The method of computation for other points in the arch is similar, and stresses should be determined at sections where they appear to be the maximum.

From table 2 it is evident that although at point 20 the moment due to dead and live load is very small, its combination with moments due to temperature and rib shortening makes it one of the critical points. The moment and thrust due to live and dead load and rib shortening is $M = -656 - 3030 = -3636$ ft. lb. and $N = 14840 - 610 = 14230$ lb. Hence, $e_0 = \frac{3686}{14230} = 0.26$ ft., for $h = 1.97$, $\frac{e_0}{h} = 0.13$, $p = 0.0037$.

Inspecting the lower part of Fig. 177, page 569, it is seen that the whole section is in compression. From the same diagram for $\frac{e}{h} = 0.13$ and $p = 0.0037$, $C_e = 1.65$. Using formula (52), page 568, $f_c = \frac{14230 \times 1.65}{1.97 \times 12 \times 12} = 83$ lb. per. sq. in.

Combine now the moment and thrust due to live and dead load with those due to temperature and obtain $M = -(10180 + 3686) = -13866$ ft. lb., $N = -1970 + 14230 = 12260$ lb., $e = 1.13$ ft. $\frac{e}{h} = 0.57$.

In Fig. 179, page 572, $k = 0.37$ corresponds to $\frac{e}{h} = 0.57$. By locating this value of k in Fig. 180, the constant $C_a = 0.094$ is obtained, which substituted in formula (59), page 571, gives $f_c = \frac{13866}{1.97 \times 1.44 \times 0.094} = 520$ lb. per sq. in. The stress in steel from formula (54) is $f_s = 15 \times 520 \frac{1.67 - 0.37 \times 1.97}{0.37 \times 1.97} = 10000$ lb. per sq. in.

Similar computations should be made for all critical points and when the stresses are either too small or too large, the dimensions or even the shape of the arch must be changed. Small changes may be made without refiguring the whole arch. For larger changes, all computations should be repeated and a new line of pressure determined.

LOADINGS TO USE IN COMPUTATIONS

The usual practice is to make two sets of computations; in the first place, proportion the arch ring for a live load covering the entire span and then for one covering only one-half the span. These two loadings are approximations, more or less exact, to the true loadings which produce the maxi-

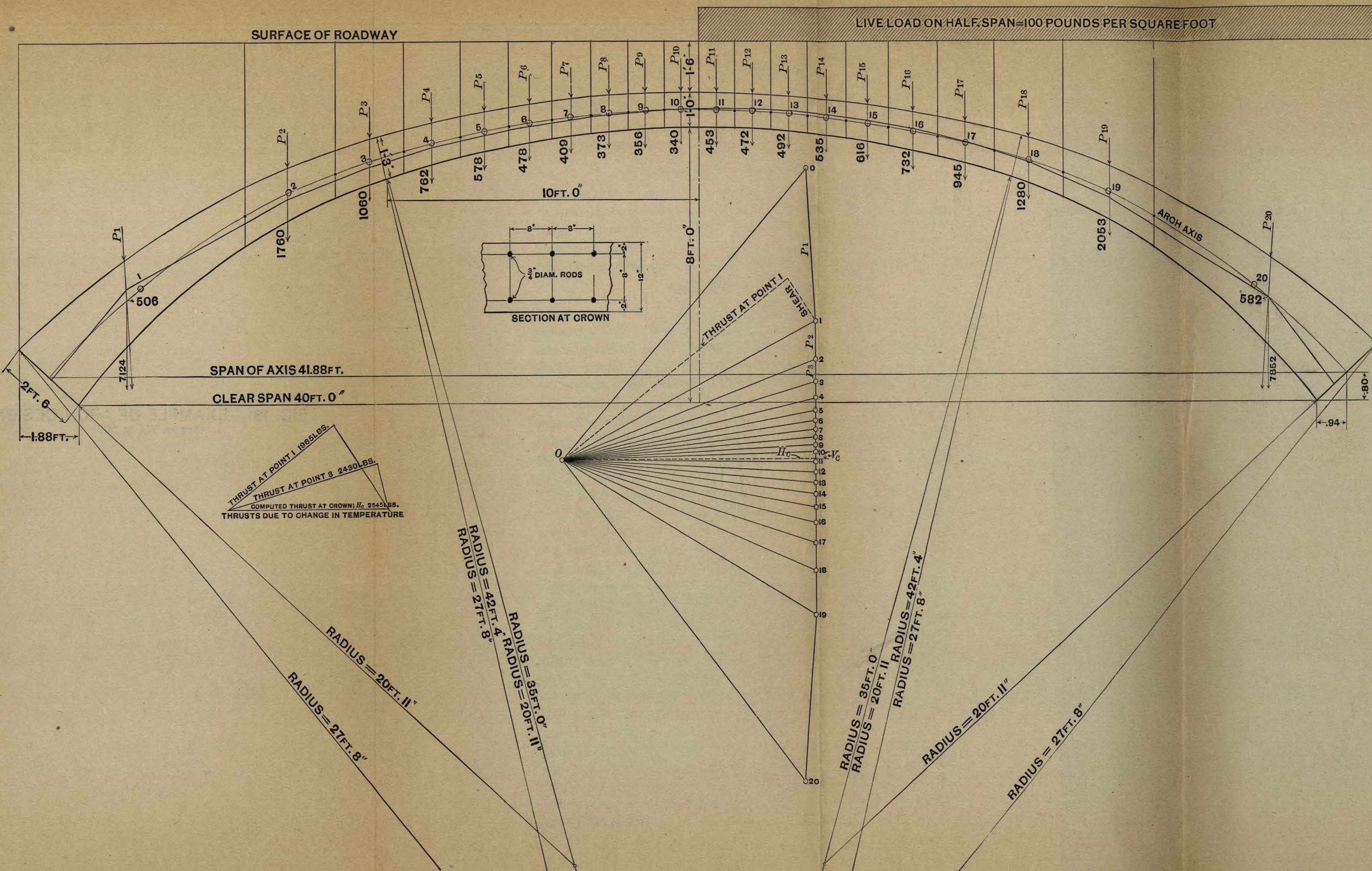

Fig. 181.—Example of Arch Design.

mum effects. By computing a table for the thrusts and moments due to a load of unity at different points, or by the use of influence lines, the exact loading to cause maximum stresses may be found.

ALLOWABLE UNIT STRESSES

For highway bridges the maximum compression in the concrete of the ring should not exceed 500 pounds per square inch due to live and dead loads, nor more than 600 pounds per square inch due to live and dead loads, temperature and rib shortening combined. For railroad bridges three-fourths of the above values may be used.

DESIGN OF ABUTMENT

The design of the foundation of an arch bridge is as important as that of the arch itself. The arch is designed on the assumption that the foundation is unyielding, and this condition must be approached as nearly as possible in order to insure the stability of the whole structure.

The depth of the foundation as well as the shape is dependent upon the local conditions, and in the more difficult cases these have to be chosen after exhaustive studies. A certain shape of abutment is first assumed, and this is then reviewed to see that the load upon the ground does not exceed the allowable load and that it is well distributed. Allowable loads are discussed on page 541.

The forces acting on the foundation are:

(1) the thrust of the arch; (2) the weight of the foundation; (3) the weight of the earth above it; and (4) the lateral earth pressure. The thrust of the arch is the largest when the live loading extends over the whole span of the arch, and for this the line of pressure should be drawn first. A line of pressure for the thrust on account of the total dead load and of the live load extending only over one-half the span opposite to the abutment also should be drawn to see whether, because of intersecting the abutment higher up, it does not produce larger pressure on the foundation. A good scheme is to design the abutment in such a way that the line of pressure on account of one thrust intersects the base a little way to the left of the center while the other intersects to the right of the center. In some cases a third line for the total dead load, plus live load on the half span nearest the abutment should also be drawn.

The line of pressure of the forces should be as near to the center of the base as possible, since the maximum unit pressure is the smallest when the load is distributed uniformly over the entire section. This also prevents uneven settling of the foundation, and thus adds considerably to the stability of the whole structure.

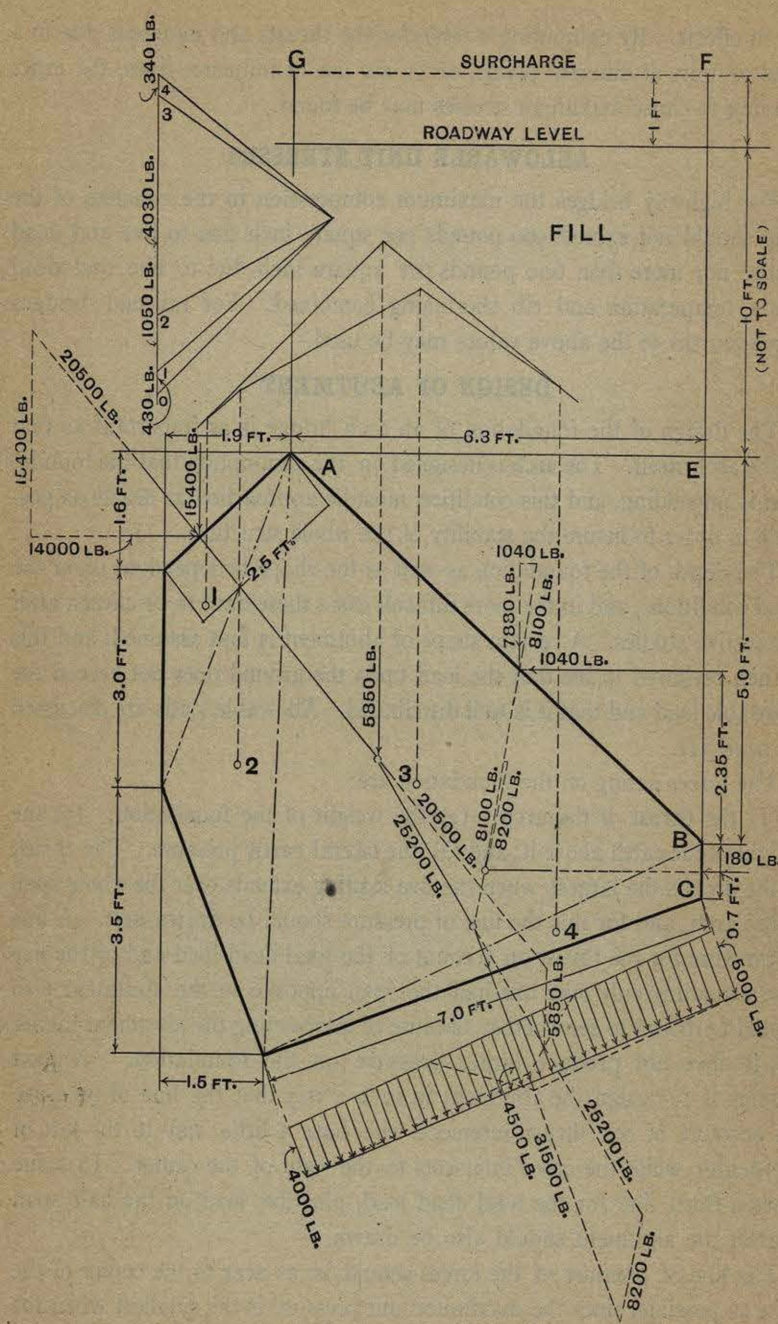

FIG. 182.—Design of a Foundation for an Arch. (*See p.* 585).
(To simplify the drawing only one position of thrust and one line of pressure is drawn.)

Fig. 182, page 584, clearly illustrates the design of an abutment. The outline is assumed, then the location and magnitude of the forces acting upon the abutment are found and the line of pressure determined. If the assumed outline is not satisfactory it should be revised.

For the benefit of those who are not familiar with the common principles of such design, the steps will be considered in detail. The magnitude, 20,500 pounds, and position of the arch thrust is given in the arch example. Since the weight of the masonry acts through its center of gravity, this point must next be found and this is most readily done by dividing the outline of the abutment into triangles and rectangles. The weights of each of these prisms one foot thick are readily computed, and the center of gravity found through which the weight force acts. A force polygon for any pole distance, as shown in the upper left corner of the diagram, is drawn and the equilibrium polygon, by the intersection of the closing lines, locates the resultant of the weight which, by computation, is found to be 5850 pounds.

The pressure on AB consists of the horizontal pressure on BE, and the weight of the prism of earth whose cross-section is $ABFG$* and thickness one foot. Taking the weight of one cubic foot of filling at 100 pounds, the weight of the prism would be $\frac{10 + 15}{2} \times 6.3 \times 100 = 7880$ pounds.

The horizontal pressure on BE is equal to the difference between the pressures on BF and EF.

Let

w = weight of one cubic foot of earth,

then, if the weight of earth is assumed at 100 pounds, from formula (2), page 664, pressure on the plane

$$BF = \frac{w}{6} \times BF \times \tfrac{1}{2} BF = \frac{100}{6} \times 15 \times \tfrac{1}{2} 15 = 1870 \text{ pounds},$$

and on the plane

$$EF = \frac{w}{6} \times EF \times \tfrac{1}{2} EF = \frac{100}{6} \times 10 \times \tfrac{1}{2} 10 = 830 \text{ pounds}.$$

Hence horizontal pressure on plane BE = 1040 pounds.

The point of application is found from the formula (7), page 666.

In the case under consideration $H = 15$ feet, $h = 10$ feet, where H is the depth of point B and h the depth of A or E below the line of surcharge.

The horizontal pressure on BC is by formula (6), page 666, 180 pounds, and the point of application may be assumed in the middle of BC without appreciable error.

* The live load being 100 pounds per foot is equivalent to a surcharge one foot in height.

Having thus located all forces and found their magnitude, the line of pressure is drawn. This procedure consists simply in finding the resultant of two forces intersecting in one point. The line representing the thrust is prolonged until it intersects the line representing the weight of masonry, 5850 pounds. Beginning at this, the magnitude of the thrust, 20,500 pounds, is laid off to any desired scale and the resultant of this with the weight of the masonry, 5850 pounds, is found to be 25,200 pounds. Combining this new force in turn with the earth pressures of 8100 pounds and 180 pounds completes the line of pressure with a final resultant thrust of 31,500 pounds.

Having found the line of pressure, the thrust is divided by the projection of the base on a line at right angles to the thrust and the maximum pressure on the ground is found by formula (36), page 562, to be 5000 pounds per square foot.

The same result is obtainable by the following simple graphical method: Find the average unit pressure by dividing the thrust by the area of the projection of the base, drawn perpendicular to the thrust. In this case we have $\frac{31500}{7} = 4500$ pounds per square foot. Plot this, to any convenient scale, perpendicular to the projection to the base at its center; connect the $\frac{1}{3}$ points of the base with the top of this perpendicular, as shown by the dash lines in Fig. 182, and produce one of these lines till it intersects the line representing the direction of the thrust. The perpendicular distance of this point from the projection of the base is the maximum thrust and the distance of the other intersection of a slanting line with the thrust line is the minimum thrust. To draw the trapezoid of pressure, draw, through these two intersections, lines parallel to the projection of the base, as shown, and the extremities of these parallel lines will fix the two corners of the trapezoid. The maximum pressure is always at the end of the base nearest the thrust.

ERECTION

As in other reinforced structures, the erection is as important as the design. Perhaps the first essential is the centering which should be planned out in advance almost as carefully as the arch itself.

Methods of Arch Construction. There are two general methods of laying the concrete in an arch, each of which has strong advocates. By the first, the arch is laid in separate blocks across the bridge, and by the second, in narrow ribs from abutment to abutment. If the block method is followed, the lowest stones at the springing line are laid first, then stones intermediate between the spring and the key, next the two stones each side of the key, and finally, after filling in the intermediate blocks, the key is placed. This distributes the weight of the concrete uniformly over the arch center, and prevents unequal settlement, which tends to crack the arch near the springing lines. On the other hand, the entire weight falls upon the center, and the latter must be very strongly built. The arch thrust acts at right angles to the joints, and as the blocks extend clear across the bridge, there is no danger of longitudinal splitting, but the radial joints offer planes of weakness in bending.

By the other method the work can be readily arranged so that a day's labor consists of the laying of a single rib, thus forming a complete arch of itself, which as soon as it sets bears its own weight. This arch section has no joints, so that when subsequently loaded the bending moment is best resisted.

A small arch, where the center can be solidly built, may be laid at one operation, commencing at both abutments and working toward the key so that it is in fact a monolith.

The spandrel or face walls may be carried up at the same time the arch ring is laid, or may be connected with it later by leaving short lengths of steel projecting radially from the concrete of the arch.

If steel is introduced, the consistency of the concrete must be wet enough to thoroughly coat it. This may be accomplished by a quaking or jelly-like mixture, which requires but slight ramming.

From an architectural point of view, the treatment of the face is of much importance. For a discussion of the different methods reference should be made to page 288.

Railings and ornamental work may be cast in molds if preferred and put in place after hardening.

Centering. The falsework for concrete arches is practically the same as for stone arches except that close lagging is necessary. It must be rigid during the construction of the arch and stiff enough to prevent its distortion from the unsupported weight of the concrete before the keying of the arch.

The design of the centering is frequently governed by the character of the ground underneath. In general the framed wood centering made into a truss rests upon pile or trestle bents. The spacing of these bents is determined by the foundation and the difficulty of placing them, and by the height and span of the arch. In certain cases it is possible to support the centering in whole or in part by the reinforcement, although this is not usually economical because more carefully framed steel is required than is necessary for reinforcing the arch. In at least one case* reinforced concrete forms were used.

In connection with the description of arch centers which he has built, Mr. James W. Rollins†, Jr., gives the following notes:

For small arches the simplest center is a circular rib made of three pieces of 2-inch plank, laid with broken joints, all being spiked solidly together, with a tie of plank at the springing. On this, 1-inch lagging is laid close. For a larger arch, the circular rib, as above described, with generally three braces, one at center and one on the quarter at each side, is used, the center of the whole rib having a post under it. We have used such a center up to 30-foot span for both brick and granite arches, carrying a 30-inch arch sheeting.

The design of a center for larger arches depends upon local conditions, also upon the relation of rise to span. In flat arches, with low side walls, it is well to use posts with intermediate bracing, on numerous supports. In a high arch we may use long braces extending directly from a center support to the rib, at intervals of 6 feet to 8 feet.

Mr. Rollins advocated for wedges, seasoned oak, 8 inches wide, 4 inches thick at the thick end, 2 inches at the thin end, and 18 inches long, planed on sliding faces, and thoroughly greased. When setting the center, these wedges, placed between the caps on the bents and the corbels under the lower chord of rib, are tacked together to prevent slipping.

Boxes filled with sand are frequently used between the caps of the bents and the lower chords of the trusses in place of wood wedges. The sand in these must be thoroughly packed to prevent settlement of the concrete before setting. The sand is readily removed by letting it out through a hole in the box. Jack-screws also may answer the same purpose as wedges or sand boxes. By any of these means the centering is easily lowered.

The ribs of the centering are usually made of several pieces of plank spiked or bolted together. Upon the ribs rests the lagging, which usually consists of one or two layers of planking having the top surface smoothed to give a good surface to the soffit of the arch, and laid with tight joints. With thin lagging care must be taken to prevent deflection.

Instead of the ribs forming a part of the truss, they are frequently supported directly upon the wedges resting upon the caps of the bents, the posts of which run up to the soffit of the arch for that purpose.

The centering should be cambered, that is, should be made higher than called for in the arch plans at the center, so that when it is removed, the arch will be in the position assumed for it in the design. Some engineers make

*Engineering News, Aug. 30, 1906, p. 215.

†Journal Association of Engineering Societies, July 1901, p. 10. For examples of centers built in various places, see References, Chapter XXXI.

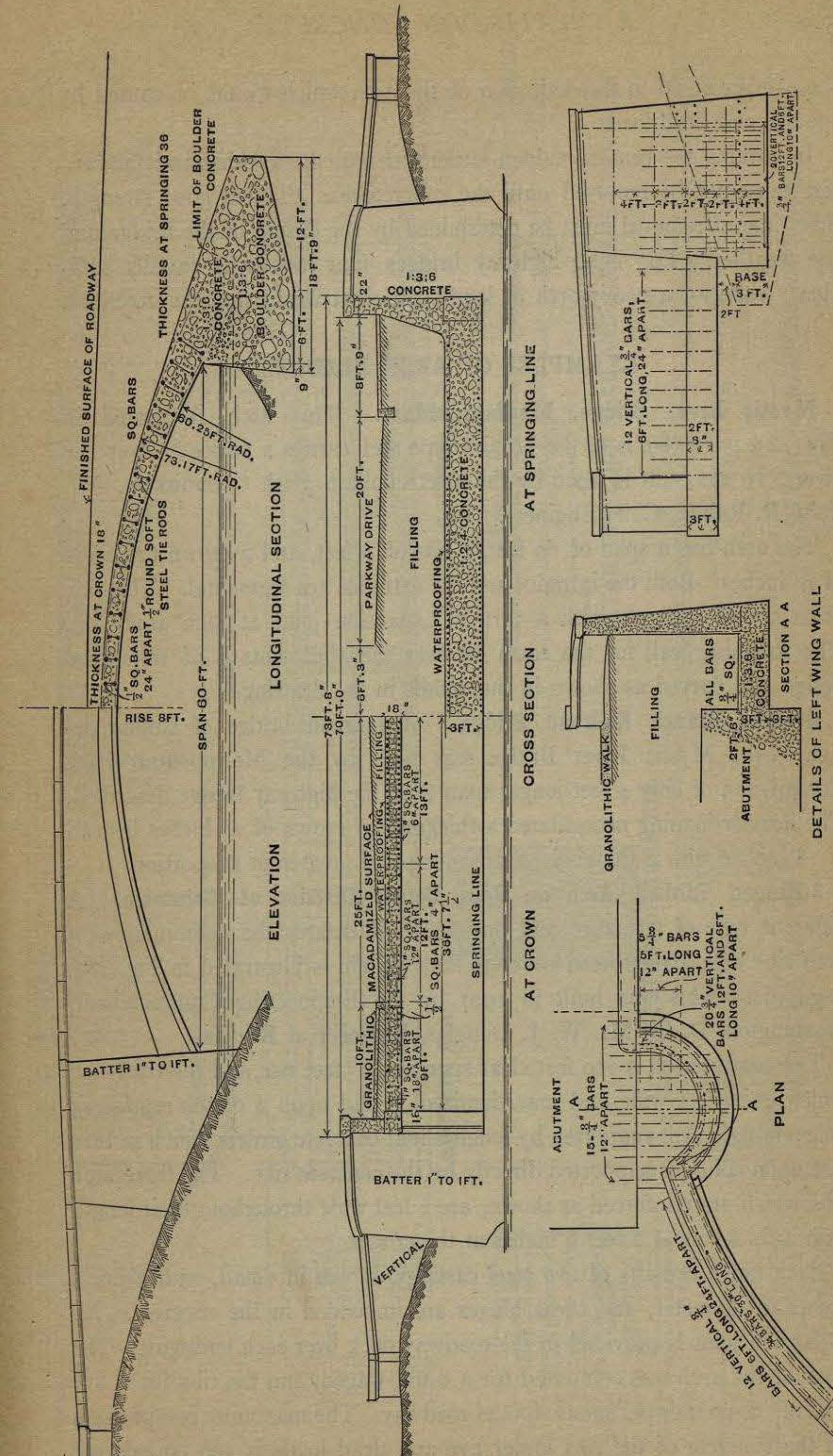

FIG. 183.—Design of Mystic River Bridge, Medford, Mass. (See p. 596.)

the camber equal to the deflection of the arch which would be caused by the live and dead loads.

In striking the centers sudden settlement must be avoided and the centers must not be removed until the concrete has attained good strength. The time of removal must be determined by the design of the bridge and the weather. For light highway bridges four weeks is usually sufficient, while for a heavy arch of long span eight weeks may be required.

EXAMPLES OF ARCH BRIDGES

Mystic River Bridge, Medford, Mass. This arch, illustrated in Fig. 183, page 589, is of the Monier type and carries a parkway over the river. It was built in 1906 by the Metropolitan Park Commission, Mr. John R. Rablin, Chief Engineer.

The arch has a span of 60 feet, a rise of 8 feet, and a crown thickness of 18 inches. Both the intrados and the extrados are segmental. The side walls are of concrete with a vertical expansion joint at each abutment. The retaining wall for the earth fill over the abutments is of reinforced design and curved as shown in the details in the drawing.

Granite Branch Railroad Bridge. A railroad bridge of similar design to the Mystic River Bridge was built by the Metropolitan Park Commission of only 4 feet longer span than the highway bridge described. The heavier loading necessitated a thickness of crown of 24 inches instead of 18 inches with a thickness at springing still greater in proportion.

3-Hinged Ribbed Arch on Ross Drive, District of Columbia. A different type of structure and one which illustrates the combination of arch ribs with a reinforced concrete floor system is illustrated in Fig. 184, page 591. This was built in 1907 by the Engineering Commissioner, Washington, D. C., Mr. W. J. Douglas, Engineer of Bridges.

The central arch is 100 feet clear span and 15 feet rise, and the roadway, which is 16 feet wide and macadamized, is laid upon a 6-inch reinforced concrete floor slab supported by longitudinal concrete girders which in turn rest upon columns supported directly by the concrete ribs. The three arch ribs, which are reinforced as shown, are 2 feet wide throughout their length with a thickness of 2 feet 6 inches at the crown.

Each hinge consists of two steel castings, shown in detail, with a pin 4 inches in diameter, and these hinges are imbedded in the concrete. An expansion joint is provided in the roadway deck over each springing. The floor of the arch was computed for a 6-ton wagon, and the ribs for a live load of 100 pounds per square foot of roadway. The maximum compression on the concrete of the ribs under live and dead loads is 500 pounds per

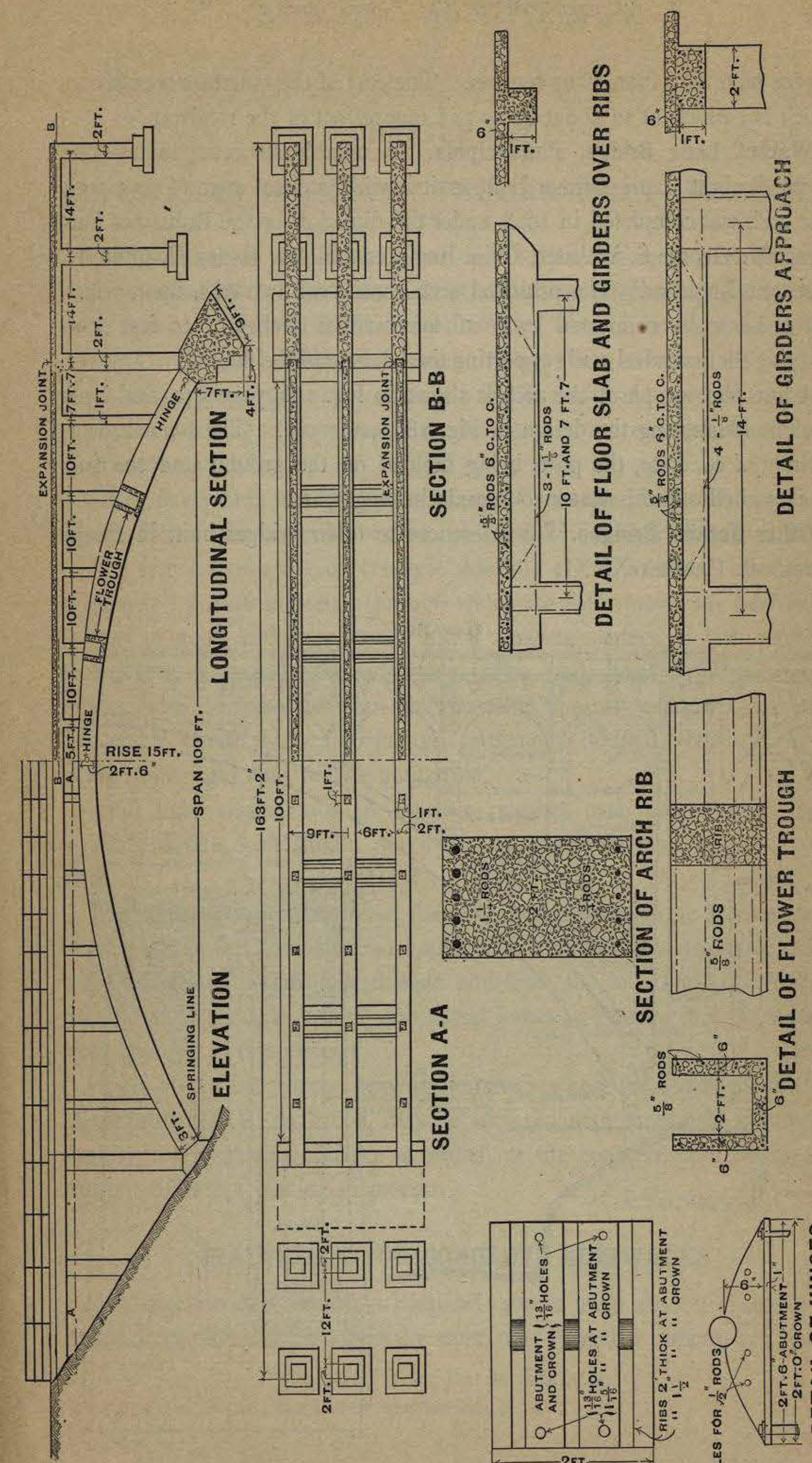

FIG. 184.—Three-Hinged Ribbed Arch, Ross Drive, District of Columbia. (*See p. 590.*)

square inch, and there is no tension. The cost of the structure was $8000, which is equivalent to about $3.00 per square foot of the roadway.

Walnut Lane Bridge, Philadelphia. A notable structure in concrete is the Walnut Lane Bridge built as it is with a clear span of 233 feet. The arch was completed in 1908 under the direction of the Bureau of Surveys, Mr. George S. Webster, Chief Engineer and Mr. Henry H. Quimby, Assistant Engineer. The principal arch consists of two ribs, upon which rest cross walls connected by small longitudinal arches of 20 feet span carrying the spandrel wall supporting the I-beams of the floor.

A fine photograph of the arch is shown in Fig. 156, page 532, and cross sections illustrating the design in Fig. 185, page 592. The balustrade is entirely of concrete, the posts being molded on the ground and the surface washed off with water to reveal the aggregate.

Other Notable Bridges. For references to other bridges built in recent years, see Chapter XXXI.

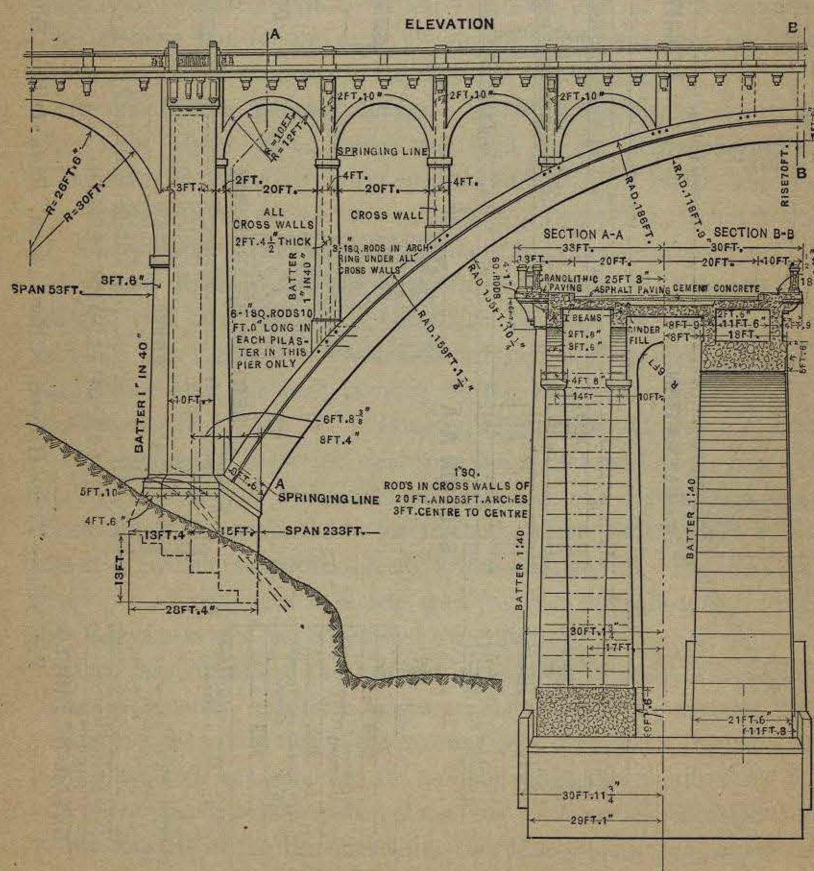

FIG. 185 Walnut Lane Bridge, Philadelphia. *(See p. 592.)*

CHAPTER XXIII

SIDEWALKS, BASEMENT FLOORS AND PAVEMENTS

The introduction of reliable American Portland cements has rendered concrete available for sidewalks and other similar purposes at a price not more than two-thirds of that previous to 1890, when German and English cements were used. Portland cement being thus commercially within reach of builders, masons have become familiar with its use, and concrete sidewalks, because of their economy and durability, are supplanting those of other materials.

Street pavements are also being made of concrete, and with apparent success,* by methods similar to those which obtain in sidewalk construction.

The essentials for a good concrete sidewalk are an artificial foundation of firm but porous material, through which the rain water may percolate, a base of good strong concrete, and a wearing surface of rich mortar, troweled to a smooth, dense surface. The walk must be divided into blocks, with the joints between them forming lines of weakness, so that if any cracks occur through shrinkage, settlement, or frost, they will occur at the joints and thus not be noticeable.

Vault light construction in concrete requires even greater skill than ordinary walks, and should never be attempted by inexperienced constructors.

The construction of basement floors is similar to sidewalk work except that in dry ground an artificial foundation is not always necessary, and, there being less danger of settlement and frost, the blocks of such a floor may be of larger size, having occasional joints to provide for contraction from changes in temperature.

Floors above the ground level in buildings whose design is considered in Chapter XXIV, page 609, may be surfaced with mortar in a manner similar to the wearing surface of walks, or the concrete may be floated without the extra coating of mortar.

MATERIALS FOR CONCRETE SIDEWALKS

The selection of a first-class Portland cement is an absolute necessity.† Natural cements will not stand the wear, and Puzzolan cements are liable

Engineering News, Jan. 28, 1904, p. 84.

†See Cement Specifications, p. 29.