A dam in the form of a buttressed wall with a vertical up-stream surface has been suggested by Mr. George L. Dillman,* the dam in plan consisting of parabolic arches.

The design for a dam at Ogden, Utah,† consists of a number of piers, triangular in vertical section, forming buttresses to support an up-stream sloping face composed of circular concrete arches from 6 to 8 feet thick. The arches are designed to be covered on their upper surface with ¼-inch steel facing. The top of the dam, which is also formed by arches between the piers, carries a roadway.

CORE WALLS

Concrete is largely superseding rubble masonry for core walls in earth dams and dikes. The forms can be roughly made without reference to the appearance of the faces, while a thin wall of concrete may be built water-tight more easily than one of rubble masonry. Unless reinforced, core walls are generally of the same thickness as those of rubble masonry. The Natural cement concrete core wall of the Sudbury Dam, built by the Boston Water Commissioner and his successor upon the work, the Metropolitan Water Board of Massachusetts, is 2 feet thick at the top, with a batter of one in fifteen on both faces, until it reaches a maximum width of 10 feet. At Spot Pond Reservoir, several dikes with core walls of Portland cement concrete, of 15 to 18 feet average height, are 2½ feet in thickness throughout.

The dike for the Jersey City Water Supply Company at Boonton, N. J., is designed for a total height of 54 feet. The lower 30 feet is 4 feet 8 inches thick, and at this height it begins to batter, so as to reach a width of 3 feet at the top.

Although core walls may often be economically built of rubble concrete, the stones must be of smaller size, and cannot occupy so large a volume of the mass as in gravity dams, since the sections are thinner. In the construction of the Boonton Dike, mentioned above, one contractor was placing rubble to the extent of 20% of the total mass, while another was placing 33%. In the former case the stones were loaded on to derrick skips and unloaded by hand; in the latter case, they were hooked by the derrick. This 33% probably represents a maximum for a wall 5 feet thick or less.

Since a thin wall of reinforced concrete may be made equally strong, and more elastic than a thick wall of plain concrete, reinforcement may eventually be employed to reduce the section, and therefore the quantity of material.

*Transactions American Society of Civil Engineers, Vol. XLIX, p. 94.

†Henry Goldmark in Transactions American Society of Civil Engineers, Vol. XXXVIII, p. 290

CHAPTER XXVII

CONDUITS AND TUNNELS

Since the principal stresses in arches are compressive, concrete is peculiarly suitable for all classes of arched structures. Eccentric loading may be provided for by increasing the thickness of the concrete at the points of greatest stress, by steel reinforcement, or by both. The steel may also prevent failure of thin sections of the arch from excessive stresses due to suddenly applied loads or to settlement of the foundation.

Concrete is supplanting cut stone in arch bridges because of its relative cheapness. Although not entirely acceptable from an architectural standpoint because of the difficulty in obtaining a satisfactory surfacing, several methods of treating the face have been used with fair success. (See p. 288.) This objection may also be met by facing the arch with cut stone. Methods of arch design are treated in Chap. XXII.

Concrete arches and conduits are likely to be cheaper than brick even at the same price per cubic yard, because the greater strength of the concrete makes a thinner section possible.

Tunnels (see p. 689) and subways (see p. 692) are now built almost exclusively of concrete, or of combinations of concrete and steel.

CONDUITS

Sewer and water conduits of almost any size or shape may be built of concrete. In the larger sizes, and in conduits under pressure, steel reinforcement occasionally may be advisable from the standpoint of safety and economy.

Concrete was first used in conduits to form in bad ground a foundation for a brick invert. Later it was adopted instead of brick for the entire arch, and finally, in many instances, the brick invert lining has also been replaced by concrete.

While concrete may not be preferable to brick in all localities and under all conditions, its advantages are sufficient to always warrant a very careful investigation of its adaptability to the work in question.

As far back as 1850 sewers and aqueducts of béton or béton-coignet (see p. 1) 8 feet in diameter were constructed in France. The materials consisted of ¼ part heavy Paris cement, one part hydraulic lime, and 5 parts sand.* Some of these structures, notably the viaduct of La Vanne, are said to have cracked and flaked.† Not until the beginning of this century, however, was concrete extensively used for conduit construction, although in the extreme western part of the United States for a number of years it had been employed to a certain extent upon irrigation works for lining both canals and tunnels, a thickness of 4 or 6 inches corresponding to 8 inches or two rings of brickwork.‡

Comparison of Brick and Concrete Conduits. Even with no reinforcement Portland cement concrete is unquestionably stronger, when properly proportioned and laid, than brickwork of equal thickness. Therefore, even if the cost per cubic yard of the two materials, including centering, is practically the same, the concrete is made more economical than brick by the adoption of a thinner ring, or a ring of varying thickness proportioned to suit the actual stresses.

A comparison of data shows that concrete conduits can be built at one-fifth to one-third less cost than brick conduits of equal diameter. Williamsport,§ Pennsylvania, furnishes an example where bids were obtained for brick, plain concrete, and reinforced concrete. The contract bids on the plain concrete section averaged considerably less than the brick, and the bids on reinforced construction the lowest of the three.

Referring to the reconstruction of sewers necessitated by the New York Subway, Mr. William Barclay Parsons, Chief Engineer, makes the following statement in his report to the Board of Rapid Transit Commissioners: ‖

> During the year 1901 an experiment was made to construct sewers *in situ* in concrete. The first experiment gave such satisfactory results that the principle has been extended to other sewers in a similar manner during the year, except that instead of building the arch of brick, as was done at first, the whole sewer in many cases has been built of concrete. The advantages of this form of construction are that a perfectly smooth surface is obtained without joints, with all connections, curves, cut-waters and other details molded to perfect lines, and that construction can be carried on more rapidly.

*Leonard F. Beckwith in Transactions American Society of Civil Engineers, Vol. I, p. 108. Mr. Beckwith also gives a table of strength of béton from Michelot.

†O. Chanute in Transactions American Society of Civil Engineers, Vol. X, p. 307.

‡William Barclay Parsons in Transactions American Society of Civil Engineers, Vol. XXXI, p. 314. See also description of the lining of a water works tunnel with concrete in Massachusetts, by Desmond Fitzgerald, Transactions American Society of Civil Engineers, Vol. XXXI, p. 394. See also References, Chapter XXXI.

§*Engineering News* Supplement, Sept. 11, 1902, p. 92.

‖Report for 1902, p. 271.

It is reported that these concrete sewers have cost one-third less than brick sewers of the same size.*

Concrete, especially if reinforced, has another great advantage over brick, in that it is able to withstand internal water pressure.

Water-Tightness of Conduits. Water-tightness is to a certain extent dependent upon the proportion of cement to sand. If for a concrete conduit the sand and cement are mixed in the same proportions employed for the mortar between the joints in a brick sewer, the structures ought to be equally impervious. For example — a 1 : 2½ : 5 concrete should be as water-tight as brick laid in 1 : 2½ mortar.

If the concrete invert is laid in separate sections, these may be connected by a stepped joint similar to one of the many joints between the different courses in brickwork. A conduit to resist water pressure without leakage must be longitudinally reinforced.

The best proof, however, of the practicability of laying concrete conduits which will prevent the percolation of water, is the fact that sections 4 inches and 6 inches in thickness, which satisfactorily withstand water pressure, have been and are still being built.†

Lime thoroughly hydrated or slaked, or Puzzolan cement, may eventually prove to be the most satisfactory ingredient to mix with Portland cement concrete as a substitute for a portion of the cement, its extreme fineness assisting in filling the minute voids and thus increasing the imperviousness.

The general subject of water-tightness is discussed in Chapter XIX.

Durability of Concrete Inverts. Concrete inverts have proved in practise to be equal, if not superior, in durability to the best hard-burned brick.

The hardness and smoothness of surface obtainable with concrete reduce the friction to a minimum and render it less liable to erosion than are other materials. Concrete sewers built at Duluth, Minnesota, furnish a practical example of the ability of Portland cement mortar to resist erosion. After twenty years of wear, they show no appreciable deterioration or enlargement in diameter, while brick sewers laid at the same time required rebuilding after six or seven years. A section of the Duluth drains, about 2 000 feet long and 4 feet in diameter, was built on a 13 per cent. grade where the velocity of the water was 42 feet per second, with an invert of flat granite flags laid with 1 : 1 Portland cement joints. The flow of water during heavy storms was tremendous, carrying down with it quantities of sand and boulders, but after two years of wear the invert

**Engineering News*, March 6, 1902, p. 201.

†See Sewers and Conduits in References, Chapter XXXI.

showed ridges of mortar between the granite flags, indicating that the Portland cement mortar was more durable than the granite.

Experiments by Mr. Eliot C. Clarke indicate that Portland cement mortar in proportions 1 : 2 will withstand erosion better than either richer or leaner mortar. (See p. 125.)

Design of Concrete Conduits.* The selection of shapes and sizes of conduits suitable for different flows of water and sewage is treated in literature on hydraulics and sewerage. If the material adopted is concrete, it should be of a minimum thickness consistent with good workmanship, strength, and durability. Steel reinforcement reduces the quantity of concrete required for the larger sizes, but for a diameter of 3 feet or less there is no practical advantage in its use unless the conduit is under pressure, because the minimum thicknesses which can be advantageously placed in a sewer trench are sufficient to withstand all strains. Even in larger conduits the use of steel reinforcement is not usually advisable under ordinary conditions, because of the cost and the difficulty of properly placing the metal.

In preference to an entire concrete section, many engineers advocate an invert of one or sometimes two rings of brick laid in a concrete foundation and surmounted with an arch of either brick or concrete. Others favor a concrete invert paved with a granolithic wearing surface, — thoroughly troweled, — from one-half to one inch thick.

The design of a conduit is dependent upon the depth and character of the material through which it passes, but a few typical illustrations may afford hints for special cases. The proportions of the concrete should be carefully determined by an examination of the aggregate at hand. (See Chapter XI, page 183.) A mixture of one part packed cement, 2 parts sand, 4 parts stone or gravel, is rich enough for important work, while proportions as lean as 1 : 4 : 8 may sometimes be employed for sub-foundations or backing. In most cases the selection will lie between these two extremes. Natural cement, because cheaper than Portland, is especially adapted for foundations and filling which are not subject to stress or to wear. Puzzolan cement is also suitable in many instances.

The Weston Aqueduct of the Metropolitan Water Works, Massachusetts, built on a gradient of one in 5 000, has in loose earth a typical section shown in Fig. 221. In compact earth the excavation is narrower, and the width of base is reduced as shown by one or the other of the dotted lines, AB or CB. In embankment, the foundation is carried lower and horizontal reinforcing rods are sometimes placed at intervals just below the brick invert lining.

*Earth pressure on conduits is discussed on page 693.

In the Chicago Clearing Yards* drainage is accomplished by concrete sewers. The 36-inch and 42-inch diameter mains are 8 inches thick, the 48-inch diameter are 10 inches thick, and the 84 and 90-inch mains,

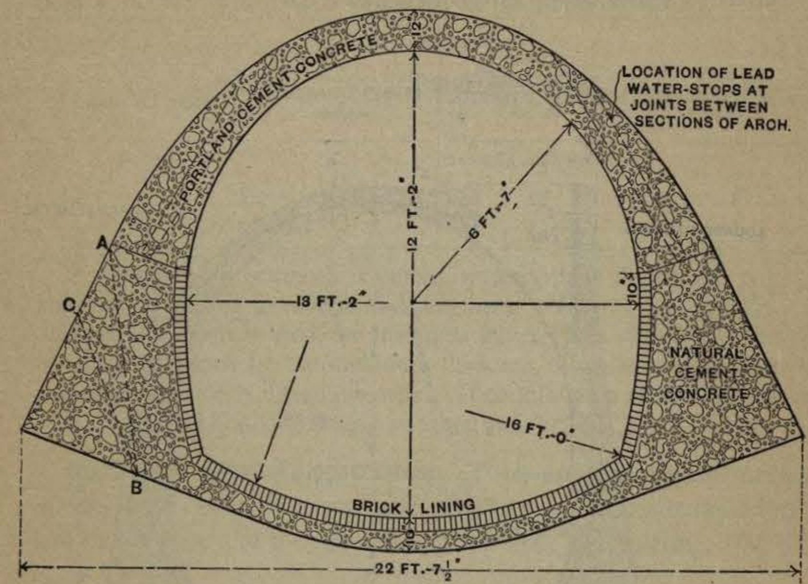

FIG. 221. — Typical Section of Weston Aqueduct in Loose Earth. (*See p.* 682.)

12 inches thick. The ring in each size is of uniform thickness, and the lower portions of the interior surface are covered with a ½-inch coat of plaster.

In large concrete conduits, even when of circular shape, and passing through material which needs no foundation, it is good practice, whether or not reinforcement is employed, to thicken the walls at the spring of the arch. At Williamsport, Pennsylvania, a 11-foot concrete sewer, suggested as a possible substitute for a 4-ringed brick sewer, was designed 13 inches thick at the crown and invert, and 19½ inches thick at the haunches with no reinforcement.

The Jersey City Water Supply Company constructed in 1903 a conduit reinforced with twisted steel. A typical section, taken through a manhole, is shown in Fig. 222, as designed by Mr. William B. Fuller. Longitudinal reinforcement consists of $\frac{3}{16}$-inch rods spaced about 18 inches apart, and circumferential reinforcement is formed by rings of ⅜-inch rods about 12 inches apart. Through rock open cut the metal was placed only in the

*See article by E. J. McCaustland, *Cement*, Sept., 1902, p. 265.

arch, and as far down on each side as the filling would extend. The open-cut conduit is shown in process of construction in Fig. 97, page 278.

At Kalamazoo, Michigan, Mr. George S. Pierson adopted for a creek culvert* a section shown in Fig. 223.

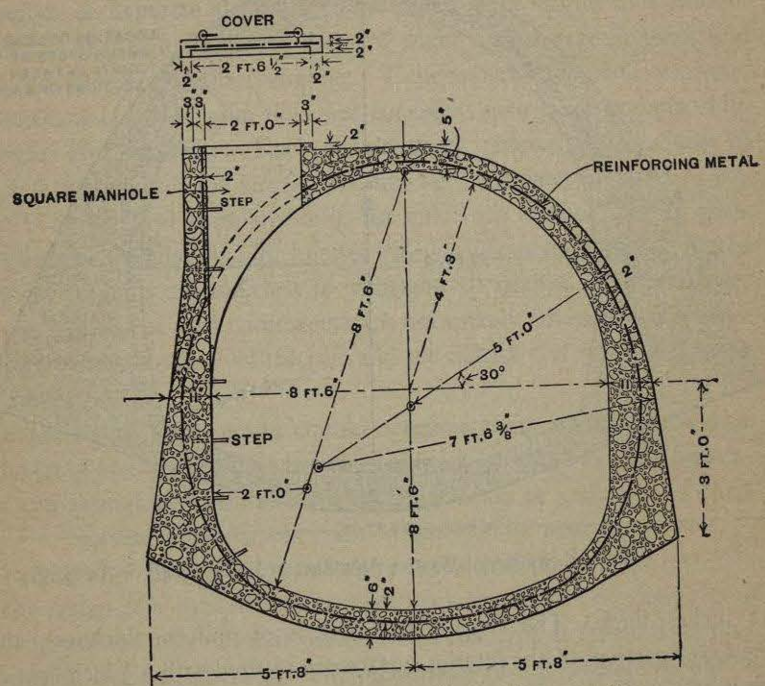

FIG. 222.—Typical Section of Jersey City Water Supply Conduit in Loose Earth. (*See p.* 683.)

At Grenoble, France,† in 1902, a concrete-steel penstock was built to withstand a pressure of 65 feet head of water. The thickness of wall is from 8 to 10 inches, reinforced with longitudinal bars ¼ to ½ inch diameter and circular hoops ⅜ to ⅞ inch diameter, forming a mesh about 4 inches square.

Thickness of Conduits. Mr. Fuller's general rule‡ for determining the thickness of concrete in conduits is as follows:

If concrete is not reinforced and ground is good, — able to stand without sheeting, — make crown thickness a minimum of 4 inches, and then one

*Described in *Engineering News*, Feb. 12, 1903, p. 163.
†*Engineering Record*, Mar. 7, 1903, p. 249.
‡Personal correspondence.

inch thicker than diameter of sewer in feet. Make thickness of invert same as crown plus one inch except never less than 5 inches. Make thickness at haunches two and a half times thickness of crown, but never less than 6 inches. This rule is expressed in the following table:

Thickness of Conduits.

Diameter of Conduit.	Thickness of Crown, inches.	Thickness of Haunch, inches.	Thickness of Invert, inches.
2	4	6	5
6	7	18	8
12	13	33	14

If ground is soft or trench is unusually deep, these thicknesses must be increased according to experienced judgment.

If reinforcement is used, the thickness for conduits of ordinary sizes is usually determined by the minimum thickness of concrete which can be laid so as to properly imbed the metal. This minimum for the large diameters where steel is advisable may be taken as 6 inches.

Methods of Conduit Construction. There are four general methods of construction of concrete conduits: (1) The lower portion of the invert is laid by template and the remainder of the circle by centering. (2) The

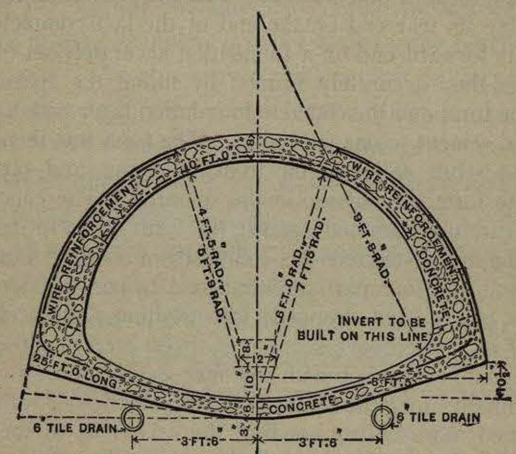

FIG. 223.—Creek Culvert at Kalamazoo, Mich. (*See p.* 684.)

invert is formed by an inverted center, and the arch by an upright center. (3) A center the size of the entire sewer, but with a removable bottom, is placed, the sides and arch are built, and then the bottom of the center is removed, and the invert is laid. (4) The entire sewer is formed as a monolith. The size of the sewer and the character of the work influences the choice of method.

If the invert is to have a brick lining or a granolithic finish, after excavating the material to the required grade and shape, profiles or templets are placed in advance of the finished concrete, and the surface is formed with the aid of a straight-edge placed longitudinally from the finished concrete to the nearest template. If the sides run up sharply, as in a small sewer, the concrete may be held in place by strips of lagging, 2-inch by 2-inch for a very small sewer, or wider for a larger size. This lagging rests at one end on the finished concrete, and at the other end on the template, and is placed as the work progresses. In horseshoe sewers the invert may be shaped with templates and straight-edge, and the side walls laid back of plank forms.

One of the simplest methods of constructing a small sewer whose invert is to be entirely of concrete, without reinforcement, is that adopted by the New York Transit Commission.* The process is described as follows:

Previous to setting the invert form in place for constructing a length of invert, concrete was placed on the bottom of the trench in a layer thick enough to bring its top surface up to within from ½-inch to ¼-inch of flow-line grade. To insure the accuracy of this work and also to insure the accurate alignment of the form a template was suspended from the trench timbering and adjusted to line and grade. After placing the bottom layer of concrete the form (a center 12 feet in length) was accurately set in position by resting its rear end on the end of the last completed invert and supporting its forward end on a foundation accurately set in grade. The flow-line was then accurately formed by filling the space between the bottom of the form and the concrete foundation layer with a mortar of one part Portland cement to one part sand. The form was then firmly braced in position by struts nailed to the trench sheeting, and vertical planking was set up to form the outside of the spandrel. The concrete was then placed and carefully rammed against the form so as to insure a smooth surface. The invert concrete was composed of one part Portland cement, two parts sand and four parts broken stone to pass a 1-inch ring. This mixture was placed (not dropped) into position and carefully rammed. The ends of each successive section of invert were mortised to insure a firm and intimate connection with the next section, and 2 by 4-inch strips, laid longitudinally along the center of the tops of the side walls of the invert section, formed mortises for bonding the arch ring to the invert. The forms were left in place at least 24 hours to allow the concrete to set. After the invert was set and the form withdrawn a thin cement wash was brushed over its surface to smooth any slight roughness. This work gave a surface almost polished in comparison with the best brickwork.

This method of procedure affords no opportunity of troweling the surface, but in a sharply curved invert it is difficult to use a trowel. The plan

*Engineering News, Mar. 6, 1902, p. 199.

described is not suitable for a large reinforced sewer because so much time is required to set the center and the steel that the layer of concrete in the bottom sets too hard to unite with the mortar finishing coat.

In a large conduit the smoothest and best wearing surface is obtained by laying a comparatively narrow strip of invert by means of profiles or templets and straight-edge, and troweling it. If desired, a granolithic (or mortar) finish may be given, but with thorough troweling, excellent results are secured with concrete. The arch center, which in such cases must be nearly a complete cylinder, is placed after the strip of invert concrete has set, mortar is spread on the edges of the invert strip already laid, and the circle is completed with fresh concrete. A longitudinal groove also assists in forming a tight joint.

To avoid this joint, a similar plan has been followed to that just described, except that the form, which is a complete cylinder open at the bottom, is placed, before laying any concrete, upon concrete blocks previously prepared in molds and then laid in the bottom of the trench. The lowest strip of invert is not laid until after the sides and arch are in place, the concrete for it being let down through holes left in the crown for the purpose, and troweled as thoroughly as the obstructions of the forms will permit.

It would at first appear that the sewer could more readily be made monolithic by placing a complete cylinder and pouring concrete around it for the invert arch. The objection to this, however, is the great difficulty in placing the concrete in the extreme bottom, and also the tendency of the center to "float" from the upward pressure of the concrete. This difficulty is also encountered to a less extent in the method described in the preceding paragraph.

In a sewer whose invert and arch are constructed separately, the arch centers are made and placed as for brick, except that a smoother and tighter surface is necessary, and the forms are oiled to prevent adhesion. A covering of sheet metal has often been successfully used. In order to lay the concrete of the arch sufficiently wet to obtain a smooth surface, an outside set of forms, open at the crown, is usually essential.

The laying of a large water conduit for the Jersey City Water Supply Company is illustrated in Fig. 97, page 278.

If a plaster finish is required by the specifications, the mortar may be spread upon the arch center before placing the concrete, or troweled on to the intrados after the completion of the work. In the aqueduct of the Metropolitan Water Works, Massachusetts* (see Fig. 221, p. 683), a

*Third Annual Report, Metropolitan Water Board, 1898, p. 56.