Portland cement wash was first used on the Portland concrete arch, but it was afterwards found that thin plastering gave better results. The plastering was put on to increase the water-tightness and to make a smoother surface. As a rule, the authors do not consider it necessary or advisable to plaster the arch.

Conduit Forms. The construction of forms* so that they may be readily "struck" and removed requires considerable ingenuity and design. Invert centers for a small sewer, designed by Mr. William G. Taylor and employed in the Medford, Massachusetts, sewers, are illustrated in Fig. 224.

FIG. 224. — Center for Invert of 30-inch Sewer at Medford, Mass. (*See p.* 688.)

Conduits in Tunnel. The methods of construction, except as regards the handling of the concrete, are substantially the same in tunnel as in open-cut. It is generally necessary, however, to provide loose longitudinal lagging for the arch, and place it stick by stick as the concrete is laid. The extreme crown or key for a width, say, of 2 feet, is most easily laid

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*Various styles are referred to under "Forms" in References, Chapter XXXI.

upon cross strips or short segments in the same way that a brick arch in tunnel is keyed. The concrete for the key must be mixed fairly dry, and rammed lengthwise of the tunnel.

The tunnel section of the conduit of the Jersey City Water Supply Company is similar in inside dimensions to the open-cut section. (Fig. 222, p. 684.) It is plain concrete with no reinforcement. The thickness of the arch and sides is 8 inches and of the invert 6 inches, but points of rock are allowed to jut into this section "provided a minimum thickness of 6 inches is maintained in the arch, and of 3 inches in the sides and bottom."

TUNNELS

The general principles of design and methods of construction for large railway tunnels are similar to those for sewer and water conduits. The external strains are of course greater and must be provided for according to local conditions. In some cases water-tightness is essential; in others, which compose the large majority, the drift is through dry material, and the ballast may be laid directly upon the bottom.

Tunnel Design. The standard section of a double-track tunnel of the Pittsburgh, Carnegie & Western R. R.* has an arch 26 inches thick and side wall laid on a batter, inside, of one inch to the foot, and of such thickness as to reduce to 26 inches at the springing line.

The standard section of single arch† in the New York Subway for a tunnel 25 feet wide is 18 inches at the crown. In rock drift this thickness is carried down to the springing line, from which point the inside face is battered inward. In deep open-cut construction the arch is thickened at the haunches to about 4 feet, and the outside of the wall is waterproofed.

The East Boston Tunnel, completed in 1904, is shown in section in Fig. 225. The sketch also illustrates the general construction of steel framework and lagging which, after completion, were entirely removed. The invert between A and B was laid after the rest of the section was complete. The method of carrying on the work is described on page 691.

The approaches to the Harlem River Tunnel‡ of the New York Subway were excavated in open-cut, then roofed over, and the tube thus formed pumped out. The section of this tunnel under the river is lined with cast-iron segments.

The single-track tubes of the Pennsylvania R. R. tunnels§ under the

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**Engineering News*, May 21, 1903, p. 447.

†Contract Drawing No. C 9.

‡George S. Rice in Journal Association of Engineering Societies, Dec., 1902, p. 224.

§*Engineering News*, Oct. 8, 1903, p. 327.

channel of the Hudson River at New York City are designed with a cast iron shell made in segments bolted together and lined on the inside with concrete 2 feet thick.

Methods of Tunnel Construction. Concrete side walls and arches in tunnels constructed without the use of compressed air are laid by means of forms and centers, whose design varies with the character of the excavation and the general arrangement of the structural machinery.* To provide clearance so that the arch center may be lowered and moved ahead, the side walls may be carried up above the springing line. For supporting the center, a temporary frame consisting of a timber resting on posts is set up close to each side wall, and the center is jacked up to line and supported by wedges. By placing the side timbers in advance, the arch may be hauled ahead on rollers by hand tackle or hoisting engine.

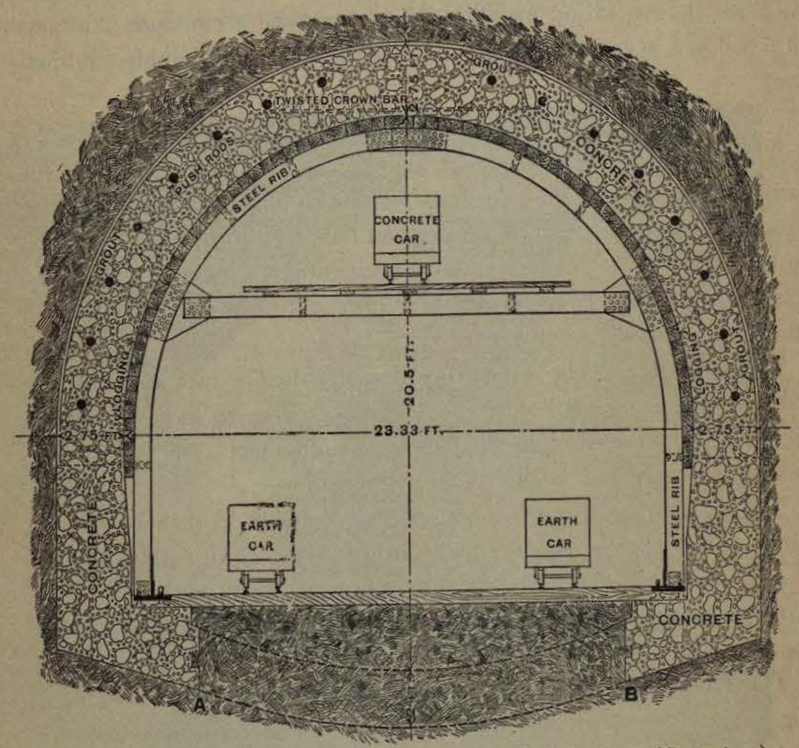

FIG. 225.—Section of East Boston Tunnel during Construction. (*See p.*691.)

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*In the serial on The New York Rapid Transit Railway, *Engineering News*, Sept. 18 and Oct. 8, 1902, are excellent descriptions with sketches and illustrations of the methods of construction on one of the sections of the New York Subway and in the Harlem Tunnel. See References for further examples.

The East Boston Tunnel, shown in Fig. 225, is an interesting illustration of a tunnel entirely of concrete built with the aid of compressed air.* Two side drifts, solidly timbered, were kept from 60 to 150 feet in advance of the shield, so that the concrete side walls, which were built in these to a height of about 16 inches below the springing line of the arch, had an opportunity to set for about ten days before the shield reached them. The shield, resting on rollers, moved along on these side walls, and the main excavation was made under it. The concrete arch was built under the tail end of the shield, in lengths of 30 inches, as soon as the earth was removed. The shield was forced ahead by 16 hydraulic jacks, acting against the cast-iron cruciform push rods, 3 inches in diameter, shown in the drawing, which were placed in the concrete in 30-inch lengths, so as to form continuous rods the entire length of the tunnel. The supports for the centering consisted of steel ribs,† also shown in the figure, placed 2½ feet apart, and supporting 4-inch lagging, against which the concrete was laid. Portland cement grout, usually 1 cement to 2 fine sand, was forced in on top of the arch so as to form a film about 1½ inches thick. The invert was laid as the shield progressed. The progress of excavation and lining in May, 1901, was about 6 feet in twenty-four hours, about 60 men being then employed on each of the two shifts.

The specifications for the East Boston Tunnel‡ limited the sizes of the gravel to 2 inches, and stated that 5% only should be less than ¼ inch. The proportions required that "to each 123 pounds of dry Portland cement there shall be 2½ cubic feet of sand and 4 cubic feet of gravel, and such a proportion of water as the engineer shall from time to time determine. The sand and gravel shall not be packed more closely for the above measurements than is done by shoveling in a dry state into a measuring box." Compensation was awarded the contractor when these proportions were varied. Crushed stone screenings were largely used instead of sand.

Closing Leaks. In the East Boston Tunnel a layer of neat cement mortar was spread upon a surface of old concrete before laying a new section, but even this did not prevent slight percolation of water at these joints after the removal of the air pressure. Although the leakage through these was almost inappreciable, they gave the walls a somewhat unsightly appearance, and to stop them holes 6 inches or less in depth were drilled in the concrete, and ⅜-inch pipes inserted, through which neat cement grout was forced by a power pump. The leakage in September, 1904, in 1.4

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*Howard A. Carson in Journal Association of Engineering Societies, Dec., 1902, p. 205.

†Ribs were of wood on one of the sections.

‡Construction Contract, Boston Transit Commission, Section B, East Boston Tunnel, 1900.

miles of tunnel,—over one-half mile being directly under the harbor,—was not more than 7 to 8 gallons per minute.

SUBWAYS

Subways are technically distinguished from tunnels as constructions in open-cut instead of drift, although portions of a subway are often really of tunnel construction. The term *subway* is applied to accessible conduits for water mains, electric cables, etc., as well as to underground passages for traffic, but it will be considered here in the latter sense only.

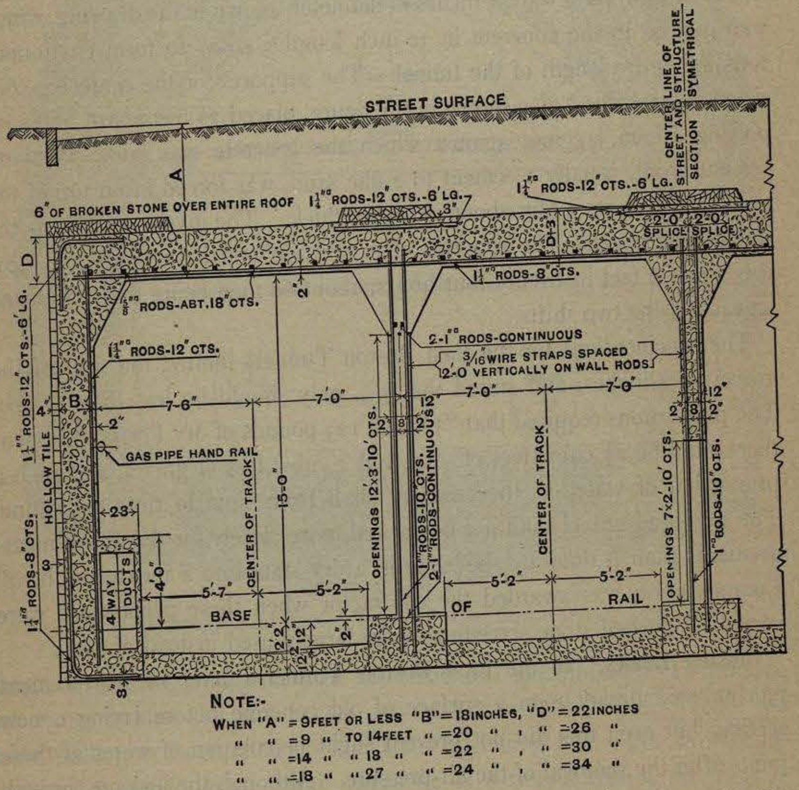

Fig. 226.—Typical Section of Reinforced Concrete Construction in New York Subway. (*See p.* 692.)

Subway Design. To save the headroom required by a circular arch, the roof of the subway is usually made flat. The older portion of the New York subway is built with a framework of steel I-beams, the bents being spaced about 5 feet apart and the roof formed by arches of concrete[*] sprung between the lower flanges of the cross girders, which are also completely imbedded in concrete. The walls are of concrete, 15 inches thick, forming arches between and imbedding the posts.

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[*] Concrete has superseded brick for such arches.

The typical design of the Philadelphia subway is reinforced concrete throughout, except that steel columns incased in concrete are used for the supports between the tracks. The walls are longitudinally reinforced to prevent shrinkage or temperature cracks with about $\frac{3}{10}$ of 1% of steel,[*] and this was found sufficient to prevent all except very small cracks, so that the structure is practically dry even although the backfilling may retain considerable moisture above the level of the underdrains.

The more recent portions of the New York subway also are entirely of reinforced concrete, the typical design[†] in 1909 being shown in Fig. 226, page 692.

During the course of construction in New York it was decided to widen one of the portions already complete. The contractors moved the concrete side walls and roof, 275 feet long, bodily, without injury[‡].

DESIGN OF CONDUITS

The external pressure on structures buried in the ground is very indefinite, depending not only upon the character of the fill, but also upon the method of excavating and filling the trenches and tamping the filling.[¶]

For small depths up to 3 feet the sum of the weight of the earth and the live load may be taken as acting on the structure. For larger depths, however, the sum of these two forces would be excessive, and may be decreased. According to Mr. Frühling[§] the effect of the live load decreases as a parabola until it is zero at 16½ feet, and may be represented by formula (1) using notation below.[‖]

$$q_1 = w\,(h - 00.6h^2 + 0.0012h^3) \quad (1) \quad \text{and} \quad q_2 = \mathcal{Q}\,\frac{(16.5 - h)^2}{269} \quad (2)$$

The weight of the earth increases only to a depth of about 16½ feet according to formula (2) and is constant for larger depths.

The sum of the force q_1 and q_2 thus found gives the working load per square foot. Allowance should be made for impact when necessary.

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[*] Personal correspondence with Mr. Charles M. Mills, Principal Assistant Engineer.

[†] Presented by courtesy of Mr. Henry B. Seaman, Chief Engineer.

[‡] See descriptions and illustrations in *Engineering News*, June 11, 1903, p. 515.

[¶] For an excellent treatment of this subject with formulas for moments, see "Tests of Cast-Iron and Reinforced Concrete Culvert Pipe," by Arthur N. Talbot, University of Illinois, Bulletin No. 22, 1908.

[§] Handbuch für Eisenbetonbau, Band III, p. 510.

[‖] Notation. q_1 = pressure per sq. ft. due to dead load; $q_2 = t$ pressure per sq. ft. due to live load; w = weight of earth per cu. ft.; $\mathcal{Q}$ = unit live load; h = depth in ft.

Conduits with Arch Top Only. The computation of the arch is similar to that for an arch bridge, and is given in Chapter XXII. The loads are carried to the sides of the arch conduit, which act as abutments. Experience indicates that it is not safe to count to a large extent upon the filling at the sides of the conduit to prevent them from cracking.

Longitudinal bars should be introduced to assist in providing for unequal settlement as well as to resist temperature stresses.

Circular Pipes. Under vertical forces the maximum positive moment acts at the top and bottom of the pipe and produces tension on the inside surface, and the maximum negative moment acts on the sides, causing tension on the outside surface*. Double reinforcement however is usually introduced.

Rectangular Conduits. Square and rectangular conduits† are designed as rigid frames loaded by weight of earth and live load acting on upper horizontal slab, reaction acting on lower horizontal slab, and earth pressure acting on sides of conduits. The stresses may be computed as in ordinary slabs (see page 421) after determining the moment by formulas given below.

Let

M_1 = negative moment at the four corners and at the center of vertical slabs, caused by vertical loads.

M_2 = positive moment in the center of the lower or upper slab, caused by vertical loads.

I_l, I_h = moment of inertia of horizontal and of vertical slabs, respectively.

l, h = span of horizontal and of vertical slabs, respectively.

w = uniformly distributed load.

Then

$$M_1 = \frac{wl^3}{12}\,\frac{lI_h}{lI_h + hI_l} \qquad (3) \qquad \text{and} \quad M_2 = \frac{wl^2}{8} - M_1 \qquad (4)$$

The formulas apply to vertical loads as indicated above.

For earth pressure, assuming it as uniformly distributed, these same formulas may be used, but the earth pressure, which acts at right angles to the vertical load, causes positive moment, M_2, in center of vertical slabs and negative moment, M_1 at corners and also at center of horizontal slabs. For the earth pressure moments l and h must be transposed. The moments, M_1 and M_2, due to earth pressure must be computed separately and then may be combined with M_2 and M_1, respectively, due to vertical loads. The moments to be combined are of opposite signs and their sum may not represent the most unfavorable condition, which, of course, must be selected.

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* See footnote † page 693.

†A table of dimensions and reinforcement for square and for rectangular conduits under different conditions is given by Sanford E. Thompson in "Concrete in Railroad Construction," published by the Atlas Portland Cement Co.

CHAPTER XXVIII

RESERVOIRS AND TANKS

A new field has been developed for concrete design in the building of covered reservoirs and filtration plants for water purification works. Plain or reinforced concrete is now commonly employed for the floors, columns, vaulted roofs, tanks, and filter basins. The Filtration Works at Little Falls, N. J.,* furnish a modern example of such construction. For open reservoirs, concrete is frequently substituted for stone masonry both in the retaining walls and core walls, and also is used for lining the bottom. Concrete tanks are used not only for water but for chemicals.

OPEN RESERVOIRS

The principles of design and construction of retaining walls have already been discussed in Chapter XXVI. The contraction cracks, which are almost certain to occur in long walls of any class of masonry, may be provided for by some form of expansion joint. Cut-off walls of clay† may be placed to prevent the passage of water through these vertical joints, or open wells‡ may be left at intervals in the walls, and after setting for a month or more filled with concrete. This concrete filling is placed preferably upon a cold day, when the contraction in the wall is greatest.

The lining for the bottom depends upon the character of the underlying soil or rock. Usually a layer of 1 : 2½ : 5 concrete 4 to 8 inches thick, if properly laid and troweled, will provide a lining sufficiently impervious for practical purposes.§

In small reservoirs, where earth and rock meet so as to present danger of unequal settlement and consequent serious leakage, a strip of reinforcing metal may be placed over the line of division.

COVERED RESERVOIRS

A common type of design for covered reservoirs consists of a concrete bottom, underlaid, where necessary, with 12 to 16 inches of clay puddle

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*Transactions American Society of Civil Engineers, Vol. L, p. 394.

†See paper by Chas. W. Paine in Journal Association of Engineering Societies, October, 1902, p. 151.

‡Transactions American Society of Civil Engineers, Vol. L, p. 406.

§For other methods of lining see Chapter XIX on water-tightness.