Trautwine gives the following formula for the depth of keystone:

$$\text{Depth of key in feet} = \frac{2\sqrt{\text{radius} + \text{half span}}}{4} + .2 \text{ feet.}$$

This is for cut stone. For concrete the result should be increased by one-eighth.

Rankine's rule for crown thickness is:

For single spans — $2\sqrt{.12 \text{ radius}}$

The crown thickness may also be found approximately by first determining the approximate crown thrust. This may be found by obtaining the centre bending moments for all loads, as for a beam, and dividing by the rise. The proper value for crown thrust is that one producing equilibrium about the point of rupture.

Trautwine's rule for determining the thickness of abutments for arches, in feet, at the springing line, for any abutment, the height of which does not exceed one and one-half times the thickness at the base is: The required

$$\text{thickness} = \frac{\text{radius in feet}}{5} + \frac{\text{rise in feet}}{10} + \text{or} - 2 \text{ feet.}$$

The radius used is that of a circle passing through the two springing lines and the crown, on the soffit.

This formula is applicable to a semi-circular, segmental, or elliptical arch. This thickness is given to resist the thrust on the wall, arising from the earth pressure of the embankment of any height, over and around the wall.

Where the earth only extends a few feet above the top of the arch, it is evidently safe to consider the half arch, with its abutment and weight above, as the equivalent of a vertical faced wall of the height of the embankment, and find the thickness of the wall to insure stability, as in retaining walls, or using the thickness followed in practice, that is, from two-fifths to one-half the height. Any greater height of embankment would probably not require any greater thickness of abutment wall. The great stability of the wall, resulting from increase of weight of material above, would balance the increased thrust.

A more extended discussion is impossible on account of the very involved character of such a discussion.

The following method of designing semi-circular arches of reinforced concrete, for spans up to fifty feet and with not more than ten feet of fill over crown is suggested by Dan. B. Luten:

$$\text{Crown thickness} = \frac{\text{span}}{30} + \frac{1}{3}.$$

The outer to be drawn with the centre one-tenth of the span below the centre of the inner circle. The back of the abutments tangent to the outer circle and battered one in four.

The square inches of steel required to reinforce one edge of the arch for one foot in width to be $\frac{HL}{400{,}000C}$.

Where H is the height of the opening in feet.

C is crown thickness in inches.

L is the live load in pounds that can be concentrated in single track, over half the span.

Reinforcing of Culverts.—These remarks will apply chiefly to the semi-circular arch culvert, as they are practically the only culverts built without reinforcing of any kind.

Anyone at all familiar with the condition of the arch culverts along our railroads is aware of the only too common occurrence of cracked concrete culverts.

The most frequent cause of failure is the unequal settlement of the foundations under the two ends of the structure, causing ugly, disfiguring cracks at right angles to its longitudinal axis and, indeed, often noticed extending across the intradosal face of the arch. Similar cracks often occur in the invert. Another type of crack much in evidence is one running longitudinally along the centre line of the invert where the arch usually has the least thickness, indicating unequal settlement of the sidewall foundations.

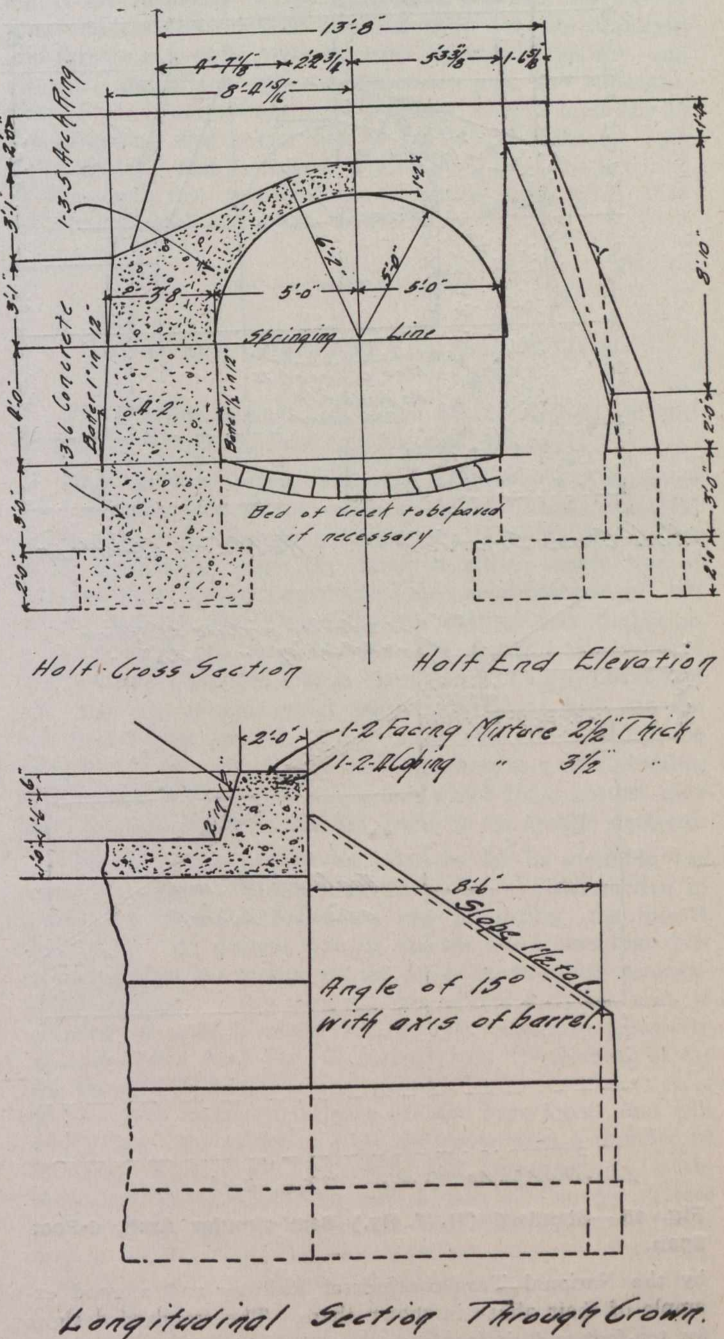

Fig. 14.—Standard (N. T. Ry.) Semi-circular Arch, 10-Foot Span.

Contraction and expansion from changes of temperature, as well as shrinkage stresses, have also been known to have caused cracks in concrete culverts, but these causes of failure are not so common as unequally yielding foundations.

If the culvert is properly reinforced, such conditions as those described above do not occur because the culvert will act as a monolith. The culvert will be capable of beam action and cracks will not appear so readily as in a plain concrete structure, thus far greater durability is assured.