity of 2 250 gal. per min., of which only 1 200 gal. capacity was available for shaft discharge to the surface, the remainder handling the drainage from the bench face to the shaft, as the grade at the Bronx end was away from the shaft. Four additional pumps, each having a capacity of 600 gal. per min., were put in, by which the capacity of the tunnel drainage to the shaft was increased to 1 650 gal. per min.; and the surface discharge capacity was raised to 3 000 gal. per min. This plant was fully capable of handling all the subsequent water from the Bronx end.

8.—Recovery of Tunnel.

Observations of the rise of water in the Astoria Shaft were carefully made, and also the tidal readings during the continuance of the shaft inundation. It was observed that the water rose and fell with the tide, but that the entire tidal rise was not obtained, the rise in the shaft being only about one-half that in the river. From the continuance of these conditions, and also from the flow obtained through small pipes in the Bronx bulkhead, it was apparent that the water flow had not choked itself as had been hoped. After due consideration of various methods of attack, it was decided to grout from the Bronx end into the water-filled chamber between the Astoria and Bronx bulkheads, with the object of filling this with cement to the extent of permitting the unwatering of the tunnel from the Astoria end. At the same time diamond-drill borings were to be driven from the Bronx bulkhead, the purpose of which was to intercept the fissure at a point beyond its opening into the tunnel, carefully calculated and directed to the desired point, and through this to inject cement, in an effort to seal the source of flow beyond the tunnel. The first hole drilled was intended to tap the fissure at a point 5 ft. below and 5 ft. beyond the point of flow into the tunnel, this location being determined by a close study of the geological formation previously encountered. This hole measured 120 ft. from the bulkhead face to the point. The accuracy of both the location and pointing of this hole was conclusively proved, not only by the injection of 870 bags of cement, but by the conditions disclosed when driving through this section in February, 1914. The grout in this instance was evidently well directed into the fissure, but naturally followed the line of least resistance, going no farther than the débris in the fissure would permit.

The second step in the programme of attack was to fill completely the space between the completed arch and the rock bench between the bulkheads, and began by drilling through the Bronx bulkhead and the small disused heading bulkhead with a diamond drill, using a packing tube fitted with an exterior valve inserted in the bulkhead, through which the diamond drill rods were threaded and operated. These drill rods were pushed into the chamber as near as possible to the fissure location. Grouting through this diamond-drill tube began at 3 P. M., on November 10th, and continued without interruption until 4 P. M., on November 12th, during which time 8 580 bags of cement were injected at a pressure of 400 lb. per sq. in. The drill head, fitted with its diamonds, was recovered later from the mass of cement grout during the subsequent excavation. The grouting was discontinued on the appearance of cement in the seepage around the Bronx bulkhead door.

From the action of the water in the Astoria Shaft, it was quite evident that this grouting had been effective in sealing, to a large degree, the direct passage and subsequent leak between the tunnel and the river, but had not entirely sealed the leak through the Astoria bulkhead, as the draining of water through numerous small pipes in the Bronx bulkhead lowered the water in the Astoria Shaft some 17 ft. This water receding in the Astoria Shaft, and its subsequent loss of pressure head, resulted in an unequal condition of pressures on the freshly injected grout in the fissure, so that, when an absolute pressure of 11 lb. existed on the fresh grout, from the drop in the Astoria shaft water, the grout gave way, causing the water from the fissure to flow again into the tunnel, and the shaft water to rise.

Meanwhile, the long tubing was kept free, both inside and outside, and was withdrawn for this purpose to within 7 ft. of the inner bulkhead wall. It was again pushed forward in the early morning of November 14th, and 775 bags of cement were injected. Later the same morning, 622 bags were injected, followed in the afternoon by 986 bags. On the following morning 316 bags were injected, when the pressure gauge on a pipe extending through the bulkhead began to jump in excess of the hydrostatic pressure, and, as grout began to appear through the bulkhead pipes, the operations were discontinued. Again, however, on November 17th, an additional 164 bags were injected through this tube, making a total of 11 342 bags of cement.

Meanwhile, the diamond drill borings had been continued, and, although water and greensand were encountered, only a small quantity of cement could be injected. It was evident, later, on removing this piece of bench, that the fissure in question was pierced only by the first drill hole. By opening the various pipes in the Bronx bulkhead, in order to test the hydrostatic pressure and to ascertain the effect of the grouting, it was found that they gave water, but without pressure, and, therefore, it was considered quite safe to commence immediately the unwatering of the tunnel from the Astoria end.

The consideration of the various possible alternative methods for unwatering the tunnel contemplated in every case the ability to hold the Bronx tunnel intact up to the emergency bulkhead, and the method adopted and subsequently carried out was based on that understanding. However, it was also considered as a possibility that this method might not prove successful in stopping the open leak from the river so as to enable a battery of pumps, which could be practically erected, to control the flow. As the heading had been entirely carried through and the test borings had defined quite clearly the position of the seams, it was thought that, if the plan of drilling with diamond drills, as previously described, and grouting through the diamond drill holes, did not prove successful, another alternative would still remain, by which a steel trestle could be erected over the tunnel on the bed of the river and from the deck of such a trestle, above high-tide level, numerous drill holes could be accurately placed and extended vertically to intercept the line of the seam, and through such drill holes grouting could be executed at any pressure desired, which would be amply adequate to fill the seam and plug it effectively. Fortunately, this last expedient was not found necessary.

Unwatering.—Existing in the Astoria shaft prior to the flooding were an 18-in. ventilating pipe (extending from the surface, down the shaft, and into the tunnel a distance of 970 ft.), and three 8-in. discharge lines (extending from the pumps at the foot of the shaft to the surface). These four pipes were converted into a pneumatic water-lift system by placing a 3-in. air pipe inside the 18-in. ventilating pipe, extending the former to a depth of 251 ft. below the ground surface, or a depth of 240 ft. below mean sea level, and by placing a 2-in. air pipe inside each of the 8-in. lines to the same depth. The discharge ends of these air lines, for some 24 in. in length, were perforated with small holes drilled at an angle of 45°, so that the air discharge would point upward. These air lifts all discharged at the shaft surface. This emergency equipment was the only means used to lower the water 176 ft. from the top of the shaft, and down to that depth, proved both rapid and effective.

During the operations at the Bronx end, an emergency plant had been secured and prepared for operation at the Astoria Shaft. This consisted of six Cameron reciprocating pumps (one of 1 000, one of 800, and four of 600 gal. per min., a combined rated capacity of 4 200 gal. per min.). On a steel pontoon, designed and constructed specially for the purpose, and floating in the shaft, were placed the two emergency pumps (of 1 000 and 800 gal. per min.) with the discharge connected to an 8-in. discharge line in the shaft. Three 600-gal. pumps were placed in the elevator wells after the water had been lowered 172 ft. below mean sea level. These pumps were lowered from time to time as the water dropped, and, when it had been lowered to a level of 13½ ft. above the tunnel invert at the shaft, the submerged permanent pumps were brought into play.

The 18-in. and two of the 8-in. air lifts were operated continuously from 8 A. M. to 9 P. M., on November 24th, when the water had been lowered a depth of 160 ft., displacing 1 147 028 gal. of water in 797 min., or an average discharge of 1 439 gal. per min. The two pumps on the pontoon were then started and worked continuously until 6 A. M., on November 25th, with a net gain of 15 ft. The three pumps in the cage wells were then operated, it being necessary to change the pipeline connections quite frequently. On November 30th, at 10.40 A. M., the water had been lowered to a level 13½ ft. above the tunnel invert at the shaft portal. During the progress of this stage of the pumping, in order to avoid a column of water forming at the Astoria bulkhead and a consequent probable regurgitation of the water in the shaft, air under pressure was forced into the tunnel through a 2-in. pipe, which was in place and extended from the surface about 3 200 ft. into the tunnel. At 10.40 A. M., on November 30th, the original shaft pumps were started, and, as this gave in all a battery of eleven pumps, the water was quickly drained from the tunnel. During the period occupied in pumping at the Astoria end, a 2-in. and a 5-in. pipe in the Bronx bulkhead were kept flowing, and materially aided in the unwatering. Table 6 is a summary of the water pumped and the time occupied.

TABLE 6.—SUMMARY OF WATER PUMPED, ETC.

AIR LIFTS—ASTORIA END:	
Time worked	13 hours 17 min.
Volume of shaft unwatered	1 147 028 gal.
Average per minute	1 439 gal.
PUMPS—ASTORIA END:	
Time worked	162 hours 53 min.
Volume of shaft and tunnel unwatered	8 415 353 gal.
Leakage into tunnel	15 608 873 gal.
Total water pumped	24 024 231 gal.
Average per minute	2 458 gal.
AVERAGE LEAKAGE INTO TUNNEL THROUGH THE FISSURE DURING THE PERIOD OF UNWATERING:	
Flow through pipes, Bronx bulkhead	938 gal. per min.
Leakage through Astoria bulkhead	997 " " "
Average leakage through fissure	1 935 " " "
Period of unwatering approximately 25 000 000 gal	7⅛ days.

On Sunday evening, November 30th, with the water 4½ ft. below the crown of the arch at the portal, two boats containing the tunnel engineers entered the tunnel and continued on a tour of inspection to the Astoria bulkhead. It was found that comparatively little damage had been done by the flooding, although a considerable quantity of grout and sand had entered the tunnel through the door which, in the inception of the flood, was not securely closed, and through the 8-in. drain which the men had been unable to close, as previously mentioned. Sand deposits occurred at frequent intervals throughout the first 2 300 ft., and beyond this a layer of sand, mud, coal, shells, etc., covered the tunnel invert, accumulating in quantity toward the bulkhead. At a distance of 3 000 ft. from the shaft, the grout, with a small proportion of sand, formed a bank 12 in. deep, gradually sloping up to the bulkhead, a length of about 500 ft., where it was 12 ft. thick, or nearly to the top of the bulkhead doorway. The surface of this grout bank was in a plastic condition, some 6 in. deep, the underlying material being firm and semi-hard, the hardness increasing toward the bulkhead. This material was not well set-up grout by any means, the subsequent removal being performed with pick and shovel. From the 8-in. drain clear water, at the rate of 900 gal. per min., was flowing, and from a 3-in. cable conduit pipe in the bulkhead there was a stream of 100 gal. per min.—neither being under pressure. The air throughout the tunnel was exceptionally good.

The construction of an emergency bulkhead about 60 ft. from the closed bulkhead was immediately commenced, before making any attempt to remove the aforesaid grout bank, as the appearance and condition of the grout bank material were such as to cause very grave doubt that the leak would remain confined. A small trench was excavated in the grout bank around the bulkhead drains; the two closed ones were blind-flanged and the open one was allowed to flow, in order to prevent the development of any additional pressure on the bulkhead.

Simultaneously with the construction of the emergency bulkhead, the cleaning and righting of the tunnel proceeded. Meanwhile, the emergency pumps were erected at the shaft bottom and the original pumps were overhauled. When this work was completed the Astoria plant consisted of fifteen pumps, with a combined rated capacity of 9 600 gal. per min., which was considered quite sufficient to handle any likely flow, in view of the existence of an additional bulkhead removed from the point of danger.

The method of procedure adopted for completely sealing the water flow of October 5th consisted in driving a series of long test holes, in an effort to pierce the fissure well outside of the tunnel lines, through which the effective seal and solidification of the rock mass would be obtained by injecting grout. The short holes were drilled with percussion drills and the long ones with diamond drill equipment through the tunnel side-walls close to the bulkhead, as it was desired not to disturb the latter in any way. The direction of these holes was based on the assumption that the water-bearing fissure would be encountered in a plane produced along the line of the general strike of the rock and passing through the ends of the holes by which the presence of the fissure was first determined prior to the flood. The first hole drilled with a percussion drill to the computed depth, encountered water at full pressure at a depth of 22 ft.; the success of this hole was very encouraging, as it had been computed that water would be encountered at 21½ ft.

The observation of results attained in grouting was accomplished by the attachment of pressure gauges on both the Astoria and Bronx bulkheads and by allowing the pipes in the Bronx end to remain flowing. Grouting began at 1 P. M. on December 18th, and was followed immediately by the appearance of grout in the flowing Bronx pipes, thus indicating that the point of injection communicated to the water hole of October 5th, and that the latter was still unsealed. At 9 P. M. on December 19th, after the injection of 3 360 bags of cement, the hole finally refused.

It was quite apparent that the recent grouting had been effective, but, during the time interval necessary to allow this to set thoroughly, it was decided to make a thorough investigation of the underlying rock before attempting to open up the grout-filled chamber between the bulkheads. This investigation proceeded during the remainder of December, and consisted of drilling ten long diamond drill holes, the result being that, though the rock structure outside the tunnel lines was found to be extremely disintegrated, no water was encountered—a favorable indication of the success of the recent grouting.

On January 5th, 1914, the work of removing the grout fill between the bulkheads commenced. A small drift was driven through the Astoria bulkhead, after which the door was raised and immediately placed in working order. The removal of the grout fill was then resumed, this work proceeding with very light blasting, toward the Bronx bulkhead door, which was raised on January 15th, 1914, and preparations were made for resuming the bench excavation—after a delay of 102 days, caused by the flooding of the tunnel.

In removing the grout fill, it was found to be in an unusual condition and stratification. Certain layers were extremely hard, and others were equally soft; some sections were highly stratified—others quite massive; some layers and masses of what might be described as solidified "laitance" were found, which never attained a greater hardness than that of the softest chalk, and having a curious chemical composition, entirely different from that of the original Portland cement from which it had been produced. Layers of sand also extended through the mass, and, in the vicinity of the water-hole, a 4-ft. blanket of coal, sand, shells, bits of wood, etc., was disclosed. No indications of water were apparent, other than the usual normal seepage through the concrete lining.

Several interesting conditions were encountered during the recovery of the flooded tunnel. Although large quantities of sand, coal, bits of wood, etc., were found, having been washed into the tunnel, and thus establishing proof of a direct connection with the river bed, no signs of any fish were observed, though during previous heading flows many live fish, up to 8 in. in length, were washed in.

Of unusual interest is the fact that, though the sum total of cement injected from both ends, from the time of the flood to the completion of the grouting, was only 595 cu. yd., about 1 150 cu. yd. of solid grout were removed, in addition to 400 cu. yd. of sand, shells, coal, etc., to say nothing of the quantity of cement grout which remained in and filled the fissures themselves. A possible explanation of this is that in some manner the injected cement had mixed freely with very fine-grained decomposed dolomite, probably in sediment in the water, and that cement in the form of grout does not act as normal Portland cement in maintaining constant volume.

A peculiar disclosure was made on uncovering the end of the long grouting tube inserted from the Bronx end. The end of this tube was solidly embedded in a 12-in. cube of extremely hard grout, entirely surrounded by a 4-ft. layer of sand, coal, shells, etc., thus isolated from the bulk of the grout in the chamber between the bulkheads. Apparently, with each injection, the cement scoured away and was forced through this sand layer, which then resumed its normal form after each discharge.

In view of the recent flooding, it was resolved to exercise even greater precautions than heretofore. After careful consideration, a method of attack was devised which ultimately proved quite successful. This consisted of: (*a*) the construction of an inverted concrete arch over the remaining length of bench between bulkheads; (*b*) an even more thorough exploration of the underlying rocks with test holes as long as could be drilled by percussion drills; (*c*) the injection of cement through these holes in an effort to solidify the rock mass—the inverted arch acting as a resistance to this grouting; (*d*) the careful excavation of the exposed rock by very light blasting of small sections only; and (*e*) the immediate concreting of the tunnel lining on completing a short length of full section excavation.

The inverted arch was 24 in. thick and 8½ ft. below the concrete tunnel arch on the center line. As this working space did not permit of drilling to the tunnel invert extrados, the exploration was accomplished by first testing to a depth of from 5 to 6 ft. below the inverted arch. Drilling pits were then excavated and concrete-lined as an inverted arch, well bonded into the tunnel arch and the inverted arch slab. Test drilling was then continued from these pits, thus reaching well outside of the necessary lines of excavation.

In removing this 122 ft. of bench, the entire rock encountered was extremely wet, and, although two flows of fair volume occurred, no unusual difficulties were experienced. This was undoubtedly due to the numerous injections of grout, which had been quite effective in consolidating the disintegrated rock structure. On uncovering the water-hole of October 5th, it was found to be a greensand seam, 24 in. wide, and of unknown depth, filled with sand, coal, shells, etc., through which a 9-in. layer of hard grout extended. No water was flowing, nor was there any further trouble from this fissure.

9.—Steel Lining.

Following the completion of the bench excavation, the erection of the cast-steel ring lining began. The installation of this lining was to secure impermeability through some 400 ft. of wet rock section extending on each side of the existing 50-ft. length of cast-iron rings. Being an after consideration, it was of necessity devised for its adaptability to the existing conditions. In contrast to the 50-ft. section of iron lined tunnel, the rock structure of the zone finally lined with steel rings was of such poor quality, and so treacherous and shattered, that it would have been extremely hazardous to increase the area of excavation necessary for the insertion of circular rings. Therefore, it was desired to maintain as small an excavated section as possible, and this resulted in the adoption of a metal lining of special design.

The usual assumption in designing a metal lining for subaqueous tunnel construction is that it is surrounded by a more or less plastic medium, and that no inward collapse can occur at any point without an outward distortion taking place at other points on the periphery; usually, the most suitable section to meet these conditions is a circular one. In this case, however, the tunnel being deeply embedded in rock and of a horse-shoe section, there were certain assumptions which could not be made in the case of a tunnel surrounded by soft material without cohesion. That is to say, the assumption on which the tunnel lining was designed was that, on the completion of the work, the spaces between the metal lining and the rock would be solidly filled with concrete or cement grout, which, when placed, would support the entire metal lining and prevent any possibility of an outward distortion of the lining, the latter being designed with sufficient strength to prevent any inward collapse.

However, partly on account of the hydrostatic pressure, and partly on account of the departure from a true circular form, such stresses were produced in the metal that, without an extraordinarily wasteful design, cast iron could not be considered as a feasible material for withstanding the resultant pressures, and it appeared, therefore, to be necessary to substitute cast steel.

The cast-steel segments used for this purpose were made by the Wheeling Mold and Foundry Company, in accordance with the specifications of the American Society for Testing Materials. The segments were machined on all flanges to exact templates, so that all segments of the same letter were interchangeable. The facing of all joints of the steel segmental plates was laid out from the templates, which, at the same time, defined exactly the position of coupling bolt holes, which holes were drilled in the plate castings. Although the specifications permitted the use of cored bolt-holes, no such coring was used on account of the impossibility of obtaining the accurate fitting of segments with the irregularities which would have thereby been caused, the specifications requiring that this absolute accuracy of segment form in its relation to the bolt centers should be maintained.

This cast-steel lining, Fig. 16, was of segmental form, shaped to the neat lines of the tunnel, with the extrados 7 in. beyond these lines. As the flange depth of the rings was 6 in., and it was not desired to increase this depth at the expense of cutting away more of the exterior concrete lining, there was an allowance of only 1 in. of concrete over the ring flanges in covering the lower segments up to the springing line of the arch, being simply a protection against possible corrosion and to produce a continuously fair and smooth surface for the interior of the tunnel.

Each ring consisted of eleven segments, including the key; all joints were accurately machined. The key was placed at the top, and the joints were not staggered, as is the custom with circular iron tunnel rings. The rings were 24⅛ in. wide, this odd width being designed on the assumption that a slight excess in the gauge length of each ring would be probable, and that in erection a growth or

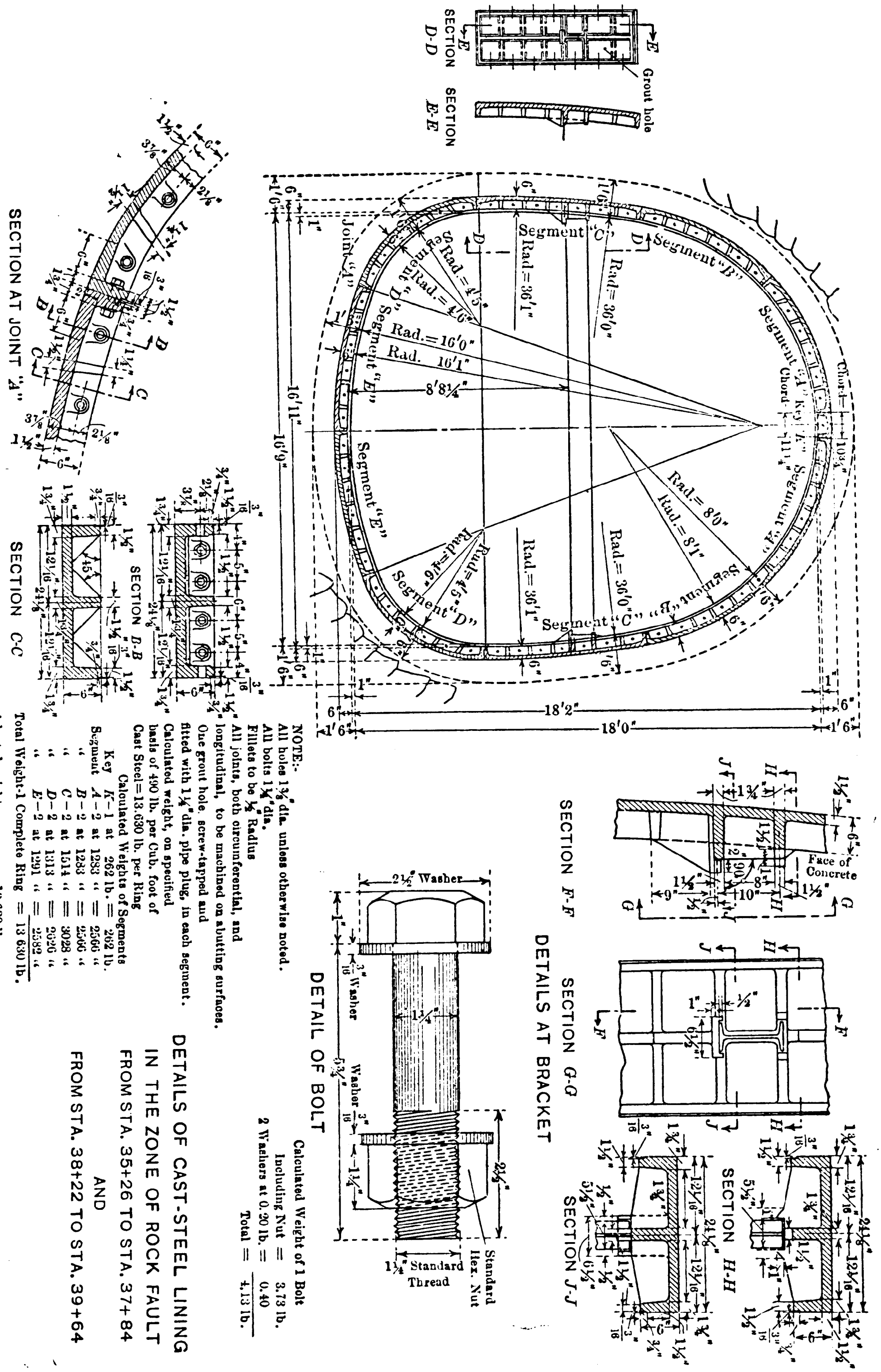


FIG. 16.

DETAILS OF CAST-STEEL LINING IN THE ZONE OF ROCK FAULT FROM STA. 35+26 TO STA. 37+84 AND FROM STA. 38+22 TO STA. 39+64 creep of ¼ in. to every six rings would occur. Actually, the machining was executed with almost perfect accuracy, and in erection no creep resulted throughout the entire length of 400 ft. Each segment, excepting the key, was provided with a tapped hole for grouting behind the rings, and each ring was equipped with brackets cast on the side plates, to carry a transverse 10-in., 40-lb., beam for the support of the permanent tunnel runway, and also to act as an additional strut to react against any possible horizontal distortion of the rings.

In consideration of the possible danger of causing serious water flows by the removal of the concrete lining necessary for the erection of the steel lining, it was decided to perform this trimming without the use of blasting but by taking off the necessary 9 in. by bull-pointing with small air-driven jack-hammers. For this same reason, a special method of procedure in erecting the steel was adopted. This consisted in erecting the 200 rings in four sections, by which arrangement, and the construction of two emergency bulkheads, the point of work was always protected, so that any unusual flows could readily be confined to a comparatively small length of tunnel.

Previous to the erection of the internal steel lining, the rock tunnel had been secured by a concrete lining, at no point less than 18 in. in thickness, which concrete was adequate, as long as it remained in perfect condition, to take all the hydrostatic pressure strains. At the same time, the concrete was not impervious, and as water would pass through it into contact with the steel lining, it would obviously transmit hydrostatic pressure to that lining. Simultaneously with the excavation of the rock bench, the exterior concrete lining was put in, but, as the arch concrete had previously been placed to the finished tunnel lines during the driving of the headings, it was necessary to chip the entire inside surface to provide space in which to erect the steel lining to the true lines called for. Consequently, there was a very small space remaining between the intrados of the concrete lining and the extrados of the steel lining. It was of vital importance, on account of the accurate machining to templates, that the rings should be erected absolutely true to the axis, and the only way in which this could be done without any question of doubt was by erecting with absolute accuracy a long stretch of the bottom plates, bolted up and laid out instrumentally to perfect alignment and grade. In order to do this, the bottom plates throughout were laid on a cradle consisting of three longitudinal strips of bar steel, 4 in. wide and ½ in. thick. These cradle bars were wedged up to proper alignment and grade, and secured by spiking with countersunk expansion bolts to the exterior concrete lining already in place. On this cradle were erected the two bottom segmental plates. The first short length of complete section lining, about 100 ft., was erected continuously on the bottom plates already set on the cradle, and each plate as erected was wedged with oak wedges to the exterior concrete lining already in place. The ends of this section were carefully secured by cementing, grouting, and packing, in order to maintain them rigidly and to plug the narrow spaces at each end, the theory then being to proceed with the grouting by leaving all grout holes open and pouring grout into each one in succession, and, as each hole indicated free flow of grout, to close each plug in its turn. It was thought that the plate lining, being held securely by hardwood wedges at each plate and the setting of the cement as grouting proceeded, would enable this section of steel to retain its form. Experience, however, showed that the hardwood wedges were inadequate to resist deformation in consequence of the pressures due to the flotation, and quite a serious distortion occurred in this section during the grouting operation, necessitating the entire removal of the section and its re-erection on the plan adopted later, as follows:

The rings were erected on the iron strip cradle previously described, on which the bottom plates for several ring lengths were first placed, followed by the same length of smaller radius side-wall plates. The remainder of each ring was then erected separately, this work being done by an erector. This method was adopted to prevent any divergence from alignment, as no special rings were provided to correct alignment deviation. The space behind each segmental joint was securely blocked with iron wedging to prevent distortion during the subsequent grouting operations. The method of grouting behind the rings consisted of forming a circumferential bulkhead of cement mortar behind two complete rings consisting of one whole and two half rings, spaced at a distance of five rings apart, and a longitudinal bulkhead behind the smaller radius side-wall plates, thus permitting grouting behind the rings in stages. This was essential to prevent distortion due to the weight of cement and the flotation of the tunnel. To insure further against the possibility of distortion, the five-ring section between bulkheads was internally braced with heavy timbering (Fig. 15). Only one set of timbers was used, grouting operations being carried along in the rear of the erection at the same rate of progress in each. By this arrangement the five-ring sections were completely grouted before the removal of the timbering, the grouting being performed in three operations: first, the lower half above the longitudinal bulkhead; second, the upper half (thus keying in the top portion); and, third, the bottom plates. The first operation was with an air pressure of 30 lb.; the second and third were with 135 lb.

The rings were grommetted and caulked on the completion of the grouting. In grommetting, which was carried on immediately in advance of the caulking, each bolt was wrapped with strands of hemp, not coated with any water-proofing substance, as is usually the practice, as it was determined by experiment that the results derived from pitch-dipped hemp were not better than with the uncoated strands. In caulking the ring joints, small air-driven caulking hammers were used, the procedure consisting simply of turning over the metal edges of the joint, in every respect as though caulking a boiler. In unusually wet places lead wire was used to stop the flow temporarily until the edges were turned. This 400 ft. of steel lined tunnel is now practically water-tight, although occasional drops are caused by the natural sweating of the metal. This in time will probably gradually dry up and disappear entirely, due to the corrosion of the metal and the silting in of fine particles of matter.

10.—Drainage.

The completion of the tunnel with the entire lining left a seepage of water to be taken care of by the permanent drainage and the pumpage of 280 gal. per min., this seepage coming in from the entire length of the tunnel and the two shafts, including the enlargement at the foot of the Astoria Shaft. Consequently, this leakage was yielded by the equivalent of some 5 600 ft. of full-sized tunnel, or a surface area of approximately 36 000 sq. yd. This inflow for the most part finds its entry through the jointing of the rock in the hardest portions of the granitic gneiss, including the Astoria Shaft and the tunnel extending from that shaft to the dolomite rock contact. The softer dolomite is, for all practical purposes, perfectly dry, and there is practically no water finding entry through the section lined with steel plates. The remainder of the inflow originates in the similar hard gneiss constituting the Bronx Shaft, and the section of the tunnel between the bulkhead line of the East River and the westerly contact.

The writer has invariably found that, so far as water flow through the rocks in the vicinity of New York is concerned, the greatest leakage is in the hardest rocks, and that wherever the mica schist or dolomite rocks exist, their softer character closes the joints and fissures to such an extent as to make these rocks practically water-tight.

Considerable efforts were spent on grouting through the lining to lessen the leakage from these hard rocks, including the drilling of long holes through the lining to intercept the minute joints and fissures, into which was forced cement grout under pressures of from 200 to 300 lb. per sq. in. For a time this would prove effective, but, within a few days after stopping the inflow, under these conditions, it would almost invariably be found that water would work its way through other channels, with the final result that the grouting of the rocks had little effect on the total quantity of water. There are indications, however, that in the course of time a great many of these minute fissures will choke themselves by the washing in of particles of solid matter to fill the crevices, a condition confirmed by observation of other tunnels.

11.—Ventilation.

The proper ventilation of the tunnel during the construction period was obtained with electrically-driven suction fans—one operated on the surface at each plant—capable of furnishing 2 500 cu. ft. of air per min. at a pressure of 5.4 oz. Each fan was at the top of each shaft, and was connected by a 12-in. inlet to an 18-in. pipe extended down the shaft and along the tunnel wall to within 200 ft. of the bench, sections being added as the advance proceeded. The fans were not operated continuously, but only until proper ventilation was secured after each blasting operation. On the Astoria side a 30-in. blower, driven by a compressed-air engine, was erected in the tunnel 1 700 ft. from the shaft, as the 12-in. fan was not efficient beyond this length. This blower was connected to the existing 18-in.

line from the 12-in. fan, the fan being discontinued when the blower was put in operation. In tunneling through the zone of decomposed dolomite, the construction of bulkheads close to the point of work in the heading naturally interfered with proper fresh air circulation, and at times the inflowing water carried with it sludge tar which had probably been discharged many years previously from adjacent gas-works and had been lying on the bed of the river in deep holes. This material gave off fumes which were unpleasant and caused a burning sensation in the eyes, but at no time during the work was there any illness or inconvenience attributable to improper ventilation.

12.—Lighting.

The tunnel was lighted electrically by current supplied at each plant by two direct-current generators, each of 250 volts, 200 amperes, and 50 kw. These were operated alternately, except at the Astoria end, where it was necessary to operate both generators at night after the tunnel had been driven 1 000 ft.

Lamps of 16 c.p. were used while in the heading and bench. Luminous-arc headlights were carried along with the advance, the result being very satisfactory, as these lamps gave a bright whitish light, quite essential through the dark, wet, rock sections, and especially in driving through some dense, black gneiss encountered. After entering the decomposed, water-bearing zone, kerosene hand-lanterns were used throughout the tunnel as a measure of safety, and were kept lighted at all times in case of emergency.

13.—Triangulation and Alignment.

The triangulation system of the Astoria Tunnel was first laid out in 1903-04, and conformed with the intentions at that time of constructing the tunnel to 111th Street, Manhattan. Subsequently, this triangulation system, with the necessary modifications, was adopted for the alignment of the present Astoria Tunnel.

The triangulation system of the present tunnel consisted of three scalene triangles constructed on an 1 800-ft. base line on the Astoria shore, with a 1 300-ft. check base on the Bronx shore, one angle point being on the extreme northerly end of the "Sunken Meadows" in the East River. The accuracy of the triangulation work was proved by the fact that the computed length of the Bronx base checked to within 0.006 ft. of the measured length, or 1 in 218 000.

The alignment was transferred down the shafts of the tunnel with suspended plumb lines which were aligned by direct sight across the river between shafts, triangulation towers being provided for this purpose. Some little difficulty was caused by the oscillation of the wires due to eddying air currents and the water seepage down the shaft sides, these conditions necessitating the use of 35-lb. wing weights. At the Astoria Shaft the base between the suspended wires was 28 ft.; in the smaller Bronx Shaft, the base was only 21 ft.

In the extension of the tunnel center line, all fixed points were placed in the concrete arch—those in the Astoria heading were at 300-ft. intervals, but in the Bronx heading a maximum of only 200 ft. could be used, on account of the continual fog. As the headings approached the water-bearing rock section, it was found necessary to reduce the sight lengths considerably, especially after the construction of bulkheads, as the fog then became, in a sense, confined. All instrument work was performed from suspended transit tables and scaffolds, thus preventing any delays to, or confusion between, the engineering and construction forces.

Accurate elevations were determined from a bench-mark on the northern shore of the Bronx Kills opposite Randalls Island. The reference of this bench-mark to a mean-sea-level datum plane was supplied to the tunnel engineers by the United States Coast and Geodetic Survey, being based on the result of 6 years of tidal observations at Sandy Hook, N. J. The location of this bench-mark necessitated a level run of 3 900 ft. to the Bronx Shaft and a run of 14 000 ft. to the Astoria Shaft, the latter route crossing Randalls and Wards Islands to reach the point of minimum width of the East Channel of the East River. Thus, the length of the combined transfer of elevations of 3½ miles on the surface to the point of closure in the tunnel was approximately 4½ miles, in view of which the error of only ⅛ in. is quite remarkable.

In consideration of the unfavorable conditions under which the underground work was necessarily performed, the meeting of the alignment and grades of the two headings is regarded as most satisfactory. As mentioned, when the tunnel entered the water-bearing rock, there was considerable difficulty in obtaining even fairly distinct sights, as there was a continual fog caused by the condensation of the air exhaust from the drills, pumps, and grout pans. The alignment, which was carried 3 900 ft. from the Astoria Shaft and 762 ft. from the Bronx Shaft, met to within $1\frac{1}{4}$ in. for line, $\frac{1}{8}$ in. for grade, and $\frac{1}{2}$ in. for stationing.

14.—Quantities and Costs.

Table 7 is a summation of the quantities incidental to the shaft and tunnel construction.

Table 7.—Summation of Quantities.

Earth excavation, for erecting plant	1 750	cu. yd.
Earth excavation, shafts	3 050	"
Earth excavation, total	4 800	"
Rock excavation, shafts	17 480	"
Rock excavation, tunnel	70 140	"
Rock excavation, total	87 620	"
Concrete removal, tunnel	4 080	"
Grout bank removal, tunnel	1 150	"
Summary of excavation—earth, rock, concrete, etc.	97 650	"
Concrete, plant foundations	1 160	"
Concrete, shaft lining	5 070	"
Concrete, tunnel	26 860	"
Concrete, tunnel bulkheads	2 070	"
Concrete, pipe foundations	710	"
Summary of concrete placed	35 870	"
Lining rings, 20 cast-iron, 50 lin. ft.	227½	tons*
Lining rings, 200 cast-steel, 400 lin. ft.	1 365	"
Lining rings, total, 220 rings, 450 lin. ft.	1 592½	"
Cement, concrete plant foundations	6 870	bags
Cement, concrete lining, shafts and tunnel	199 000	"
Cement, concrete bulkheads	16 160	"
Cement, concrete pipe foundations	4 590	"
Cement, total in concrete	226 620	"
Cement, grouted in shaft lining	1 200	"
Cement, grouted in tunnel concrete lining	45 340	"
Cement, grouted in metal lining	14 380	"
Cement, grouted in bulkheads	26 510	"
Cement, grouted in test holes	28 550	"
Cement, grouted in pipe supports	2 000	"
Cement, total in grout	117 980	"
Cement, total in concrete and grout	344 600	"

*Tons of 2 000 lb.

In this undertaking the cost of construction must be classed in two accounts: first, the cost of the shafts and tunnel constructed under normal conditions in the two types of rock formation; and, second, the extraordinary cost and expense of that portion of tunnel, approximately 400 lin. ft., constructed in the decomposed rock formation. The cost of the permanent pipes and interior equipment is an additional and entirely distinct item of expense, bearing no direct relation to the cost of the structure of the tunnel.

It is worthy of note that the unit costs, based on all work of a normal character, with the sole exception of the great expense of getting through the decomposed rock, was less than the originally estimated figures contemplated at the commencement of the work.

The unusual conditions involved in that portion of the tunnel driven through the decomposed rock formation, and the long delay in conquering the difficulties which arose, involved an actual cost for that section materially greater than had originally been allowed.

Tables 8 and 9, showing the distributed unit costs for the shaft and normal tunnel constructions, are of interest and value, and show advantageous results under the conditions governing the work. The unit costs given in these tables are the totals for both labor and material, allowing 60% of the purchase value of plant and equipment —the remainder being considered as a credit for ultimate salvage. The item "Contingencies" includes all expenses chargeable to accidents, damages, hospital, rentals, insurance, and operation of the ferry-boat used between the shafts.

TABLE 8.—UNIT COSTS OF SHAFT CONSTRUCTION—NORMAL CONDITIONS.

Items.	COST PER ACTUAL CUBIC YARD.			
	Rock excavation (Gneiss).		Concrete Lining.	
	Astoria Shaft.	Bronx Shaft.	Astoria Shaft.	Bronx Shaft.
General supervision	$0.114	$0.120	$0.130	$0.120
Engineering expense	0.193	0.204	0.221	0.205
Field office administration	0.808	0.853	0.922	0.855
Plant and equipment, installation and maintenance	0.346	0.365	0.396	0.366
Plant and equipment, 60% of purchase value.	0.867	0.915	0.990	0.917
General surface labor and supplies	0.354	0.373	0.451	0.375
Drilling and blasting	1.971	1.571	1.083	1.283
Mucking	1.652	1.797	......	......
Disposal, surface transportation	0.484	1.592	......	......
Disposal, scow line and towing	0.149	0.101	......	......
Power and plant running	1.625	1.343	......	......
Making and sharpening steels, and repairing machines	0.420	0.376	......	......
Lighting	0.157	0.171	0.134	0.161
Extending lines (air, pump, etc.)	0.173	0.124	0.100	0.098
Pumping	0.301	0.439	0.234	0.207
Contingencies	0.817	0.879	1.113	1.078
Forms and platforms, making, setting and removing	......	......	2.389	1.902
Use and waste of lumber	......	......	0.300	0.294
Handling materials	......	......	0.519	0.341
Sand	......	......	0.264	0.424
Cement	......	......	1.898	1.807
Stone	......	......	0.836	0.806
Mixing concrete	......	......	0.784	0.779
Transportation	......	....	0.055	0.000
Placing concrete	......	......	1.342	1.650
Cleaning up	......	......	0.045	0.091
Totals	$10.431	$11.223	$14.206	$13.759

TABLE 9.—UNIT COSTS OF TUNNEL CONSTRUCTION—NORMAL CONDITIONS.

Items.	Cost per Actual Cubic Yard.		
	Rock excavation.		Concrete lining.
	Gneiss.	Dolomite.	
General supervision	$0.087	$0.069	$0.064
Engineering expense	0.151	0.121	0.127
Field office administration	0.629	0.503	0.464
Plant and equipment, installation and maintenance	0.283	0.226	0.209
Plant and equipment, 60% of purchase value	0.662	0.529	0.488
General surface labor and supplies	0.327	0.261	0.326
Drilling and blasting	1.997	1.672	......
Timbering	0.005	0.001	......
Mucking	1.736	1.213	......
Disposal, tunnel and surface transportation	0.795	0.748	......
Disposal, scow line and towing	0.279	0.249	......
Power and plant running	1.262	1.055	1.256
Making and sharpening steels, and repairing machines	0.285	0.306	......
Lighting	0.158	0.152	0.183
Extending lines	0.139	0.142	0.161
Pumping	0.152	0.116	0.147
Contingencies	0.761	0.626	0.984
Wood forms, making, setting and removing	......	......	0.857
Steel forms, making, setting and removing	......	......	0.125
Steel forms, charges	......	......	0.353
Use and waste of lumber	......	......	0.187
Handling materials	......	......	0.332
Sand	......	......	0.323
Cement	......	......	1.918
Stone	......	......	0.891
Mixing concrete	......	......	0.487
Transportation	......	......	0.702
Placing concrete	......	......	1.709
Cleaning up	......	......	0.270
Totals	$9.708	$7.989	$12.563

15.—CAST-IRON PIPES IN THE TUNNEL.

The cast-iron pipes in the tunnel from Astoria to The Bronx are the largest ever made. Their internal diameter is 72 in.; the thickness of metal in the pipe walls is $2\frac{3}{4}$ in.; they have hub and spigot joints, and were cast in standard 12-ft. lengths. The weight of each pipe is 26 000 lb., and the displacement of water by each length represents some 24 800 lb., from which it is seen that, even should the tunnel be allowed to fill with water, the pipes would retain their position secure.

These mains are arranged in two parallel lines occupying the lower portion of the tunnel, and are supported on concrete bed-blocks. The structural steel runway, Fig. 17, for supporting any future utilities that may be put in, extends through the tunnel and is just above the mains. The concrete blocks are 6 ft. apart, each block supporting

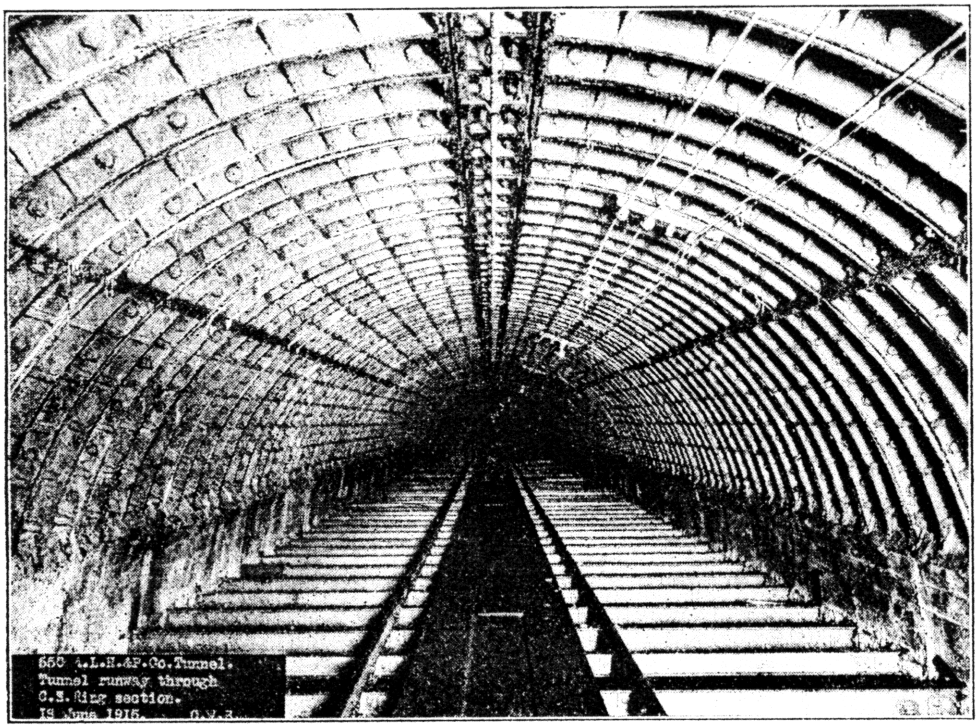


FIG. 17.—TUNNEL RUNWAY THROUGH CAST-STEEL RING SECTION.

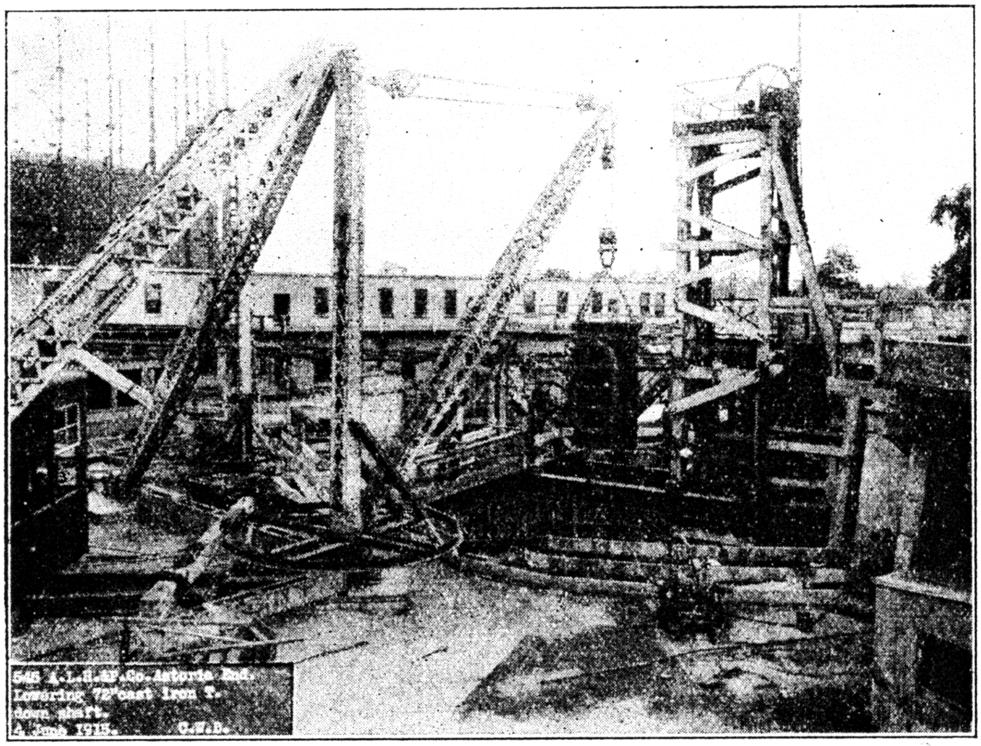


FIG. 18.—LOWERING 72-IN. CAST-IRON T DOWN SHAFT.

both lines of pipe. Each 12-ft. length of pipe is supported by two blocks, and the joints of the two pipe lines are staggered. Every second block supports a cast-iron column which braces the center of the transverse runway beams, the actual support for the runway being provided by cast-iron brackets anchored to the concrete tunnel walls. In both shafts the two 72-in. pipe lines are connected to the tunnel lines by double-spigot eccentric reducers and bell-spigot bell tees. All the vertical risers are 12 ft. long, with both the spigots and bells machined on the face to take the true bearing of the vertical pressure loads. At the top of each shaft flanged spigot tees, reducing to 48 in. diameter, connect to 48-in. pipes through the shaft lining into concrete valve pits, thence passing underground—in Astoria to the gas holders, and in The Bronx to the street feeder lines. Each shaft is equipped with an elevator and an emergency ladder, the elevator framing also acting as a bracing for the pipe lines. The tunnel runway extends to the elevator landing at the bottom of each shaft, and in the Astoria Shaft there is an operating floor in the enlargement.

During the driving of the tunnel, arrangements proceeded for putting in the permanent piping, and consisted of unloading and storing the pipe and structural steel, casting the concrete pipe bed-blocks, setting bolts in the tunnel side-walls for the support of the tunnel runway, and the design and construction of additional plant equipment necessary in laying the pipe.

The pipes, excepting those for the Bronx Shaft, were stored at the Astoria plant, as the required space was available there and as it was also the intention to lay them from the Astoria side, this shaft affording the larger working area. The concrete blocks were cast on the surface at the Astoria plant, the work being completed fully a year before the pipe-laying commenced, so as to insure the maximum strength. Collapsible wooden moulds were used, and the mix was a rich gravel concrete, as it was desired to secure a thoroughly sound block. The blocks contained reinforcing rods, bolts for securing the runway columns, and small pipe holes to which the slugs were attached when lowering into the tunnel. As the saddles were long and of irregular shape, the reinforcing rods were necessary to prevent fracture due to their dead load when lifted by the derrick.

The permanent bracket bolts for the support of the tunnel runway are 12 ft. apart, and there are two bolts at each bracket; but, as it was intended to use a traveling crane, running on steel girders secured to the tunnel walls, for which two bolts were insufficient, advantage was taken of the necessity of the permanent bracket bolts and the crane track design arranged to utilize those bolts. This resulted in placing four bolts at each bracket location. The bolts were 1¼ in. in diameter, 24 in. long, and were secured 18 in. in the concrete side-walls.

In laying out the bracket holes, the marking points were permanently secured, each consisting of a small nail driven into a wooden plug set in the concrete walls of the tunnel; thus the points were preserved until a year later, when they were used for spacing and grading the pipes. This simplified the necessary field engineering during the laying of the mains, and was a decided factor in the excellent progress attained.

The principal additions to the plant equipment, incidental to the laying of the 72-in. mains, consisted of a 50-ton steel derrick and engine, a traveling crane, and two pipe-testing machines.

The steel derrick for handling the 72-in. mains, Fig. 18, had a 50-ft. boom and a 35-ft. mast. Power was supplied by a steam-driven engine, having a 10-in. cylinder and a 13-in. stroke. The swinging gear was operated independently by a rotary engine. The hoisting rope was a six-part line of ¾-in. special wire cable, and the boom fall was a twelve-part line of ¾-in. wire cable. In operating this engine, the load was lowered by throwing the clutch into gear and allowing the engine to run backward, instead of throwing on the brakes, as the friction burned up the wooden brake bands too rapidly. This method was considerably safer, and gave better control, than by lowering with a brake. Special slings were constructed for handling one pipe and two saddles together.

The traveling crane, Figs. 19, 20, and 21—designed by Mr. Hodgson for handling and erecting the pipe within the tunnel—was constructed on a wood frame fitted with cast-steel wheels running on steel girders attached to the concrete tunnel walls by the 1¼-in. bolts previously mentioned. The wheel base of the crane was the same as the bracket spacing, so that the load on the bracket could not exceed the maximum wheel load of the crane, which was 15 000 lb. The crane was operated by two 5-h.p. air engines—one for the longitudinal and the other for the transverse movement. The speed was from 40 to 50 ft. per min., quite sufficient for the short distance covered. Each end of the crane

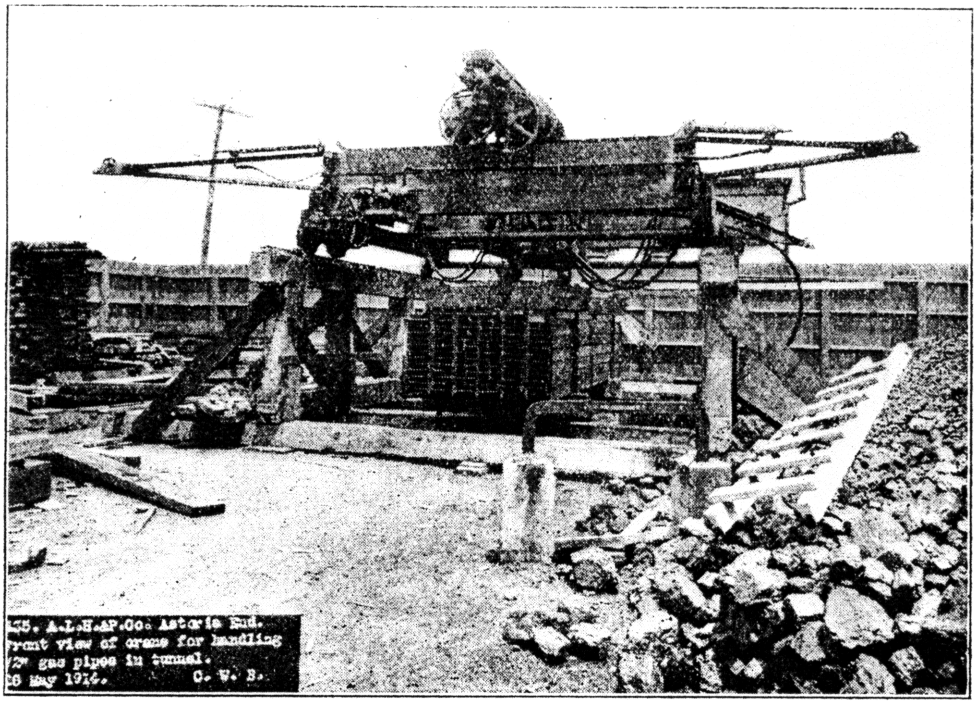


FIG. 19.—CRANE FOR HANDLING 72-IN. CAST-IRON PIPES IN TUNNEL.

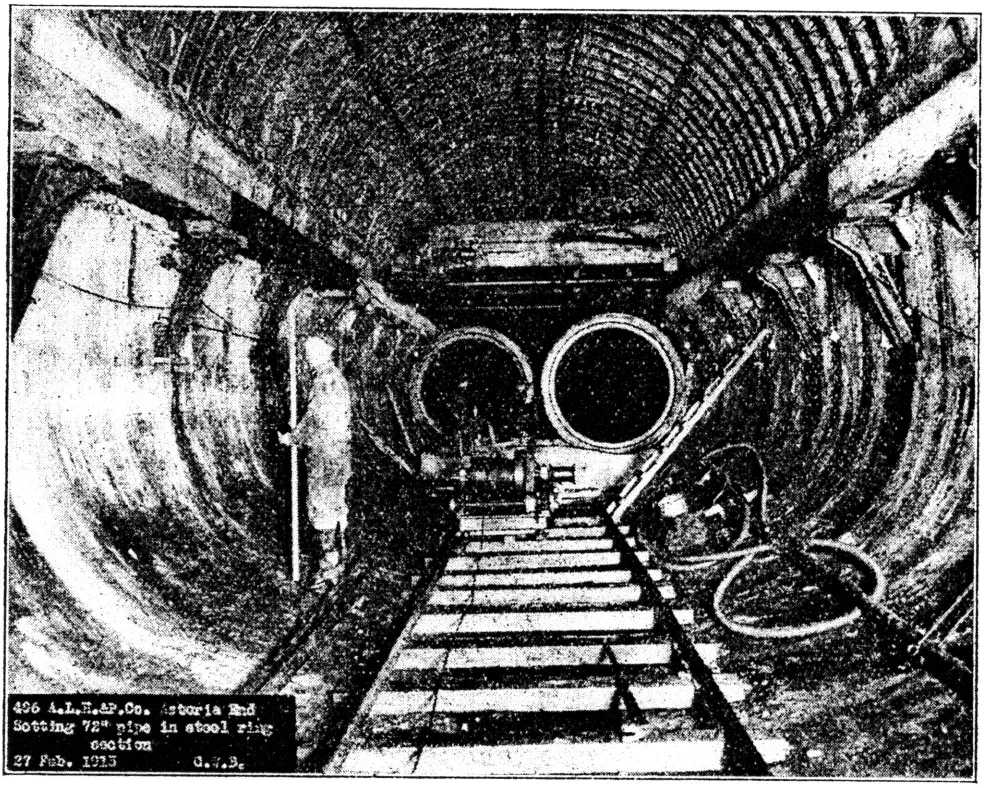
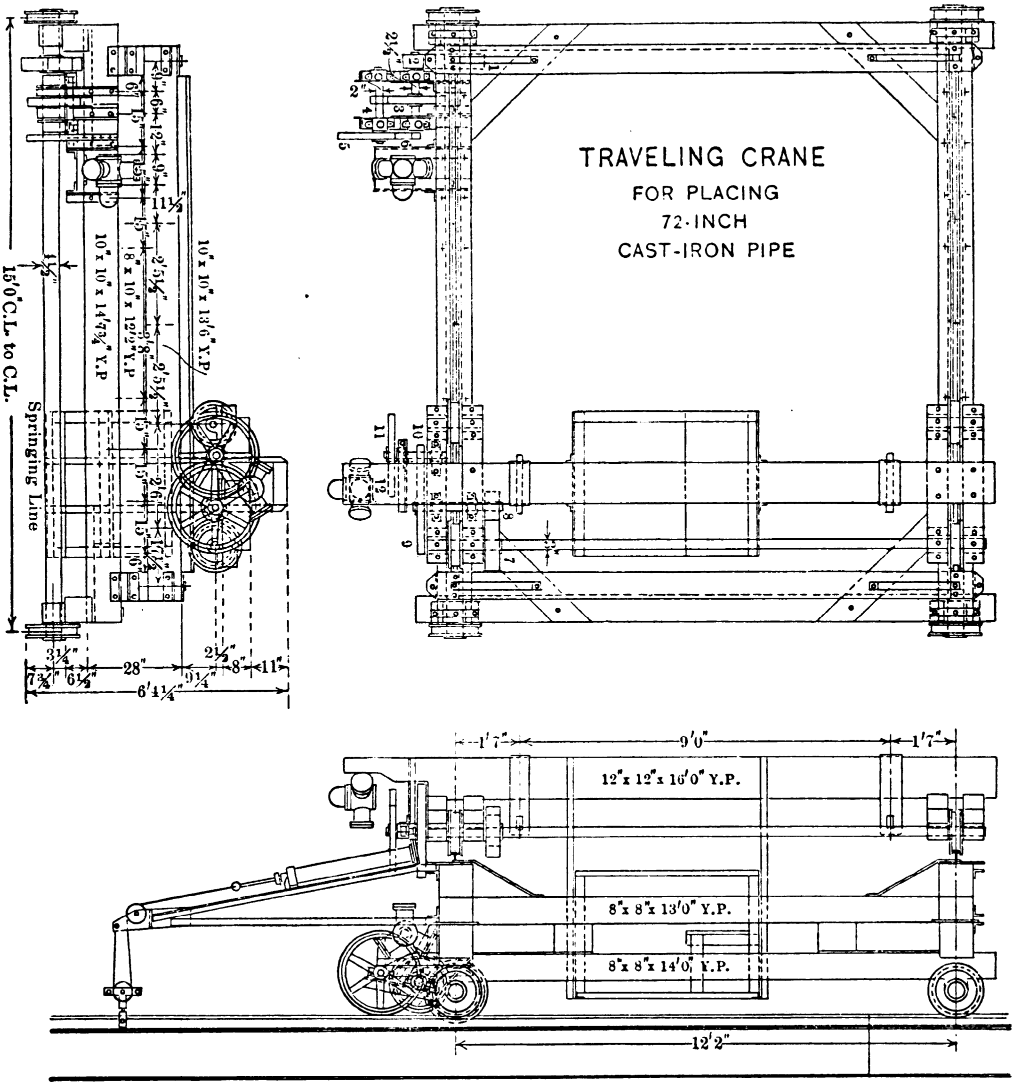


FIG. 20.—SETTING 72-IN. PIPE IN STEEL RING SECTION OF TUNNEL.



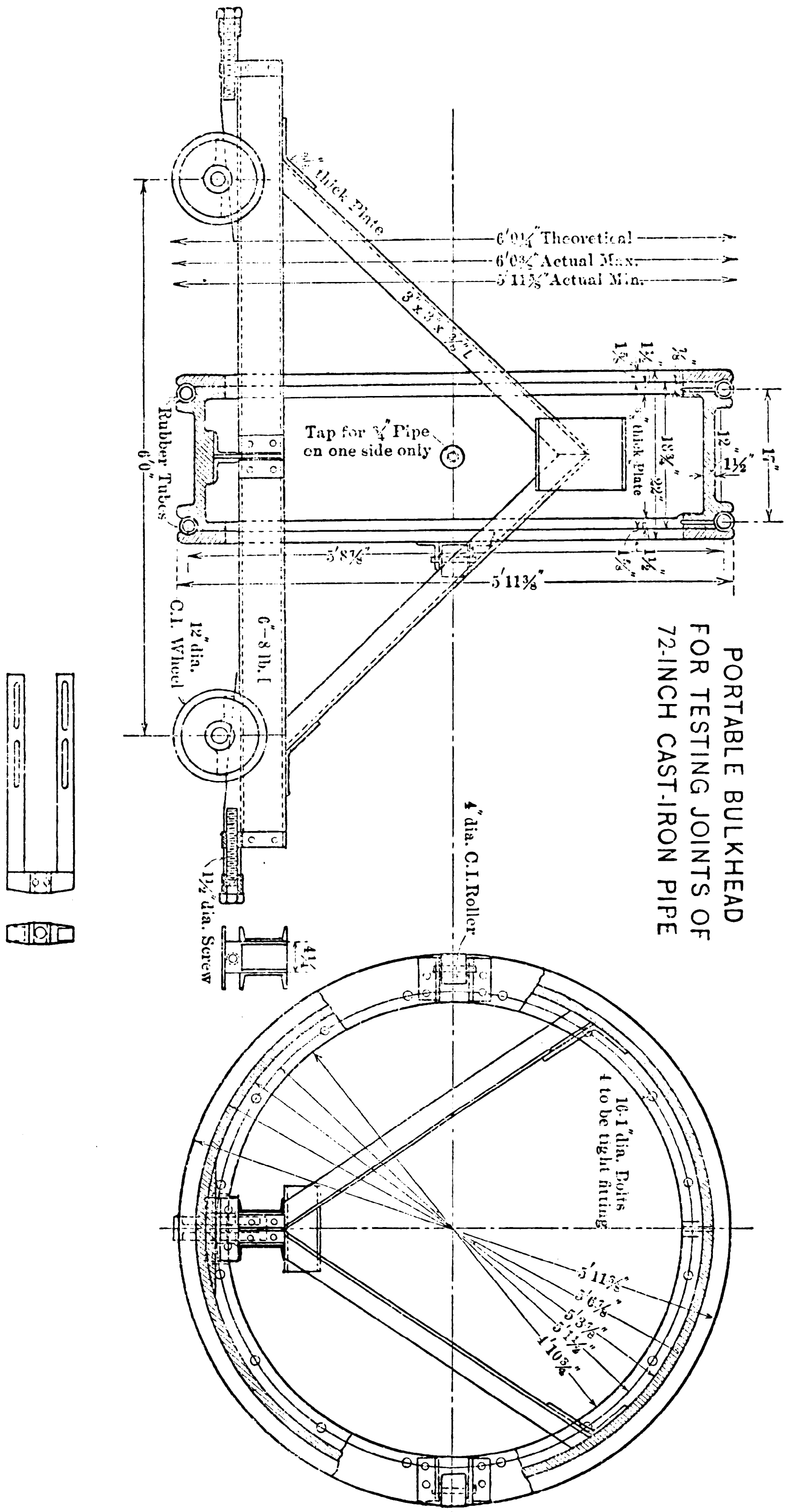
DIMENSIONS OF GEAR WHEELS

Marked	Pitch diameter	Pitch	Number of Teeth	Width of Face	Diameter of Hole	Size of Key way	Material	Hub
1	17.188"	1½" Circular	36	4"	4 23/64"	¾"	C.I.	4¼"
2	6.207"	1½" "	13	4"	2½"	⅝"	Steel	4"
3	17.188"	1" "	54	2½"	2½"	"	C.I.	3"
4	5.092"	1" "	16	2½"	2"	½"	Steel	"
5	24."	4" Diametral	96	1¾"	2"	"	C.I.	"
6	4."	4" "	16	2"	1 13/16"	⅜"	Steel	2"
7	14.483"	1¾ Circular	26	4"	2 57/64"	¾"	C.I.	4¼"
8	7.798"	1¾" "	14	4"	2½"	⅝"	Steel	4"
9	26.738"	1" "	84	2½"	2½"	"	C.I.	2¾"
10	4.456"	1" "	14	2½"	2"	½"	Steel	2½"
11	24."	4" Diametral	96	1¾"	2"	"	C.I.	3"
12	4."	4" "	16	2"	1 15/16"	⅜"	Steel	2"

FIG. 21.

had two swinging arms, to each of which was attached a cable hoist, operated by an air-driven ram, to lift the crane girders for the purpose of moving them ahead, section by section, as pipe-laying proceeded.

Although the laying of the mains in the tunnel was to be done by the tunnel construction organization, the jointing of the pipes, when and as laid, was to be done by the Street Department of Mains of the Company. At the same time, it devolved on the tunnel organization to subject all joints to test after they were caulked. The requirements were that each joint should be subjected to a test by air pressure at 20 lb. per sq. in., and that such test should be applied in each line of pipe as each ten pipe lengths were laid. It was obvious that this latter requirement would limit the progress of laying to the rapidity of caulking operations, and thus interfere seriously with procedure. Further, to consider plugging the end of the pipe main, and to have a portable end bulkhead to be erected and secured as each ten lengths were laid, would have involved great delay, as the caulking operations would have to be completed up to the last length laid before such testing could proceed. The writer, therefore, designed a novel machine (Fig. 22) for testing joints. This was a complete traveling outfit, consisting of a double bulkhead on a wheeled frame, which could be pushed by hand through the inside of the pipe mains and enclose any joint within an annular space. The two bulkheads consisted of pneumatic tires inflated to make a tight joint between the testing machine and the inside wall of the pipe. Two testing machines were assembled at the tunnel works, one being used for each line of pipe. The machine consisted of a cast-iron piston, 71½ in. in diameter, or ½ in. less than the internal diameter of the pipes. Previous to laying, a great number of pipes had been calibrated, and the internal diameter was found to range from a minimum of 71⅝ in. to a maximum of 72¼ in. This piston was 24 in. long, with exterior flanges, giving an annular space between flanges of 12 in. The two flanges were designed of cove form, to give close support to a soft and elastic rubber tube, and the exterior rings, attached by bolts to the center casting, like a junk ring to a piston, enabled the rubber packing rings to be inserted and, when inflated, to give the necessary support. These flanged grooves were fitted with a solid continuous tire tube, made of the finest inner tube rubber, and fitted with a standard automobile tire valve, the tube being 2½ in. in external diameter with ⅜-in. rubber walls. These tubes were made up



PORTABLE BULKHEAD FOR TESTING JOINTS OF 72-INCH CAST-IRON PIPE

FIG. 22.

so that when deflated the exterior diameter was 71 in. The inflation forced the tire out against the wall of the pipe and filled the grooves of the piston, and, when deflated, the elasticity of the rubber entirely withdrew it from contact with the pipe walls while the machine was pushed backward or forward within the pipes.

As the pressure to which all joints were to be subjected was 20 lb. per sq. in., it was thought that the pressure to which the tubes would need to be inflated to make a tight joint might be as high as 80 lb., but, actually, though this pressure was used in the first instance, it was found that 50 lb. was ample to make an absolutely tight joint for testing purposes. In operating the machine, the annular space was moved to a position central over the joint. Air from the high-pressure tunnel line mains was supplied by a flexible hose and, through a reducing valve—to step down the constant pressure of 50 lb.—to the manifold pipes connecting both rubber tubes. These being inflated, the test pressure was then applied through another reducing valve, a pressure gauge being fixed to the annular space, under the observation of the operator, so that the pressure might not be materially exceeded, to obviate any possibility of blowing out a joint already caulked. Another operator, on the outside of the hubs, previous to the application of the test pressure, painted the leaded joints with soap solution and watched for leaks which would be indicated by the formation of bubbles. These machines were easily operated on their roller frames, joints caulked at any point could readily be tested, and, if re-caulked, could readily be re-tested. In addition to which, owing to the form of the machine, there was no appreciable end thrust to require other precautions than were given by the machine itself to balance that thrust.

The methods adopted in laying the 72-in. pipes in the tunnel consisted of lowering both pipe and saddles down the Astoria Shaft, hauling to the Bronx end, and advancing the work toward Astoria. This work was only carried on during an 8-hour day shift, as it was not desired to run any risk in handling this heavy material at night. The pipes were laid in pairs; that is, the operations consisted of the hauling and setting of two saddles, followed by the hauling and setting of two pipes; these, in turn, were followed by two more saddles, etc. By maintaining two saddles ahead of the pipe in place, this scheme permitted an overlapping of the various operations, such as placing and setting saddles, setting pipe, moving crane girders, removing hauling track, etc., thus reducing the loss of time to the minimum.

The pipes, which varied within 1½ in. of the correct length, were all numbered, and were selected from the storage rows as the work proceeded. Each pipe was transported to the shaft by rolling it on skids by a single cable engine with the cable looped around it. They were lowered singly down the shaft by the steel derrick, and with every other pipe two saddles were lowered. A tag line was attached from the pipe to a steel cable guide stretched from top to bottom of the shaft, to prevent the load from twisting.

The pipes and saddles were landed directly on specially designed flatcars, and haulage to and from the point of work was by the endless cable system on a single track. The pipe cars were run at a speed of 6 miles per hour and the other loads at 10 miles per hour. These speeds were greater than those usually adopted for an endless cable system in tunnel work, but in this case the system was designed with the minimum number of sheaves and turns possible, so that these speeds were readily maintained and without accident.

On the arrival of the saddles at the point of work they were transferred from the flatcars to the tunnel invert by the crane and accurately set to alignment, grade being maintained by steel wedging beneath them. The pipes were taken directly from the flatcars to position by the crane, two 1-in. wire cable slings, each attached to a 10-ton chain block, being used for raising the loads.

The setting of the pipes was followed, some 200 ft. back, by the caulking, and this at a like distance was followed by the testing machines; so that there was no confusion between the various gangs engaged.

The joints were hand-caulked with small air-driven caulking hammers, hemp yarn and lead wool being well driven to a depth of 5½ in. into the caulking space, which was ⅝ in. wide. This required 4 lb. of soaped yarn, 10 lb. of dry yarn, and 225 lb. of lead, per joint, the latter including 2% waste. The average progress was sixteen joints caulked each day with sixteen hammers. Each pipe line was provided with a portable bulkhead for testing, as previously described. After this testing, the joints were thickly coated with red lead.

Excellent progress was attained in laying the tunnel pipe, especially considering the fact that the entire tunnel transportation in both directions was over a single track. An average daily progress of twelve pipe lengths was attained for the whole work, and in the half tunnel length last executed the average progress was as great as sixteen lengths per day.

The erection of the structural steel runway proceeded from the Bronx end toward the Astoria Shaft, the material being lowered down the Bronx Shaft. No difficulty was found in doing this work at the same rate as pipe-laying, and it was not featured by any incident of unusual interest.

Personnel.—The undertaking herein described was carried out for the Astoria Light, Heat and Power Company (an organization closely affiliated with the Consolidated Gas Company of New York), and was under the general supervision and direction of Mr. William H. Bradley, Chief Engineer, and William Cullen Morris, M. Am. Soc. C. E., Engineer of Construction. Mr. Colin C. Simpson, Superintendent of Mains, had direct charge of jointing the pipes inside the tunnel and of laying the street mains connecting therewith.

The development of the plan for the project of building the Astoria Gas Plant and the Astoria Tunnel herein described, must be attributed directly to Mr. Bradley.

The design, engineering, and construction of this entire work were executed by Jacobs and Davies, Incorporated, as Tunnel Engineers, for whom the writer acted as Engineer-in-Charge. The field engineering, including surveying, alignment, and detailed field work in connection with construction, was first in charge of Mr. G. F. Weismann, and during the later period was in charge of Mr. J. Chadwick Scott, who had previously acted as Assistant Field Engineer. The construction of the work, throughout, was in charge of Mr. Vivian Messiter as Engineers' Agent, assisted by Mr. Alexander W. Hodgson as Mechanical Engineer.

DISCUSSION

F. LAVIS,* M. AM. SOC. C. E. (by letter).—During the past few years there has been a notable development, and almost entirely in the vicinity of New York City, in the construction of tunnels at such depths below water level as to preclude the possibility of using air pressure to prevent the inflow of water, should seams in the rock afford it an opportunity to reach the tunnel with the full head due to the depth below the water surface. Mr. Lavis.

The other tunnels of this nature which have been built, have been along the line of the Catskill Aqueduct, where the restrictions confining the location within certain definite limits were not so rigid as in the case of the Astoria Tunnel, and, therefore, it was possible to fix them with greater regard for the avoidance of probable bad geological conditions. In the case of the deep siphons of the Aqueduct, sufficient diamond drill borings were taken to enable competent geologists to predict fairly successfully the character of the rock, and the location was made in such a way that the tunnel would lie wholly within the zone in which it was expected to find sound rock, free from faults, or to cross the latter at or nearly at right angles. So far as the writer knows, these expectations were reasonably well fulfilled, and although grouting of water-bearing seams was resorted to, and very high pressures were used, there has not been recorded, thus far, any experience comparable to that encountered in the Astoria Tunnel, and so well and fully described in this paper. The latter is unique in describing methods of driving a tunnel through unstable ground with seams of decomposed rock having direct connection with navigable waters, at a depth of more than 100 ft. below the lowest depth at which work could be carried on under air pressure, the recovery of the tunnel after complete flooding, and the solid grouting of the whole tunnel section to form a stable material through which the tunnel was finally driven.

It seems to the writer that it is out of the question to discuss in much detail the methods described in the paper; we have had no similar experience with which to compare it—the situation was unique, the methods were effective, and the job is finished. Some other scheme might have been effective, but no one can say positively that it would, the only possibility known to the writer is freezing, and there is nothing in past experience to lead one to believe that it would have been better, or so good. Probably it is only effective in fairly homogeneous material softer than rock, and probably would not work at all in the shattered rock encountered in this tunnel.

The Society, as well as the author, is to be congratulated on the excellent manner in which the paper has been presented, and the

* New York City.

Mr. Lavis. completeness of the description contained therein. The writer believes that his paper,* describing the construction of the Bergen Hill Tunnels of the Pennsylvania Railroad, contained the first tabulated statements in reference to any tunneling work in North America, showing number of feet drilled per cubic yard, quantities of explosives, actual drilling time, etc., though, in a lesser degree, such records had been published in regard to some of the Alpine tunnel work in Europe. He has noted, therefore, with considerable satisfaction, the presentation of similar data, not only in this paper, but in several other descriptions of tunneling operations in recent years. The statement of progress in number of cubic yards per shift or per day is far more definite than the statement of the number of feet of advance which may or may not be of the full clean section. The statement showing the complete items of the plant is most useful, as are also the details, so often omitted, of the smaller items, in regard to the excavation of the rock, such as quality of steel, sizes of holes, kind of fuse, batteries, etc.

The construction of the concrete arch to hold the roof in bad ground before building the side-walls or invert is not new in this tunnel, although it is a comparatively recent development in the art of soft-ground tunneling. So far as the writer knows, its first important use was in the Providence Tunnel of the New York, New Haven and Hartford Railroad, built about 10 years ago.

The question as to the desirability or otherwise of using dry rock packing to fill the space between the normal section of the lining and the actual excavation is an interesting one. In this case, as well as in nearly all cases of the tunnels on the Catskill Aqueduct, tight concrete packing and thorough grouting were clearly indicated as the only effective method of surely preventing the least disturbance by settlement of the surrounding ground. In cases similar to that of the Bergen Hill Tunnels of the Pennsylvania Railroad, however, the use of dry rock packing over the arch was not only far less expensive, but proved to be most effective in allowing the ground-water to reach the drainage pipes at the sides and thus enter the side drains in the floor, providing a dry tunnel with very little water-proofing.

The value of this paper and the importance of the work which it describes can only be fully understood by a realization of the fact that it marks a distinct step forward in the art of tunneling. For ages, almost, tunneling was only possible through fairly sound rock, or materials which could be held by close timbering. The shield and the use of compressed air, brought into really general use only within the last 30 years, although they had been used previous to that time, enable tunnels to be driven through water-bearing materials to depths of about 100 ft. below the surface of the water, the pressure at greater depths being so great as practically to prohibit effective work. We

* *Transactions*, Am. Soc. C. E., Vol. LXVIII, p. 84.

now have a method of driving tunnels at almost any depth in water-bearing ground, and, within certain limits, through almost any class of material. Mr. Lavis.

Perhaps it is not without interest at this time, when it has been suggested that mining engineers should be called in to advise as to methods of subway construction, to note—without in the least detracting from the ability of mining engineers and miners in their particular field—that nearly all the developments in the art of tunneling through difficult ground, beyond the art of timbering in comparatively small sections, have been made by civil engineers, and for transportation purposes, rather than by mining engineers or miners. In the really vast tunneling operations which have been carried on in New York City and its vicinity in recent years, it is undoubtedly within the bounds of truth to state that not only has this work been the greatest, most extensive, and most difficult of its kind, that is, of tunneling, ever undertaken and carried out successfully anywhere, but it has been done with fewer accidents, and all the engineers responsible for this state of affairs deserve commendation.

The record of this work on the Astoria Tunnel shows, also, as do all records of successful advances in the art of tunneling, and nearly all records in recent years of advance in the rate of progress, the absolute necessity of such preliminary study, careful planning, and efficient organization as usually only engineers are trained to carry out. It must be remembered, however, that though a carefully studied plan must be worked out and adhered to, engineers engaged in this kind of work must be able to adapt it to all sorts of variations as they arise. It is far from easy, amid the noise, dirt, partial darkness, and, oftentimes, apparent confusion underground, to carry out a plan which looks well on a drawing-board in a comfortable, well-lighted office; and when added to all this, the whole East River is likely to drop in on one at any minute, plans are likely to go by the board.

Milton H. Freeman,* Assoc. M. Am. Soc. C. E. (by letter).—One of the most interesting features of this paper is the description of the method of excavating through decomposed water-bearing rock. An excellent opportunity was afforded to obtain positive data concerning the results of the grouting, as the subsequent excavation exposed the grout-filled seams. In work of a similar character on the Catskill Aqueduct, the following were found to be essential features: Mr. Freeman.

1.—An impervious bulkhead against which to grout, which also furnishes an anchorage for the grout pipes;

2.—A grout tank pressure considerably above the rock water pressure against which grout is injected;

* Brooklyn, N. Y.

Mr. Freeman.

3.—Adapting the consistency of the grout to the size of the cavity to be filled, using thicker grout for very large seams, and very thin grout for the fine seams.

On the Catskill Aqueduct the first attempt to fill water-bearing seams ahead of the excavation was made at Shaft 4 of the Rondout Siphon. This difficult piece of work is fully described by John P. Hogan, Assoc. M. Am. Soc. C. E., in his paper entitled "Sinking a Wet Shaft".*

This shaft passes through water-bearing strata, 131 ft. thick. Nipples were swedged into drill holes, valves put on, and the drilling was continued through the pipe and valve into the softer water-bearing strata, the holes furnishing channels for grouting the rock seams. The method was quite similar to the procedure in the Astoria Tunnel. It was not found necessary to place a concrete blanket in the bottom of the shaft as a bulkhead against which to grout, though, at one time, the rock was so soft that considerable grout was wasted in clogging the surface seams. Altogether, 2 960 bags of cement were injected, and grout tank pressures up to 275 lb. per sq. in. were used, giving a net pressure over and above the ground-water of from 100 to 180 lb. per sq. in. Large seams were especially well filled, the largest one being 8 in. wide, and quantities of water, up to 400 gal. per min., were stopped at different groutings. As excavation progressed, however, there was considerable seepage from the smaller seams; this was not cut off, and, for the entire depth of the shaft, amounted to about 450 gal. per min.

At many other places along the line of the Aqueduct, the leakage from clean-cut open seams was stopped entirely. Near the east shaft of the Hudson River Siphon, an open seam discharging about 500 gal. per min. was completely dried by placing a concrete bulkhead across the heading and forcing in neat cement grout under a pressure of 700 lb. per sq. in., which was 200 lb. greater than the ground-water pressure.

It was common practice in permanent shafts, which were concrete-lined, to place this lining—at least, across water-bearing strata—during the process of shaft-sinking, putting in weep-pipes to vent the water, which pipes were grouted after the concrete had hardened. This method proved effectual in shutting off leaks of considerable size; for instance, a leak of 125 gal. per min. in Shaft 5 of the Rondout Siphon was completely shut off in this manner.

The grouting of the pressure tunnels proper involved one consideration which was not found in the case of the shafts, or in the case of any tunnel which, during use, is subject to normal air pressure. The lining in such a shaft or tunnel is in compression from the pressure

* *Transactions*, Am. Soc. C. E., Vol. LXXIII, p. 398.

of the surrounding rock, earth, or ground-water. The pressure tunnels of the Catskill System pass deep under the valleys, far below the hydraulic gradient, and will be operated under an outward pressure of from 150 to 650 lb. per sq. in.; although the ground-water pressure relieves much of this, there remain net bursting pressures up to 200 lb. per sq. in. under operation. Consequently, the total net outward pressure is great in the case of tunnels ranging from 11 to 14½ ft. in finished diameter. The concrete lining of such tunnels is not thick enough to hold under tension, and depends on the rock backing to carry the load. Seamy, water-carrying rock furnishes a ready channel to take away water which may escape through the concrete lining. Furthermore, rock which is very seamy and broken does not furnish such a good backing for the concrete lining. Thus, the grout which was injected into the surrounding rock seams, helped in two ways: in solidifying the rock and making a better backing for the concrete, and in closing some channels which would carry away any water that might leak through the concrete lining. To meet this condition, an attempt was made, by using the tunnel lining as a bulkhead, to grout farther back into the seams, and to fill smaller seams than had been done during the process of excavation. Mr. Freeman.

The first trial was made at Shaft 4, north, of the Rondout Siphon, where the tunnel passes through the water-bearing High Falls shale and Binnewater sandstone, both of which are broken, porous rocks, particularly so at this point, as they are twisted and crushed in a fault zone. The length of tunnel in this rock is about 250 ft. During excavation an effort was made to grout off the leakage in the heading, and a little was stopped, but the attempt was not wholly successful. No concrete bulkhead was built against which to grout, and the rock was so weak that the face could not be solidified sufficiently to form a backing for grouting pressures. Finally, a test-hole was driven with a diamond drill 250 ft. ahead through the water-bearing strata. Gradually, the leakage decreased, indicating a lowering of the ground-water level, more pumps were put in, and excavation was completed without additional grouting. The maximum leakage in this section was 2 000 gal. per min. A complete account of this work has been given by B. H. Wait, Assoc. M. Am. Soc. C. E.*

The thickness of the concrete lining through this wet section was 24 in., twice the ordinary minimum thickness. As a drip-pan to protect the soft concrete from the incoming water, and as a form of reinforcement for the tunnel lining, a steel shell was erected for a length of 174 ft. This consisted of 6-in. I-beam ribs bent nearly to a circle, but open at one side, the open ends fitting to the concrete invert which was placed first. For a covering, $\frac{3}{16}$-in. plates were

* *Engineering Record,* Vol. LXIII, p. 660, June 17th, 1911.

Mr. Freeman. bolted to the ribs, and no attempt was made to secure water-tight joints. The concrete invert contained a longitudinal drain with Y-branches to each side, which picked up the leakage. The tunnel at this point was on a 15% incline, and drained itself readily.

The space between the steel shell and the rock was very carefully dry-packed, and afterward the concrete lining was placed inside this shell. Two sets of grout pipes were used, one leading through the concrete to this dry-packed section, the other set being carried from 1 to 3 ft. into the rock seams.

The dry packing outside the concrete was grouted first, while the pipes to the seams remained open to discharge the rock leakage, except those which were closed temporarily on account of leaking grout, when some of the thick grout worked back into the larger seams. Before grouting the dry packing, the inward leakage was 900 gal. per min., but after this grouting was completed, the deep-seated pipes discharged only 540 gal. per min., as the thick grout had worked back into some of the larger seams and cut down the leakage.

A start was made to grout the rock seams proper by injecting an ordinary mixture (95 lb. of cement to 5½ gal. of water) of neat grout into a deep-seated pipe leaking about 4 gal. per min. and 3 bags of cement plugged the seam. Then, at the suggestion of T. H. Wiggin, M. Am. Soc. C. E., Designing Engineer of the Pressure Tunnels, this pipe was re-opened, cleaned out, and a very thin mixture used (23¾ lb. of cement to 28 gal. of water). Of the latter mixture, 24 bags were injected into this same hole which had refused at 3 bags of the thicker mixture. The use of the very thin grout was continued with grouting pressures up to 300 lb. per sq. in. The tunnel-service pressure was 100 lb. per sq. in., higher pressures being furnished by a Westinghouse (booster) compressor. Two compressors were piped with two grout tanks, so that either compressor could be used with either tank. With one tank charging and the other discharging, the stream of grout was kept practically continuous. The rock-water pressure grouted against was 20 lb. per sq. in. If a pipe took grout easily at a pressure of 100 lb., the mixture was thickened a little (47½ lb. of cement to 28 gal. of water), and, if this continued for some time, the thickening was increased to 1 bag per 28 gal. of water. When the injection pressure began to rise, the mixture was thinned again. Pipes were considered full which refused the thinnest grout under a pressure of 300 lb. It was noticeable that the grout traveled some distance (from 30 to 40 ft.) in the seamy rock, showing up at other pipes, and cutting down the leakage at those pipes and filling the seams back of them. Not more than one in ten of the pipes leading to the rock seams took any considerable quantity of grout, though every pipe was tried. After all grouting was completed in this section, the inward leakage was

Mr. Freeman.

less than 1 gal. per min., due, perhaps, to a good concrete lining and not wholly to grouting. In a length of 174 ft. of tunnel, 940 bags of cement were injected into the rock seams, the finished diameter of the tunnel at this place being 14½ ft.

After the ground-water level was restored, four test holes were drilled about 3 ft. out into the grouted rock, where heavy leakages had occurred at the time of excavation. Two of these holes were practically dry, the third discharged ½ gal. per min., but the fourth struck a water-bearing seam and discharged 71 gal. per min. The latter hole was in the bottom of the tunnel, the others were at the horizontal diameter and the top. It is conceivable that the bottom might show the poorest results, as the ultimate direction of grout flow is upward. A gauge reading showed the rock water pressure to be 117 lb. per sq. in.

Another section of the same siphon, through blocky, seamy Helderberg limestone, took 946 bags of thin grout in a length of 50 ft. Two test holes, 3 ft. into the rock, showed no leakage.

Though absolute assurance cannot be given that all the seams were filled, the volume of cement injected indicates that many of them were closed by this method, which thicker grout would have clogged at the openings and left unfilled.

A difficulty arose in grouting a combination of large and small seams, as the large seams furnished an easy egress for thin grout, and the small seams clogged at the entrance with the thicker mixture. By increasing the cement per batch, if the pressure of injection remained low, and decreasing it again as the pressure rose, an attempt was made to adjust the consistency of the batch to the size of the seam.

Mr. Bradley.

W. H. Bradley, Esq.*—At a time when the outlook on the tunnel work was very dark, a prominent official of the Company said to the speaker "I was informed by an engineer that the tunnel is a failure—that it will never be completed". The speaker replied "You have never heard me say that, when you do you may take it to be a fact; at present it is not a fact".

To carry Mr. Davies' description of the pipe testing a little farther: About 2 weeks ago, one of the main pipes in the tunnel was tested, first by filling it with water which was allowed to rise about 40 ft. in the stand-pipes, giving a pressure of about 20 lb.; the joints were then inspected thoroughly for possible leaks, after which the water was run out and an air pressure of 40 lb. per sq. in. was applied, each joint being inspected by applying soap and water. After this inspection, water was again put in, the stand-pipes being filled to the top of the shaft, which created a pressure of about 125 lb. per sq. in. in

* Chief Engineer, Consolidated Gas Company, New York City.

Mr. Bradley. the pipe. This may seem to have been unnecessary—after the previous tests—but it was a precautionary measure intended to expel all air from the pipe, because air and gas form an explosive mixture and there is likely to be serious trouble if a light reaches it. When the pipe was filled with water, the gas valves at both ends were opened, and, as the water was drawn out, the main was filled with gas with no mixture of air. This main is now in daily use.

The same procedure is being followed with the second main.

The head-houses are now being erected over the tunnel shafts, the elevators, pumping plant, telephone and lighting circuits are being installed, and the work will soon be completed.

Mr. Sanborn. JAMES F. SANBORN,* ASSOC. M. AM. SOC. C. E.—It would be interesting to have a description of the difficulties in putting in the vertical pipes in the shaft. Were any curving rings or shims required? The speaker asks for this information because, in the work of the New York Board of Water Supply, there was trouble in erecting the risers of the City tunnel shafts, which were steel pipes, and it was found expedient to use a hub and spigot arrangement.

Mr. Wegmann. EDWARD WEGMANN,* M. AM. SOC. C. E.—This paper is a very valuable contribution to the engineering literature of tunneling, and, doubtless, will be consulted by other engineers who encounter difficulties similar to those met in the Astoria Tunnel. The paper is very complete, as it describes in detail, not only the construction of the tunnel, but, also, the plant and methods used.

The speaker is particularly interested in the paper because he was one of the engineers on the tunnel, constructed in 1885 to 1891 under the Harlem River as part of the New Croton Aqueduct, in driving which decomposed rock, similar to that described by the author, had been encountered. The tunnel was about 1 300 ft. long and required a circular excavation, 14 ft. in diameter.

Before the work was begun, numerous diamond-drill borings were made to ascertain the character of the rock through which the tunnel was to be driven. Near Manhattan Island the rock was found to be gneiss, but for the greater part it was limestone having many seams. A pocket of decomposed rock was discovered in the gneiss formation, and was investigated by making borings about 50 ft. apart.

Based on the indications of the diamond-drill borings, the tunnel was planned so as to have its invert about 155 ft. below mean tide. It was thought that at this level there would be at least 30 ft. of solid rock above the tunnel, but when the heading had advanced about 300 ft. from Manhattan Island, a seam of rock, full of water, was struck by the drills. Water poured into the tunnel, and the workmen ran

* New York City.

Mr. Wegmann.

for their lives. Sand and stone soon filled the drill holes, and made it possible to close them with wooden plugs.

A diamond drill was taken into the heading, and the ground in front and below the heading was explored by borings. In order to insure safety while this work was going on, a strong timber bulkhead, with a suitable gate, was built in the heading, just back of the diamond drill.

The test borings showed that the seam of decomposed rock extended about 75 ft. below the tunnel, instead of terminating 30 ft. above it, as had been believed by the engineer. In front of the heading, the seam was found to be 28 ft. wide, and beyond it there was limestone containing seams in which the water was under the full pressure due to the river, *i. e.,* under a head of more than 150 ft.

The important question arose as to how the tunnel was to be constructed through the seam of decomposed rock and through the limestone. Negotiations were held with the company controlling the patents for the freezing process, which had been used very successfully for sinking shafts through quicksand. This company was very willing to undertake the work on a percentage basis, but would not give any guaranties with regard to success.

The engineers in charge of the work were anxious to try to drive a pilot tunnel through the soft ground, but the contractor who was to do this work was very loath to undertake it, as it necessitated buying large pumps. Apparently, he had more influence with the Aqueduct Commissioners, under whose direction the New Croton Aqueduct was built, than the engineers of the Commission. By an order of this Commission, the engineers were directed to abandon the 300 ft. of tunnel that had been excavated to the soft seam, and to start another heading about 307 ft. below mean tide. At this level no difficulties were encountered.

The only additional cost of constructing the tunnel at the new level was in the lowering and hoisting of materials, but this was more than offset by the fact that the tunnel was very dry at the lower level. In spite of these circumstances, the contractor, assisted by able counsel, sued the City of New York for seventy items, aggregating about \$350 000, for the additional cost of constructing the tunnel at the lower level, and for some other extras. The original contract price for the work was only about \$500 000.

The lawsuit against the City was begun in 1890, but the contractor's lawyers waited 16 years, before they brought the case to trial. They thought, probably, that their chances of success would be better when the engineers and inspectors, who had been connected with the work, had gone West or died. The City won the suit twice, but the Court of Appeals sent it back a third time for re-trial. The case was about finished before a referee, when this gentleman, un-

Mr. Wegmann. fortunately, died. Twenty-four years after the suit was begun, it was settled out of Court by the City paying the contractor $25 000 on claims amounting to $350 000. It would be interesting to know what part of the $25 000 was received by the contractor's lawyers and how much by the contractor himself. The speaker mentions this lawsuit to show some of the difficulties, other than soft seams, which engineers encounter in tunneling.

Mr. Kellogg. R. C. KELLOGG,* ASSOC. M. AM. SOC. C. E.—The Astoria Tunnel is one of the principal connecting links in a vast scheme of gas distribution which comprehends sending out from the Astoria works, at some future time, approximately 200 000 000 cu. ft. of gas every 24 hours, part of which may eventually be pumped as far as Albany. This will not only rid Manhattan Island of unsightly gas manufacturing structures, but will also benefit the towns through which the supply may travel. The Astoria gas plant itself, when completed according to the plans conceived, will contain ten units, each capable of manufacturing 20 000 000 cu. ft. of gas every 24 hours, and ten storage holders each having a capacity of 15 000 000 cu. ft.

Mr. Brush. W. W. BRUSH,† M. AM. SOC. C. E.—It may be of interest to mention the fact that the engineers of the New York Board of Water Supply studied a line for a water supply tunnel which would follow somewhat closely that of the gas tunnel the construction of which has been described so clearly and interestingly by Mr. Davies. The future water supply of New York City will necessitate the delivery of large quantities into Queens Borough, which contains the maximum area available for development within the city, and where eventually an enormous manufacturing center will probably be found, with a large consumption of water.

The studies made several years ago to locate the tunnel to deliver the Catskill supply to the five boroughs indicated that a rock tunnel could probably be driven successfully into Astoria and carried through the rock into the Borough of Brooklyn, but that the cost would be decidedly greater than a tunnel along the adopted line under the Bronx and Manhattan to Brooklyn. One of the uncertain elements of cost was the driving of the tunnel under the East River, probably passing under Randall's and Ward's Islands. The question of determining the character of the rock at the contacts between the various formations was deemed to be a difficult problem.

Ultimately, however, in all probability, a tunnel will be driven under the East River, near the Gas Company's tunnel, for the purpose of delivering an additional water supply to the Borough of Queens and in part to the Borough of Brooklyn. The experience of the Gas

* Brooklyn, N. Y.

† New York City.

Mr. Brush.

Company will then furnish especially interesting and valuable information for the engineers who will lay out the line and grade of the later tunnel. A water tunnel can readily be driven at any depth desired, and therefore the engineers may avoid some of the difficulties mentioned by Mr. Davies.

The riser pipes in the shafts of the Astoria-Bronx tunnel are embedded in concrete, and are therefore self-supporting.

Mr. Wiggin.

THOMAS H. WIGGIN,* M. AM. SOC. C. E.—In the Catskill Aqueduct pressure tunnel siphon the rock conditions were similar to those described by the author. The first case was in the sinking of Shaft 4 of the Rondout inverted siphon which crosses the valley of Rondout Creek near High Falls, west of Kingston, N. Y. This was described in a paper† by J. P. Hogan, Jun. Am. Soc. C. E., and a discussion by the speaker adds other data, notably some from a very interesting shaft of the Detroit Salt Company. In Shaft 4 of the Rondout Siphon heavily water-bearing rock was encountered, as had been predicted from the preliminary borings and pumping tests in certain of these borings. At a depth of about 225 ft. the inward flow was more than 800 gal. per min. At first ordinary drill holes, and finally diamond-drill borings, made around the periphery of the shaft from the level to which sinking had progressed, were grouted, after which excavation was resumed with continued precautions as to drilling, carrying a pilot hole ahead and grouting through water-bearing drill holes. The leakage was very much reduced by the grouting, and would doubtless otherwise have reached very large quantities. In grouting this shaft, 971 bbl. of cement were used. Some of the seams were wide, 8 in. being the maximum.

The grout when encountered in the seams during subsequent excavation was like moderately soft limestone, and showed very fair strength.

Later, in the tunnel driven from this shaft, the same wet rock strata were encountered, again in the position expected from the borings, and similar grouting was done in advance of excavation, though not so successfully. The maximum leakage into the tunnel in this stretch was about 2 000 gal. per min. This did not interfere so much with operations as it might have under other conditions, because the tunnel was driven up on a 15% grade. The water made a very pretty cascade. A heavy concrete bulkhead, with a door, had been built between this stretch of tunnel and the shaft, in order to avoid loss of the tunnel in case of meeting a sudden inflow.

Much of the rock in this piece of tunnel was divided into very small blocks by water-bearing seams, and the impression was gained,

* New York City.

† *Transactions*, Vol. LXXIII, 1911, p. 398.

Mr. Wiggin. from such grouting as was done, that general impregnation by grout would be impossible with any practicable number of holes. Hence, the leakage was taken care of by a system of bottom drains and a shield of steel angle ribs and plates laid shingle-wise, which kept the water off the concrete while it was being placed. The space behind the steel was at first "dry-packed" with rock fragments, and was grouted after the concrete lining had been placed within the shield. The drains were also grouted. This method resulted in making this very wet portion of the siphon almost bone dry when completed.

In the Hudson Tunnel, where grouting pressures of about 1 000 lb. per sq. in. were used, the rock is generally solid and hard. It is what most people, from casual examination, would call a granite; geologists call it granodiorite. In general, the rock was rather tight, but within 2 or 3 ft. of a drill hole that was almost dry, another hole struck a flow of about 200 gal. per min. which temporarily overcame the pumping facilities causing the heading, which was then about 275 ft. long, to fill.

After the tunnel was pumped out, the leakage was collected in pipes, and a concrete bulkhead was placed at the end of the heading and anchored to the rock by steel rods. Four or five additional drill holes were made into the water-bearing region, which was identified by feelers as a narrow seam across the tunnel. The combined flow of all holes previous to grouting was found to be about 550 gal. per min., but was under control by gated pipes. A ground-water pressure of 400 lb. per sq. in. was recorded when the pipes were closed. The seam was finally grouted through the drill holes under a pressure of 1 000 lb. per sq. in. The tunnel at that point is more than 1 100 ft. below sea-level, and this high grouting pressure was required to overcome the ground-water head and the friction of the grout.

The equipment generally used on the Catskill works for grouting is a tank with top door and various pipes arranged so that the grout may be mixed by the release of air through the bottom pipe and ejected by forcing air into the top of the tank. This is the so-called Canniff grouting machine. In the Hudson Tunnel, air at a pressure of 1 000 lb. was not available for forcing out the grout. At first the attempt was made to pump the grout by plunger pump, but the pump valves soon wore out. The pump was then repaired and used to force water instead of air into the grouting machine on top of the grout, thus causing gradual dilution as well as displacement of the grout, but doing perfect grouting nevertheless.

A heavy concrete bulkhead, with a thick hinged cast-steel door, had been placed across the tunnel to prevent another flooding, and a liberal pumping equipment was put in. The tunnel was then driven through the wet ground, and a narrow seam which had been grouted could be seen across the roof and sides of the tunnel, with only a few drops of water coming from it here and there. Mr. Wiggin.

This Hudson Tunnel, which is about 3 020 ft. long, had been explored by about a dozen vertical holes and by two pairs of inclined borings, the longest of which was about 2 052 ft. The holes of each pair of inclined borings passed each other near the middle of the river and solid core was taken from all the holes, so that it was known that the tunnel would be in good granite nowhere less than 150 ft. thick above the tunnel. Although considerable water in the aggregate was encountered in these holes, as is usual in granite, so large a flow concentrated at one seam was surprising, particularly as at that point the rock was not less than 700 ft. thick above the tunnel. This experience serves to emphasize the fact that in many kinds of rock very wet seams may be found, surprisingly close to very dry ground and under a thick roof of apparently sound rock.

The speaker has been very much interested in Mr. Davies' paper, and particularly in the success of the method of grouting a large number of holes, and grouting back into the body of the rock. This process has been demonstrated very beautifully by this tunnel, and also by the Catskill work, and is doubtless bound to be used more and more in difficult ground. At the same time, the speaker thinks that engineers who have had experience with wet ground will be inclined more and more to keep away from it, even at a considerable expense for exploration and the deepening of the tunnel.

On the Catskill work it was found that depth was no particular drawback. When the engineers started planning pressure tunnels, 200 ft. was thought to be pretty deep for such purposes. Some of these early studies look rather absurd in the light of the finished work. The idea of liberal depth gradually gained force; and if some of the work were to be done over again, even greater depths would probably be used in places.

WILLIAM CULLEN MORRIS,* M. AM. SOC. C. E. (by letter).—In relation to this paper, some information relative to the accident and casualty features of the work may be of interest. At the start of operations the Company decided, in view of the high rates prevailing for work of this class, to undertake the insurance, instead of placing it with a casualty company. A very liberal policy was adopted by the Company in the treatment of the men, allowing them full time during incapacity owing to any cause (either illness or accident) and furnishing medical attendance and supplies during the period of disability. Field hospitals were maintained at each end of the tunnel, with orderlies in constant attendance. Arrangements were made with neighboring hospitals for prompt ambulance service in case of emergency, and every Mr. Morris.

* New York City.

Mr. Morris. precaution was taken so that injuries could be treated to the best advantage. A physician was employed to supervise each of the hospitals, and the orderlies reported directly to these physicians all cases of first aid or disability treatment.

A force was organized for continuous inspection of the work, with a view of eradicating all preventable causes of accidents, the inspectors patrolling the work and immediately bringing to the attention of the tunnel force any features they might notice which might result in accidental injury. This feature of the work created some confusion for a time, but after several weeks of trying out, the arrangements were perfected to such an extent that there was no interference with rapid progress.

The accident treatment record and accident prevention were all under the direct supervision of the Company's Engineer, Mr. Harold Carpenter, who reported to the Company's construction office.

The record of accidents throughout the work is as follows:

Total accidents	1 525
Serious accidents	115
Total time lost	1.78%
Cases sent to outside hospitals	24
Cases treated in tunnel hospital	67
Cost of accidents in relation to pay-roll	5.36%

Mr. Davies. JOHN VIPOND DAVIES,* M. AM. SOC. C. E. (by letter).—The very interesting contributions by Messrs. Freeman, Wiggin, and Wegmann, as to the experience in the Catskill Aqueduct, illustrate the principal points of difference between that undertaking and the Astoria Tunnel. In the latter the primary feature was the consolidation of the soft and partly decomposed rock in order to permit of the construction of the tunnel, and, secondarily, the filling of the fissures, for the purpose of stopping leaks. The primary feature in the case of the Catskill Aqueduct was the absolute filling of all voids and the stoppage of leaks, and, secondarily, the consolidation of the rock.

For the stoppage of leaks and the consolidation of the rock, considerable grouting had been done in 1892 and 1893 in the construction of the East River Gas Company's tunnel at 70th Street, Manhattan, referred to in the paper. At that time the writer ordered cement, specially burned, with the elimination of any plaster admixture, so as to obtain the most rapid setting material. That tunnel was constructed at a comparatively shallow depth, and there was so little cover between it and the bed of the river that high pressure could not be used. The same condition occurred in the construction of the Hudson and Manhattan Tunnels, where large quantities of cement grout were also

* New York City.

Mr. Davies.

used for the purposes just referred to, and, in that case, also, the comparatively shallow depth of these tunnels precluded any high-pressure grouting. In this latter case it was found that grout would follow the line of least resistance and pass out with little interruption into sewers, drains, or watercourses, without generally spreading into the soil, to give the results which were attained with the high pressures and greater resistances encountered in the Catskill Aqueduct and the Astoria Tunnel.

Mr. Sanborn inquires as to the erection of the vertical risers. These pipes were of cast iron, $2\frac{3}{4}$ in. thick, with hub and spigot joints. It was specified that they were to be machine-faced on the bearing surfaces in hubs and ends of spigots, so that there should be a true fit at every joint. Unfortunately, the facing of the two ends was not executed from common centers, the result being that these pipes—which as designed should have given perfect vertical alignment—were, when erected, found to be in error, with a regular creep from the vertical, due to imperfections in foundry work, and this necessitated the use of wrought-iron shims to bring them into correct vertical alignment.

Mr. Lavis refers to the relations of mining engineers to the various tunnel operations now being carried on in New York City. It occurs to the writer that there is a general misunderstanding as to the use of the term "mining engineer" in this respect. In common with other engineers engaged on subway construction in New York City, the writer has been, to a considerable extent, brought up with coal mining and other underground operations. The timbering and methods of construction used by coal and metalliferous miners are as far removed from the methods of the engineer engaged in subway work as it is possible to conceive. The class of mining involved in subway and tunnel construction is distinctly a development of business, entirely apart from the ordinary practice of those engineers engaged in such purely mining operations. The men employed in England are known as "miners", but this class consists of those essentially engaged on engineering work in heavy soft ground tunneling, not in mining operations. A large majority of those engaged in this business in New York have learned their trade in Europe, or from those who have brought the art from Europe, and there should be no conflict in the distinction between so-called mining engineering and engineering connected with tunnel work. The so-called mining engineer knows little of the type of timbering used in these tunnels.

Mr. Morris calls attention to the provisions for attending to accidents and casualties. The writer desires to state that in the treatment of employees injured or incapacitated on this work, the Astoria Light, Heat and Power Company provided more liberally than any

Mr. Davies. employer with whom he has had any previous experience. As there were no hospitals in the vicinity of the shafts, the officers of this company decided to build them especially for this work; they equipped them completely, not only for rendering first aid, but also for the actual treatment of cases under competent medical supervision. The adjustments with employees were most liberal, and it is of interest to note that, notwithstanding this great care and the liberality in all cases, the entire cost of the accident account amounted to only 5.36% of the pay-rolls.