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design data 18

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HYDRAULICS OF CULVERTS: HORIZONTAL ELLIPTICAL CONCRETE PIPE CORRUGATED METAL PIPE ARCH

The hydraulic characteristics of horizontal elliptical pipe offer advantages, under certain conditions, over circular pipe commonly used for culverts. For minimum cover conditions, or where vertical clearance is limited by existing structures, horizontal elliptical pipe is particularly suitable, since the vertical height is less than the height of hydraulically equivalent circular pipe. Horizontal elliptical pipe also offers the hydraulic advantage of greater capacity for the same depth of flow than most other structures of equivalent water-way area.

The hydraulic design of culverts establishes the minimum pipe size which has sufficient capacity to discharge a required flow within an allowable headwater depth. The factors affecting the hydraulic capacity of a culvert are illustrated in Figure 1. For any given headwater depth, these factors interact to control the hydraulic capacity by one of the following means:

1. Geometry of the inlet
2. Combined influence of size, shape, slope and surface roughness of the culvert pipe
3. Tailwater conditions at the outlet

The type of control under which a particular culvert operates is dependent on the location of the control section which limits the maximum discharge through the culvert. In the hydraulic design of culverts where the outlet is not submerged, two principal types of control are usually considered:

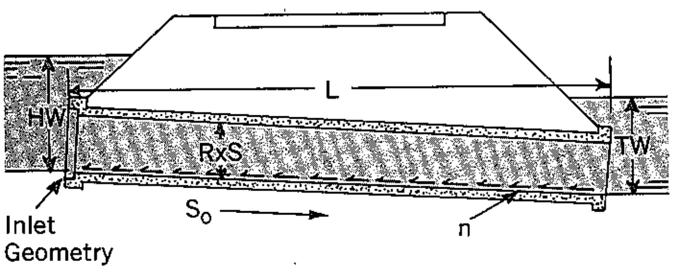
FLOW WITH INLET CONTROL

Under inlet control the control section is located at or near the culvert entrance, and for any given shape and size of culvert, the discharge capacity is entirely dependent on the inlet geometry and headwater depth. Inlet control will exist as long as water can flow through the culvert at a greater rate than water can enter the inlet. The capacity of a culvert is limited by the degree of contraction of the flow at the entrance. Therefore, if a culvert is to function as an efficient hydraulic structure under inlet control conditions, an inlet geometry resulting in minimum contraction of the flow at the entrance is of utmost importance. The geometric shape of the socket end of a concrete culvert pipe provides a more efficient entrance than the sharp edge of a corrugated metal pipe with or without a headwall.

FLOW WITH OUTLET CONTROL

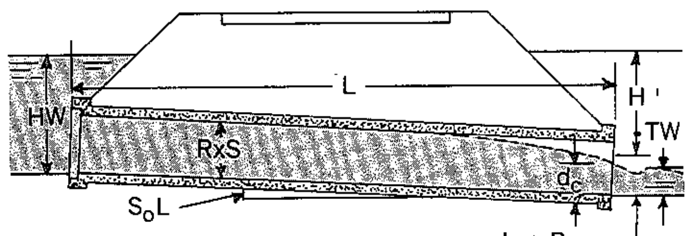
Under outlet control the control section is located at or near the culvert outlet, and for any given shape and size of culvert, the discharge capacity is dependent on all of the hydraulic factors upstream from the outlet. Outlet control will exist as long as water can enter the culvert through the inlet at a greater rate than water can flow away from the entrance. The primary factor limiting culvert capacity when operating under outlet control is surface roughness. Therefore, a culvert pipe with an in-

FIGURE 1: Factors Affecting Culvert Capacity



R=inside vertical height (rise) of pipe
S=inside horizontal span of pipe
HW=headwater depth at culvert entrance
L=length of culvert
n=surface roughness of the pipe wall, usually expressed in terms of Manning's n
S_o=slope of the culvert pipe
TW=tailwater depth at culvert outlet

FIGURE 2: Outlet Control Energy Relationship



$$HW=H+h_o-S_oL \qquad \frac{d_c+R}{2}=h_o$$

where
HW=headwater depth, feet
H=head loss, feet (velocity head, entrance loss head and friction loss head)
h_o=vertical distance from culvert flow line at outlet to "control" point, feet
S_o=slope of the culvert, feet per foot
L=length of culvert, feet
TW=tailwater depth, feet
d_c=critical depth, feet
RxS=inside rise x span of pipe

terior surface which results in a minimum of frictional resistance to flow is necessary for hydraulic efficiency. The relative smoothness of concrete pipe enables significantly greater hydraulic capacity than can be obtained by corrugated metal pipe of equivalent size.

DESIGN PROCEDURE

The hydraulic design procedures available for determining the required size of a culvert vary from empirical formulae to comprehensive mathematical analysis. Most empirical formulae, while easy to use, do not lend themselves to proper evaluation of all factors affecting the flow of water through a culvert. The mathematical solution, while giving precise results, is time consuming. A systematic and simple design procedure for the proper selection of culvert size is provided by Hydraulic Engineering Circular No. 5, prepared by the Hydraulics Branch, Bridge Division, Office of Engineering and Operations of the Bureau of Public Roads.

Circular No. 5 presents inlet control and outlet control nomographs for the selection of the more common types of culverts. The nomographs take into consideration the physical characteristics of the pipe; such as slope, length, surface roughness, size and shape of the culvert and inlet geometry. Although the nomographs provide for the ready selection of culvert size and type, the design procedures presented in Circular No. 5 still require a trial and error solution.

Because the designer is basically concerned with providing an adequate pipe capacity to carry a design discharge without exceeding an allowable headwater depth, use of headwater - discharge performance curves greatly facilitate the selection of required pipe size. Figures 3 through 22 present headwater - discharge performance curves for horizontal elliptical concrete pipe and corrugated metal pipe arch. The curves are based on nomographs included in Hydraulic Engineering Circular No. 5.

To determine the headwater depth under inlet control it is only necessary to project a vertical line from a given design discharge on the horizontal scale to the heavy curved line representing INLET CONTROL. At this intersection the inlet control headwater depth is read directly on the vertical scale.

Figure 2 illustrates the energy relationship for culverts operating under outlet control with the outlet unsubmerged. The OUTLET CONTROL performance curves presented in Figures 3 through 22 are based on the value $H + h_o$. Since $HW + S_oL = H + h_o$ it is necessary to subtract the product of the slope and the length of the culvert (S_oL) from the value given on the vertical scale. Thus, for any given design discharge and culvert slope and length, project a vertical line from the horizontal scale to the OUTLET CONTROL curve representing the given culvert LENGTH. At this intersection read $HW + S_oL$ on the vertical scale. Subtract S_oL from this value to obtain the outlet control headwater depth.

After determining the headwater depth for both inlet and outlet control, the higher value is used to indicate the type of control. The following example illustrates the proper use of curves:

Example

Given: A highway culvert 400 feet long is to be installed on a 0.75 percent slope. The culvert will be required to carry a design discharge of 200 cubic feet per second within an allowable headwater depth of 7 feet.

Find: The size of horizontal elliptical concrete pipe and corrugated metal pipe arch required and the type of control.

Solution: Enter Figure 15: **43 × 68-Inch Horizontal Elliptical Concrete Pipe,** and project a vertical line from Q = 200 on the horizontal scale to the INLET CONTROL curve and the OUTLET CONTROL curve representing L = 400 feet. At the intersecting points read HW = 6.9 feet and $HW + S_oL = 9.7$ feet on the vertical scale.

The inlet control headwater depth is equal to 6.9 feet. To obtain the outlet control headwater depth, subtract $S_o \times L$ from the outlet control figure.

$$9.7 - (0.0075 \times 400) = 6.7 \text{ feet}$$

Since the inlet control headwater depth of 6.9 feet is larger than the outlet control headwater depth of 6.7 feet, inlet control governs.

Repeat the same procedure for corrugated metal pipe arch until a pipe size is found which will handle the design discharge within the allowable headwater depth. From Figures 16, 18 and 20, the following headwater depths are obtained:

Pipe Size	Equiv. Circular	HW Inlet Control	HW Outlet Control	Control Condition	Control HW
40×65	54″	12.5′	29.0−3=26.0′	Outlet	26.0′
44×72	60″	9.1′	19.1−3=16.1′	Outlet	16.1′
49×79	66″	7.3′	13.0−3=10.0′	Outlet	10.0′

Since all of the controlling headwater depths are considerably higher than the allowable, try the next larger size.

Enter Figure 22: **54 × 85-Inch Corrugated Metal Pipe Arch,** and project a vertical line from Q = 200 on the horizontal scale to the INLET CONTROL curve and the OUTLET CONTROL curve representing L = 400 feet. At the intersecting points, read HW = 5.5 feet and $HW + S_oL = 9.9$ feet on the vertical scale.

The inlet control headwater depth is equal to 5.5 feet. To obtain the outlet control headwater depth, subtract $S_o \times L$ from the outlet control figure.

$$9.9 - (0.0075 \times 400) = 6.9 \text{ feet}$$

Since the outlet control headwater depth of 6.9 feet is larger than the inlet control headwater depth of 5.5 feet, outlet control governs.

Answer: A 43 × 68-inch horizontal elliptical concrete pipe (equivalent 54-inch circular) or a 54 × 85-inch corrugated metal pipe arch (equivalent 72-inch circular) would be required.

The concrete pipe is operating under inlet control and the corrugated metal pipe is operating under outlet control.

18-INCH CIRCULAR

FIGURE 3: 14 x 23-Inch Horizontal Elliptical Concrete Pipe

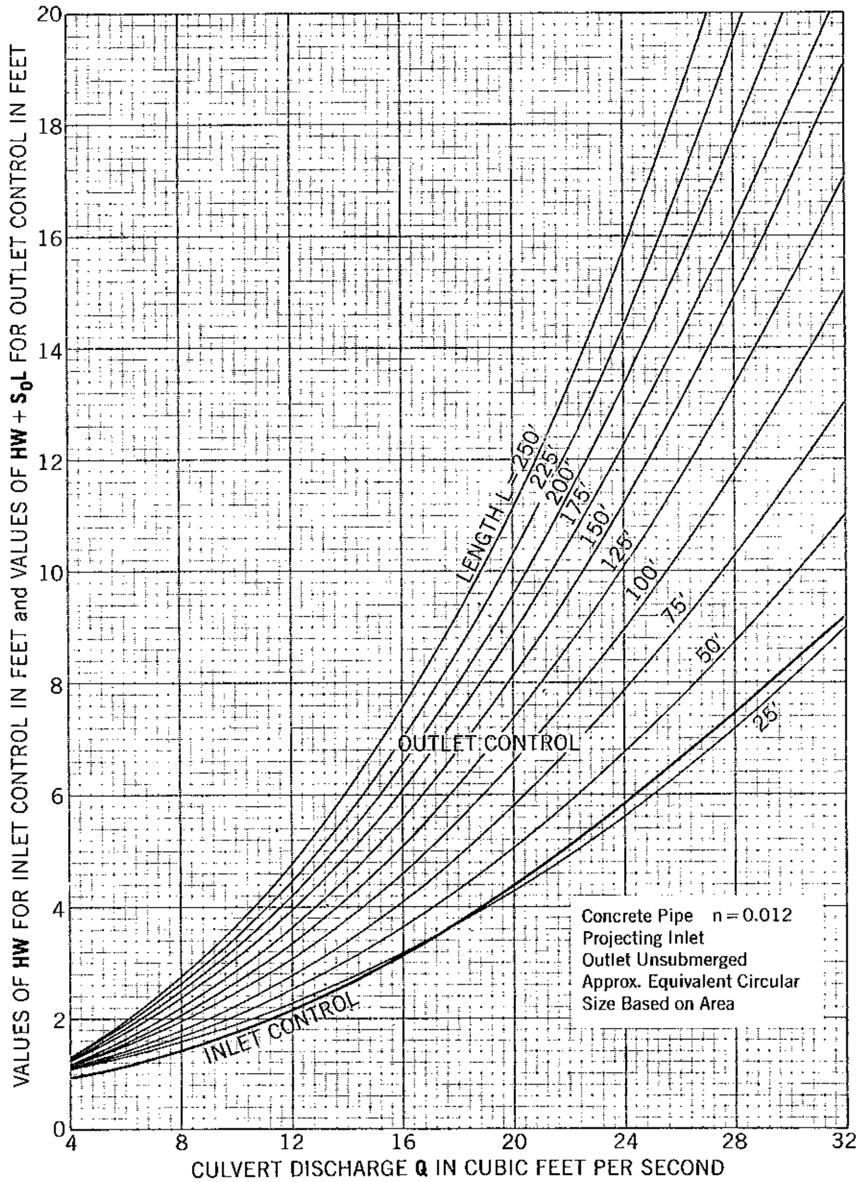
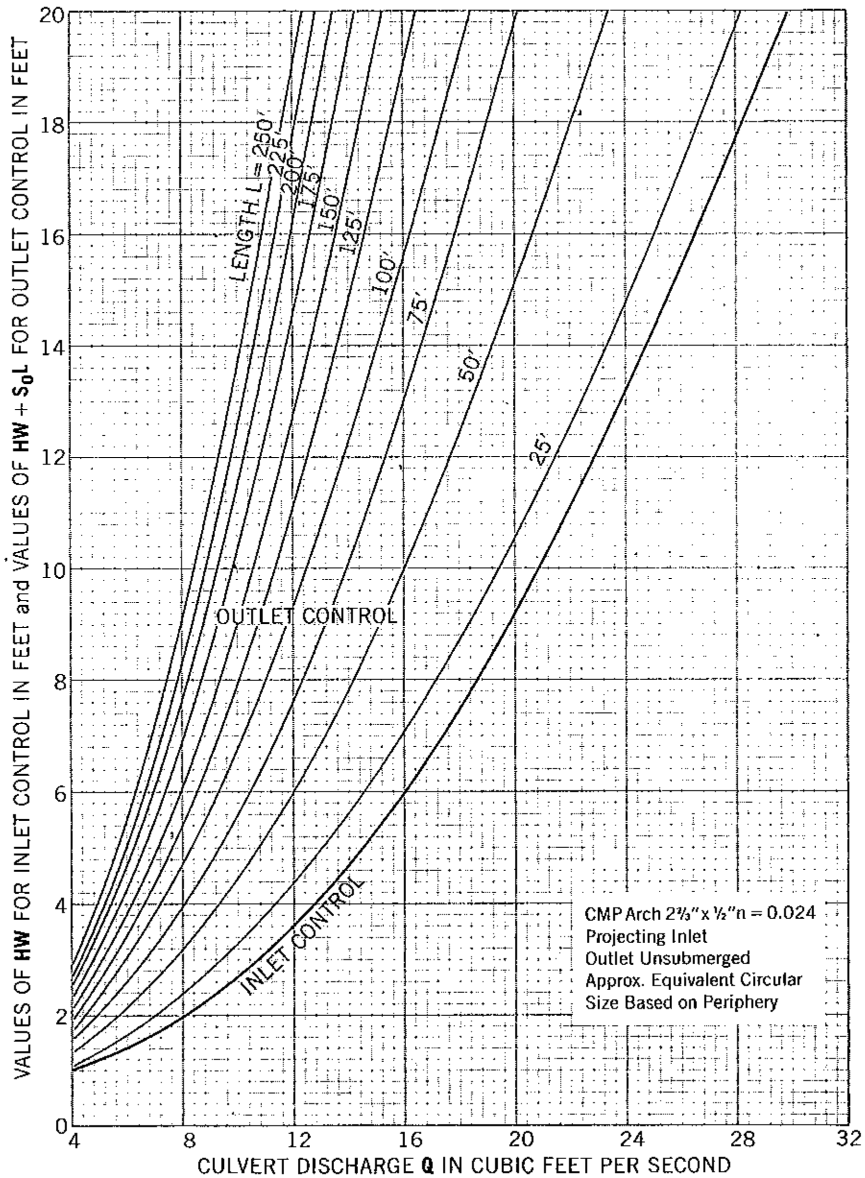


FIGURE 4: 13 x 22-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths

24-INCH CIRCULAR

FIGURE 5: 19 x 30-Inch Horizontal Elliptical Concrete Pipe

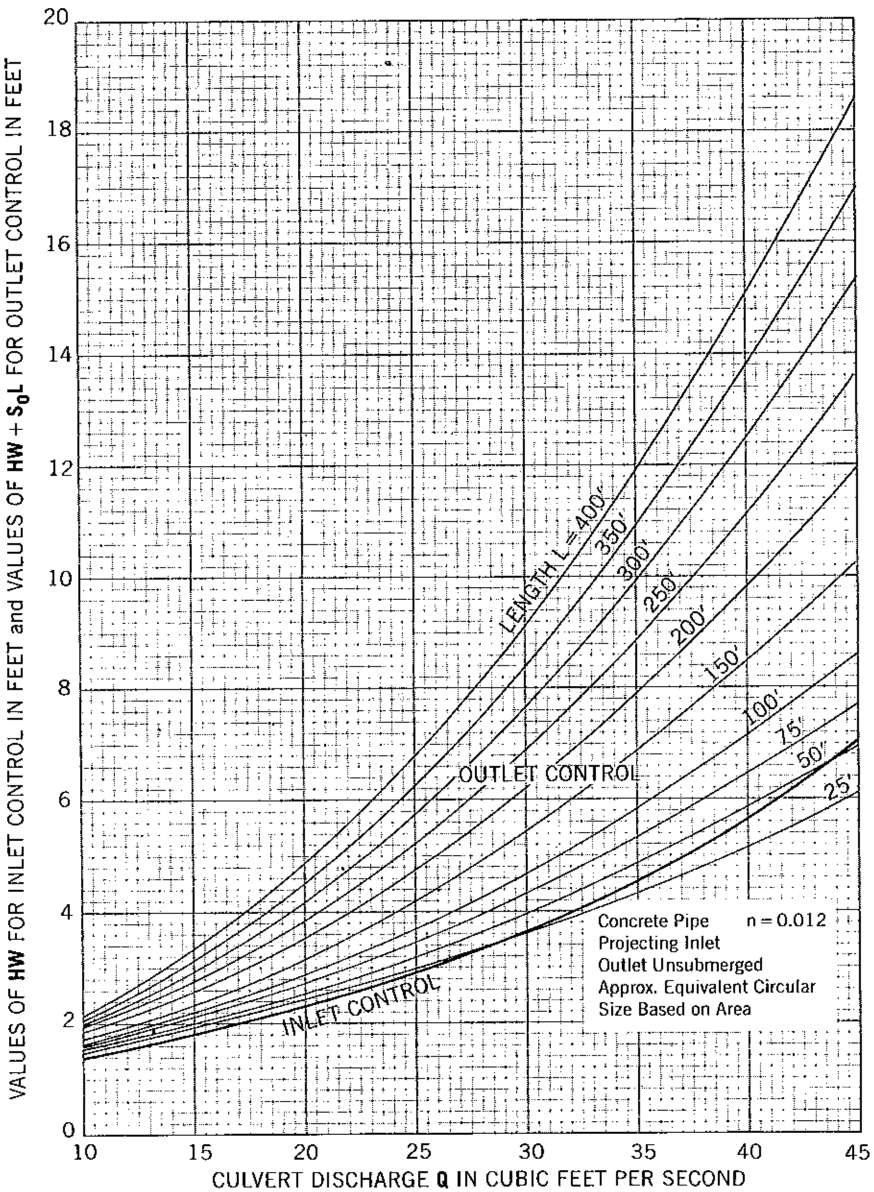
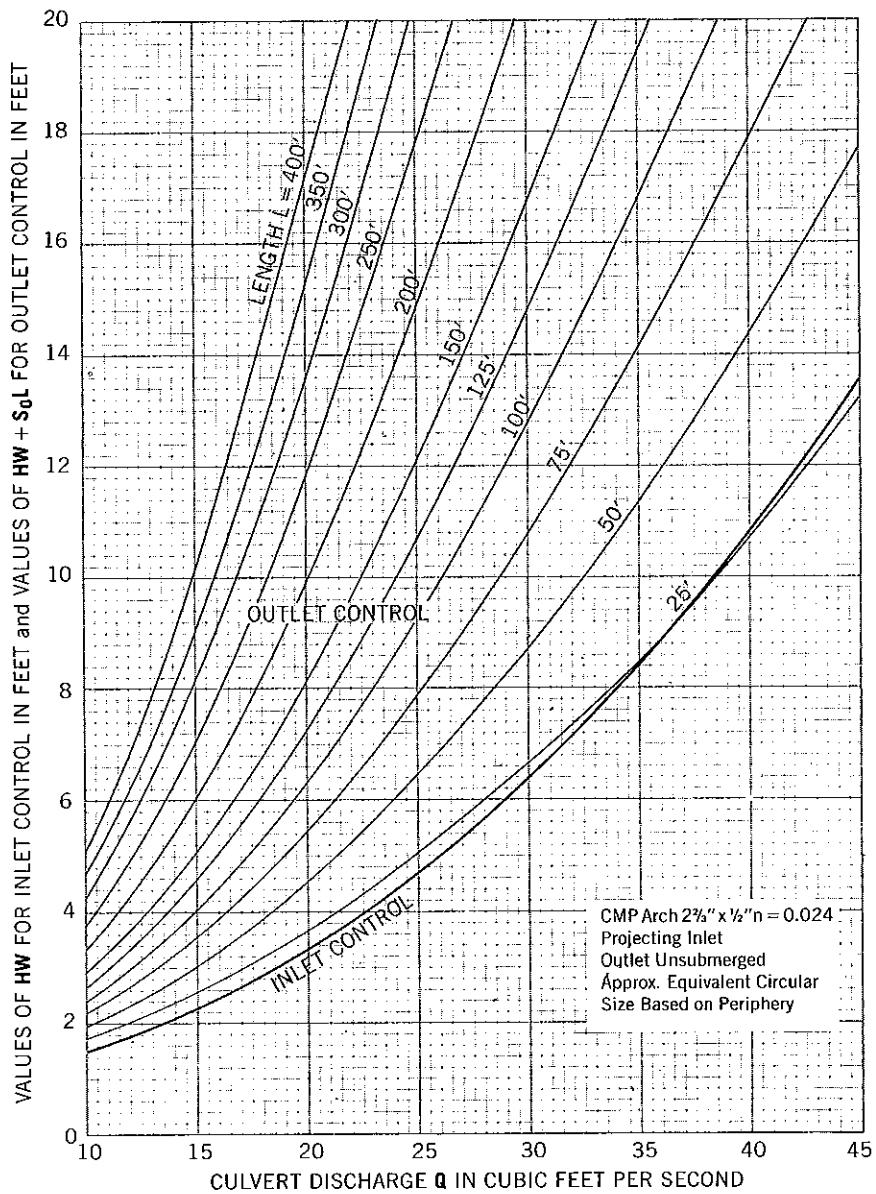


FIGURE 6: 18 x 29-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths

FIGURE 7: 24 x 38-Inch Horizontal Elliptical Concrete Pipe

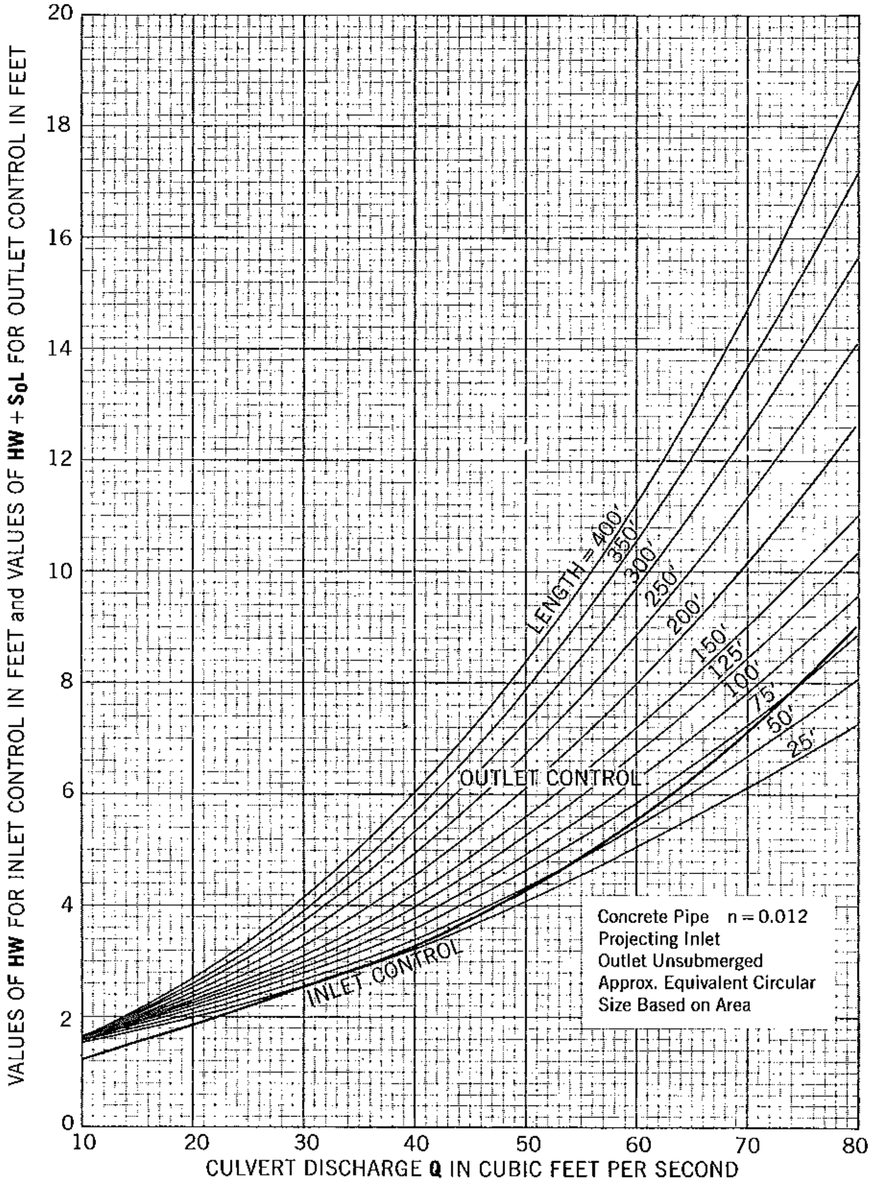
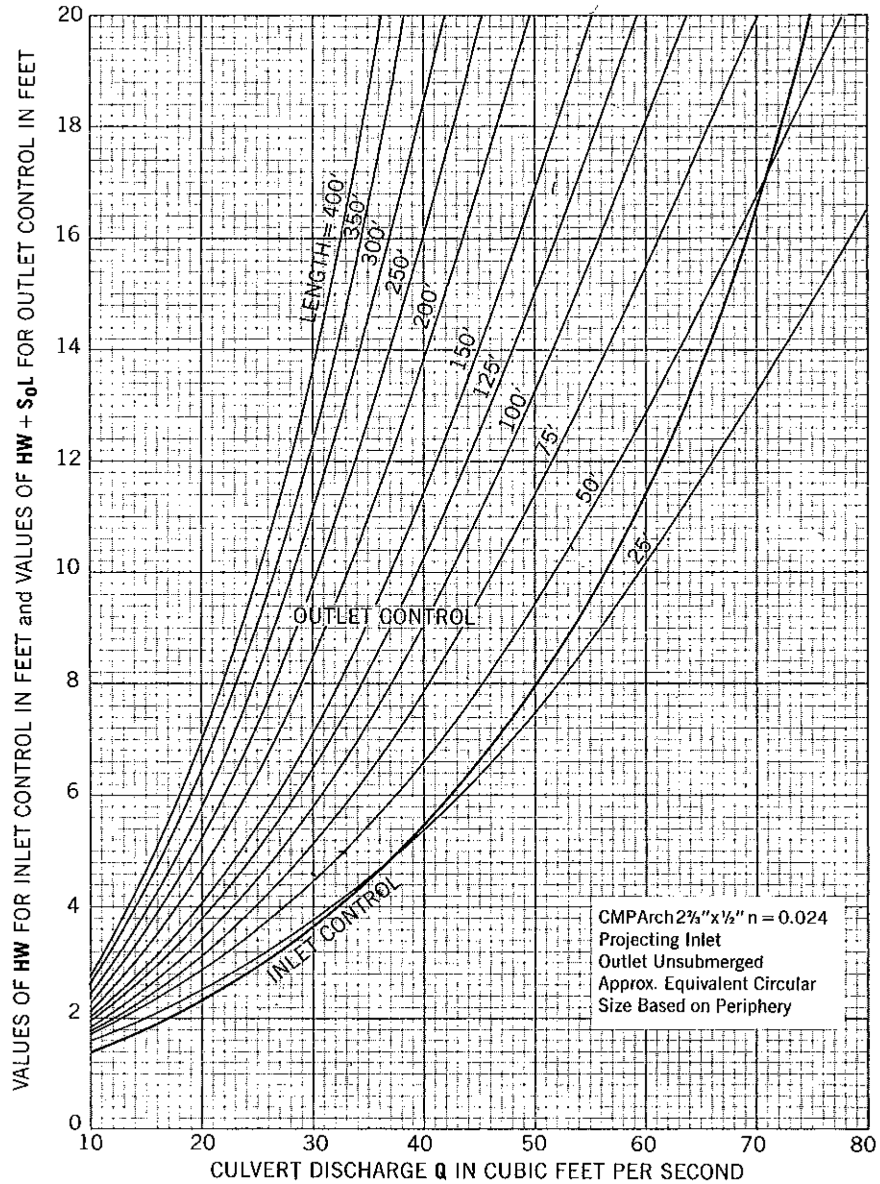


FIGURE 8: 22 x 36-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths

FIGURE 9: 29 x 45-Inch Horizontal Elliptical Concrete Pipe

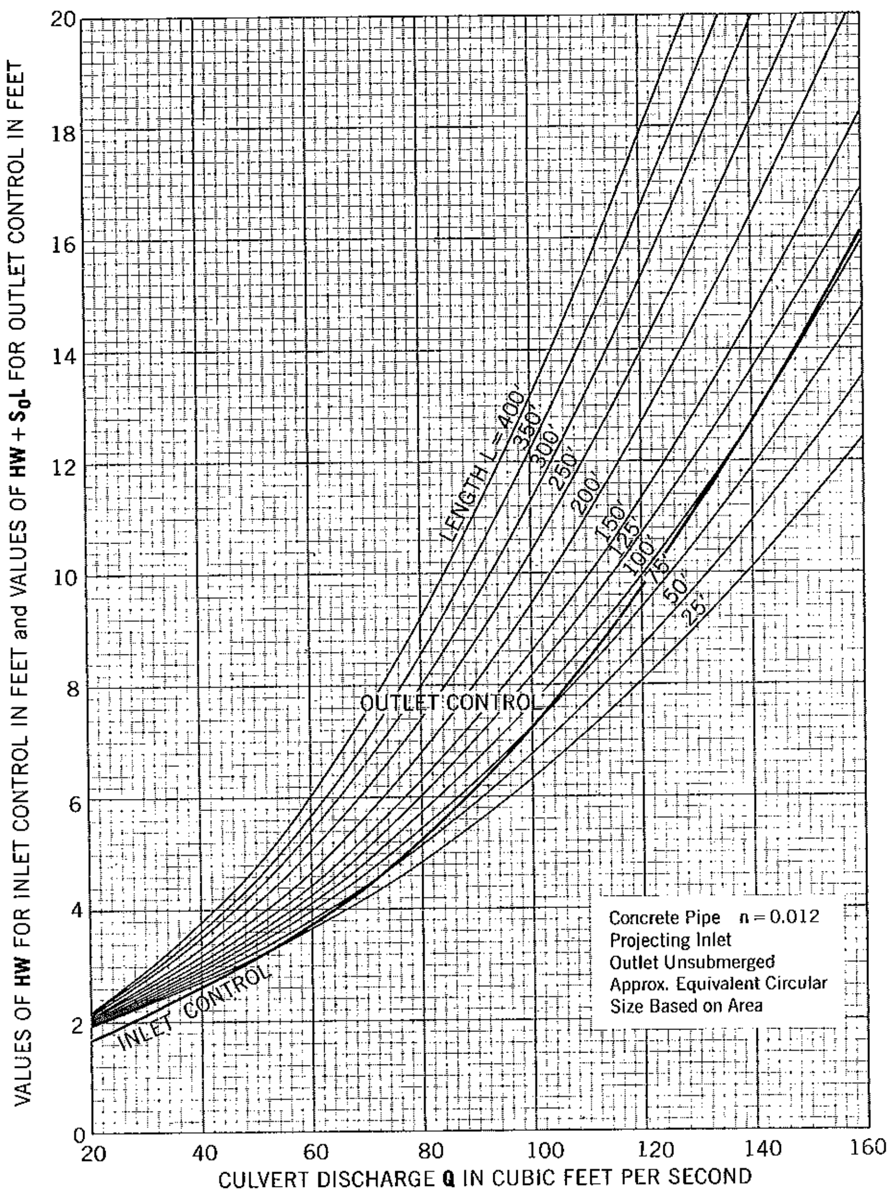
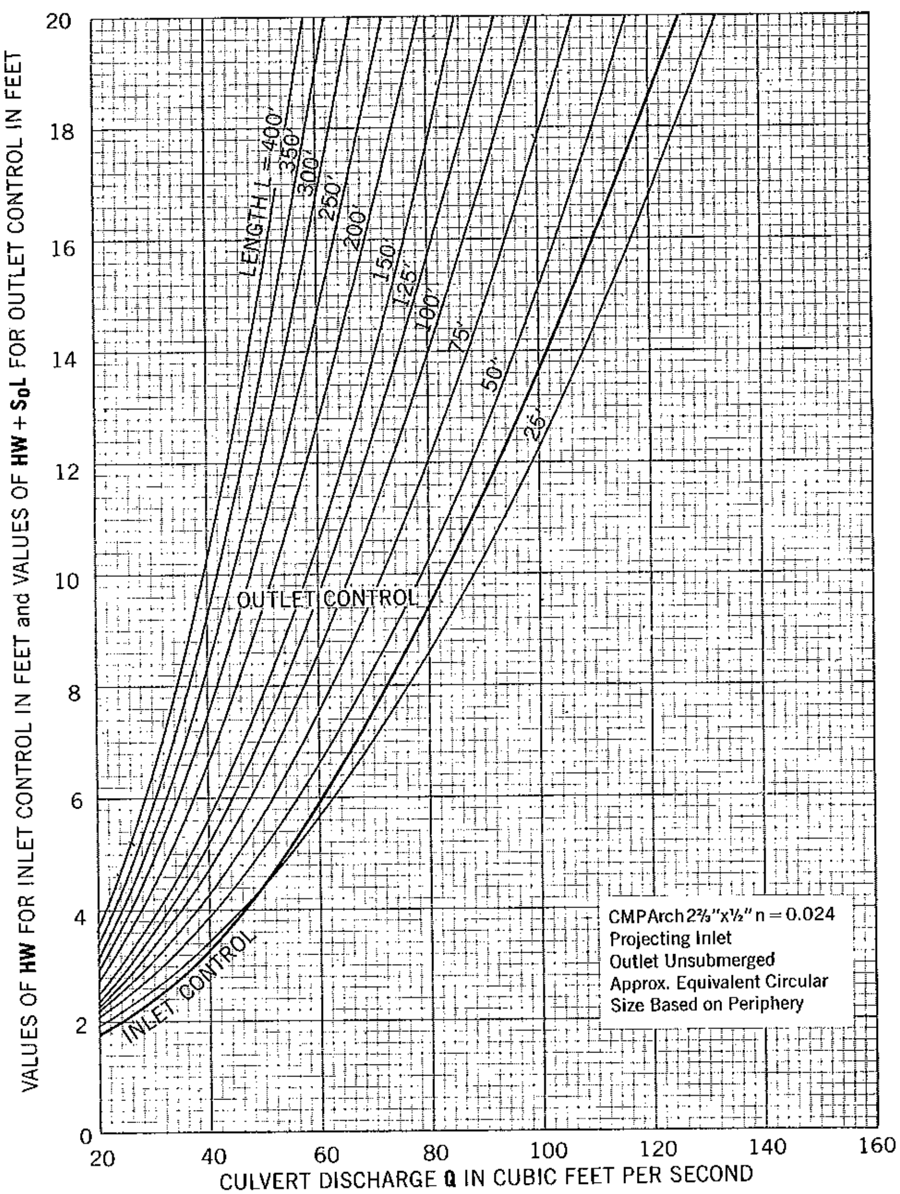


FIGURE 10: 27 x 43-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths

42-INCH CIRCULAR

FIGURE 11: 34 x 53-Inch Horizontal Elliptical Concrete Pipe

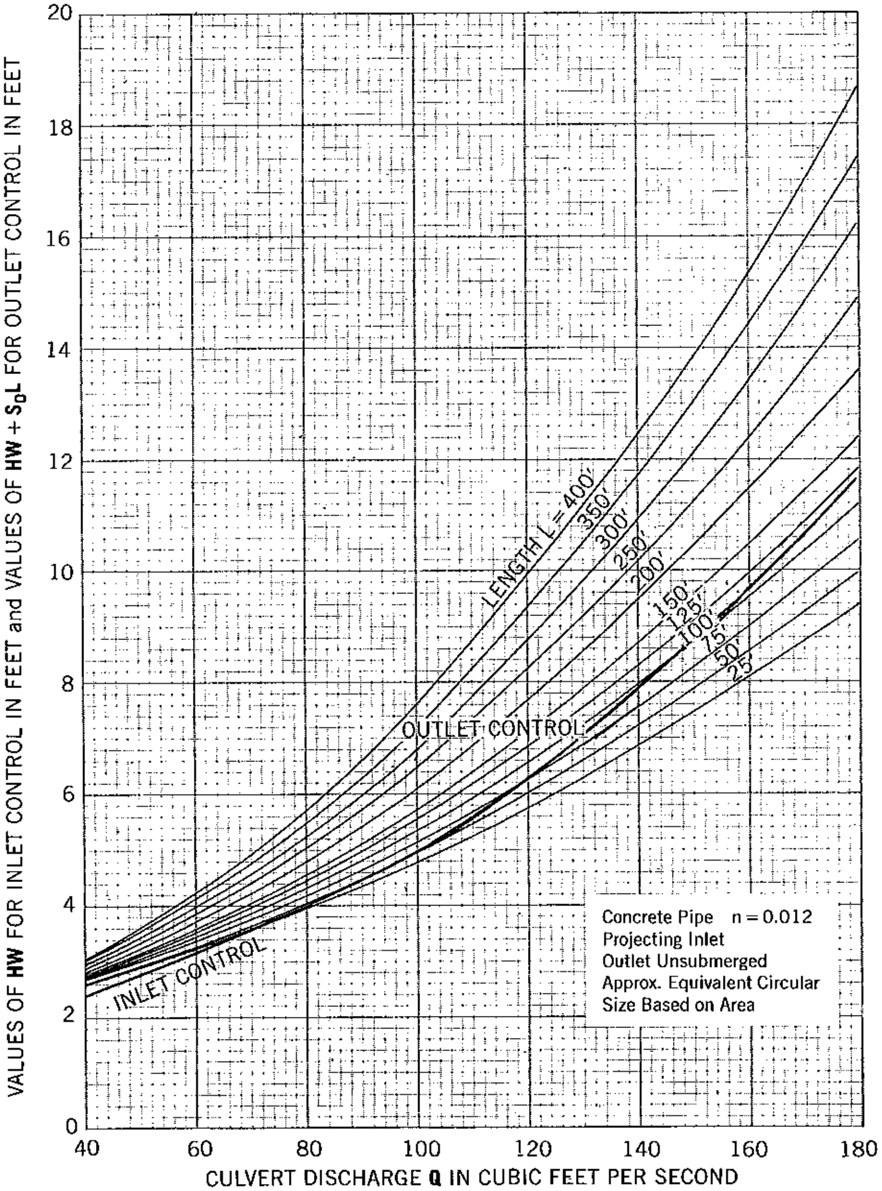
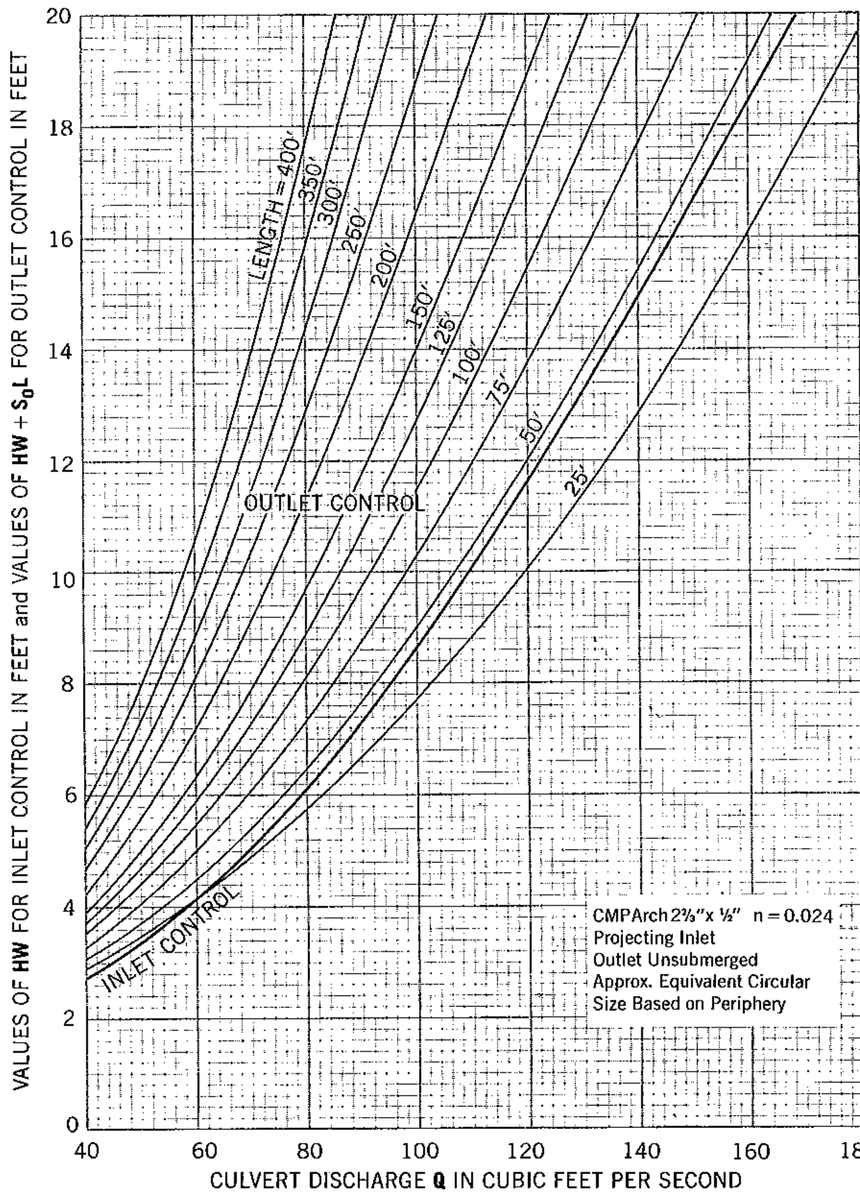


FIGURE 12: 31 x 50-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths

48-INCH CIRCULAR

FIGURE 13: 38 x 60-Inch Horizontal Elliptical Concrete Pipe

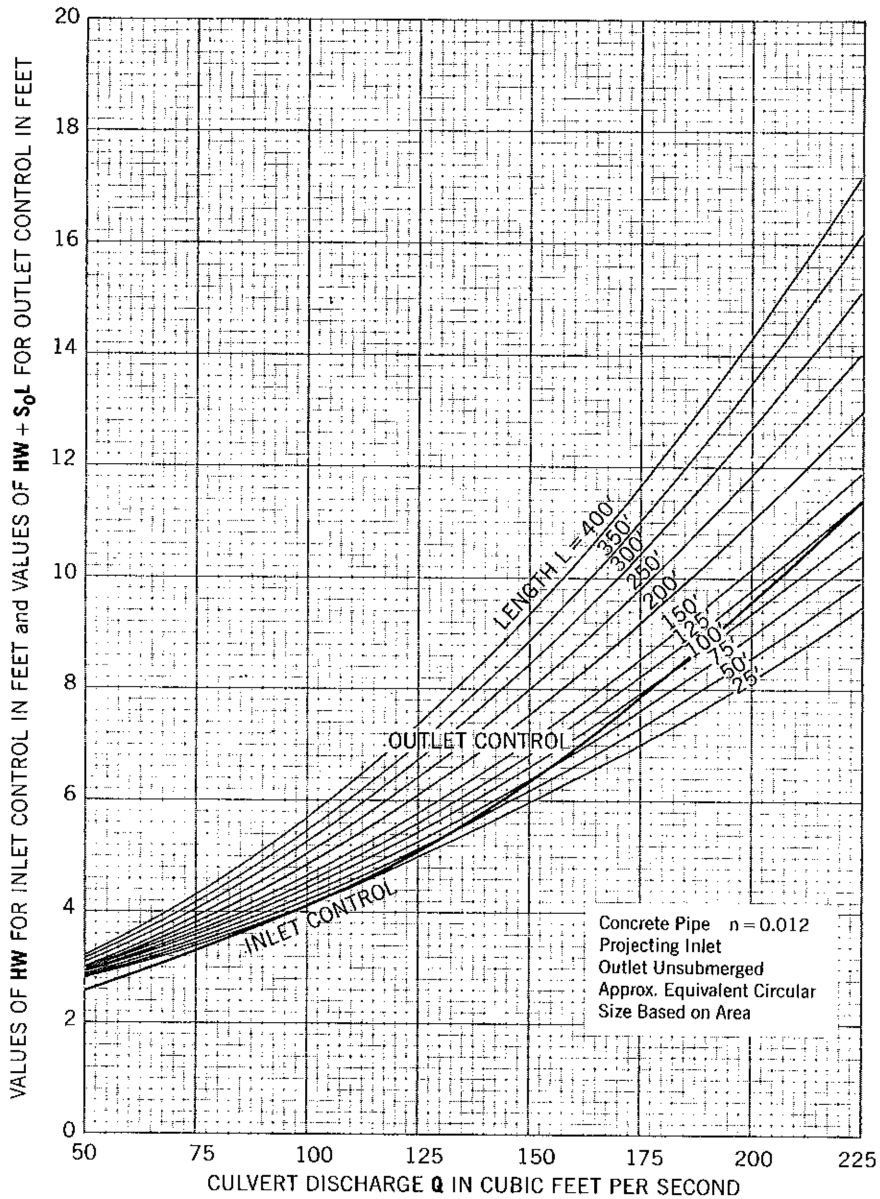
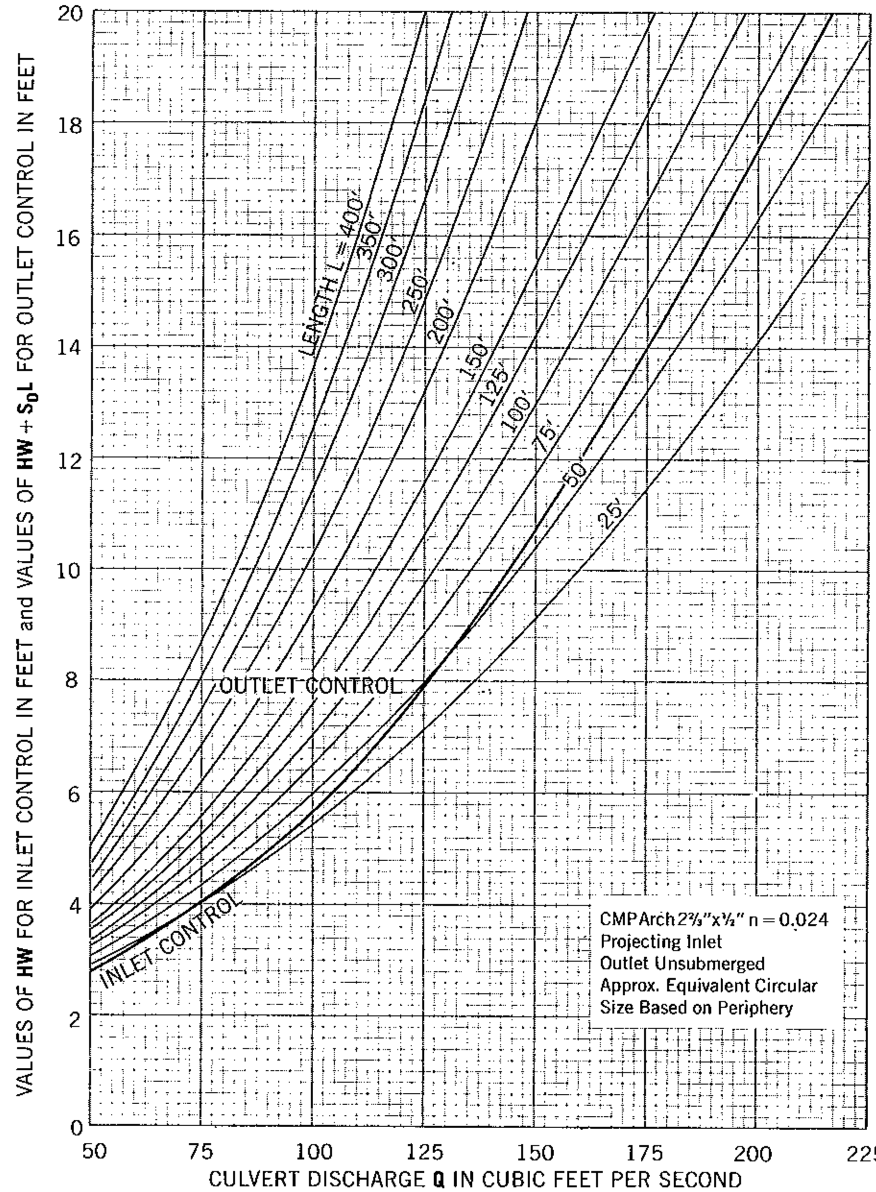


FIGURE 14: 36 x 58-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths

FIGURE 15: 43 x 68-Inch Horizontal Elliptical Concrete Pipe

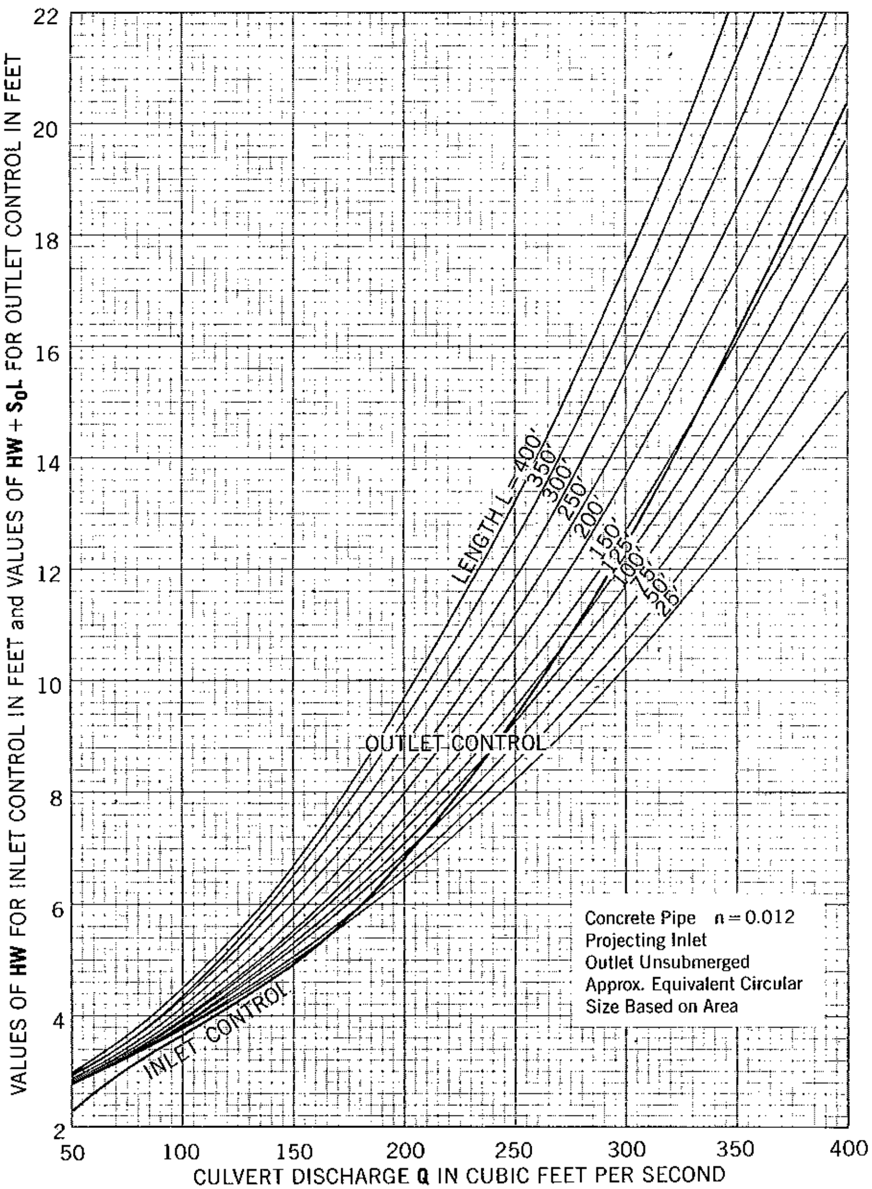
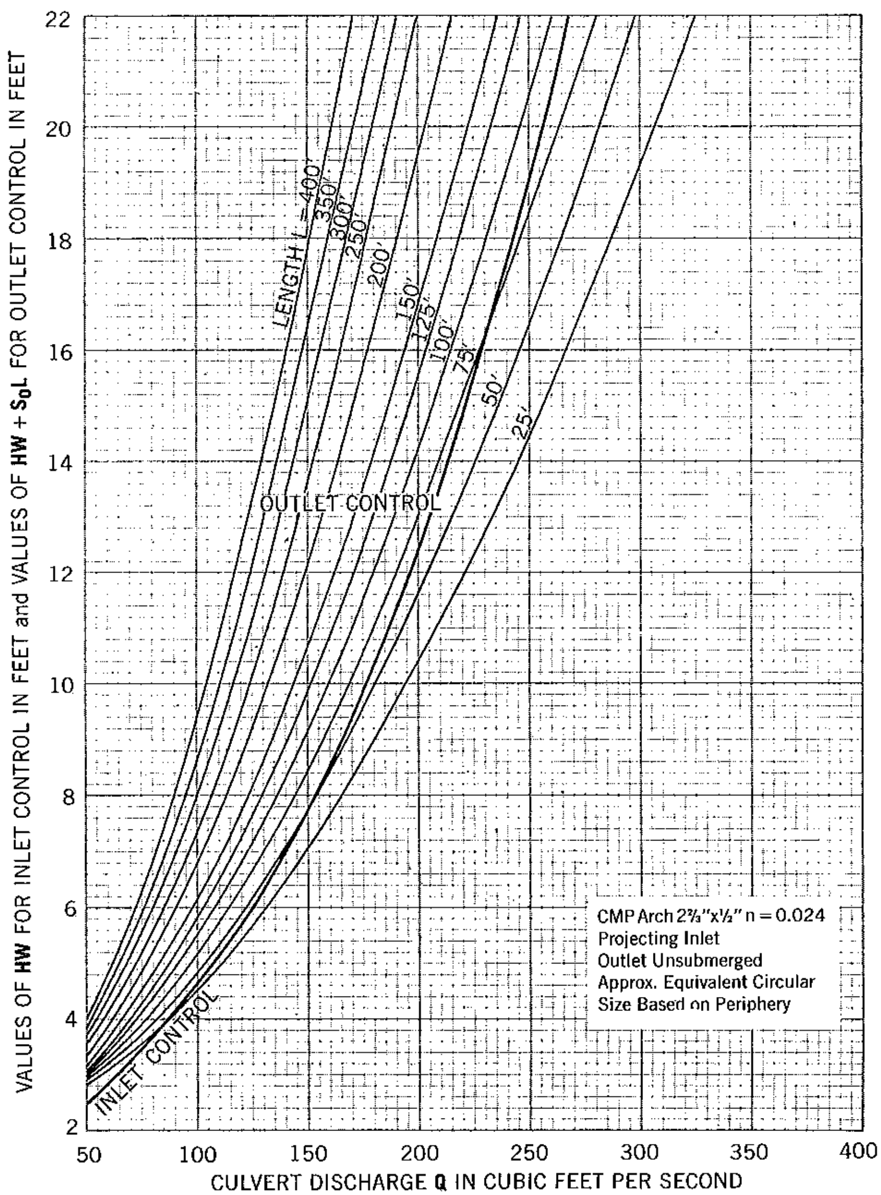


FIGURE 16: 40 x 65-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths

60-INCH CIRCULAR

FIGURE 17: 48 x 76-Inch Horizontal Elliptical Concrete Pipe

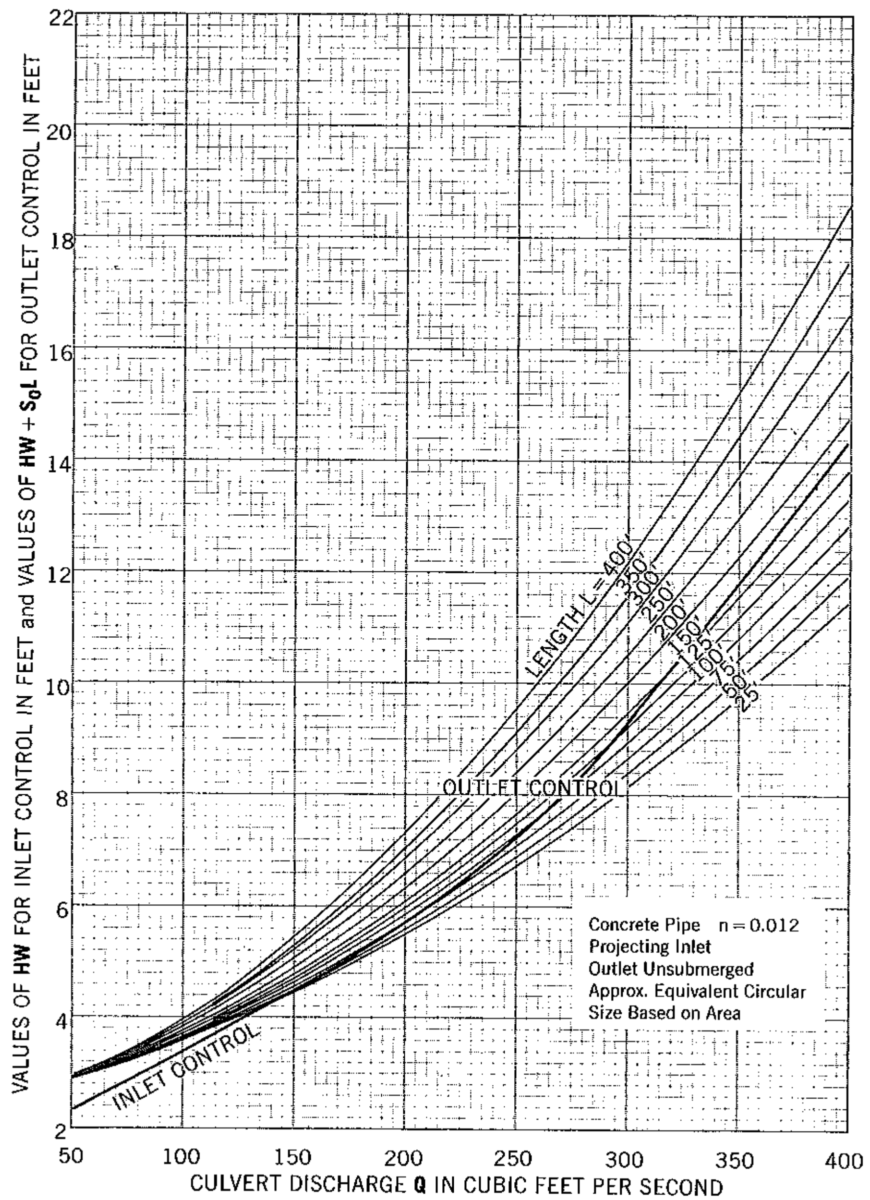
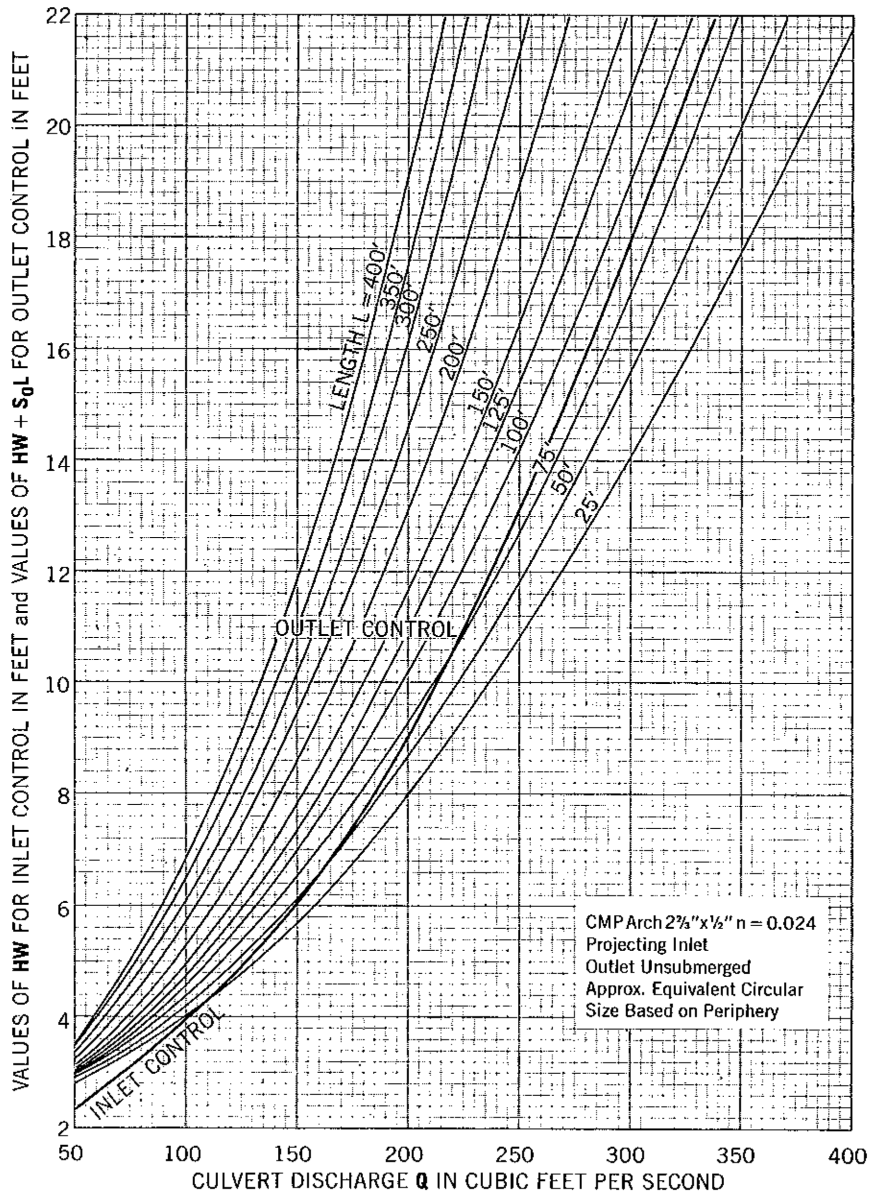


FIGURE 18: 44 x 72-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths

FIGURE 19: 53 x 83-Inch Horizontal Elliptical Concrete Pipe

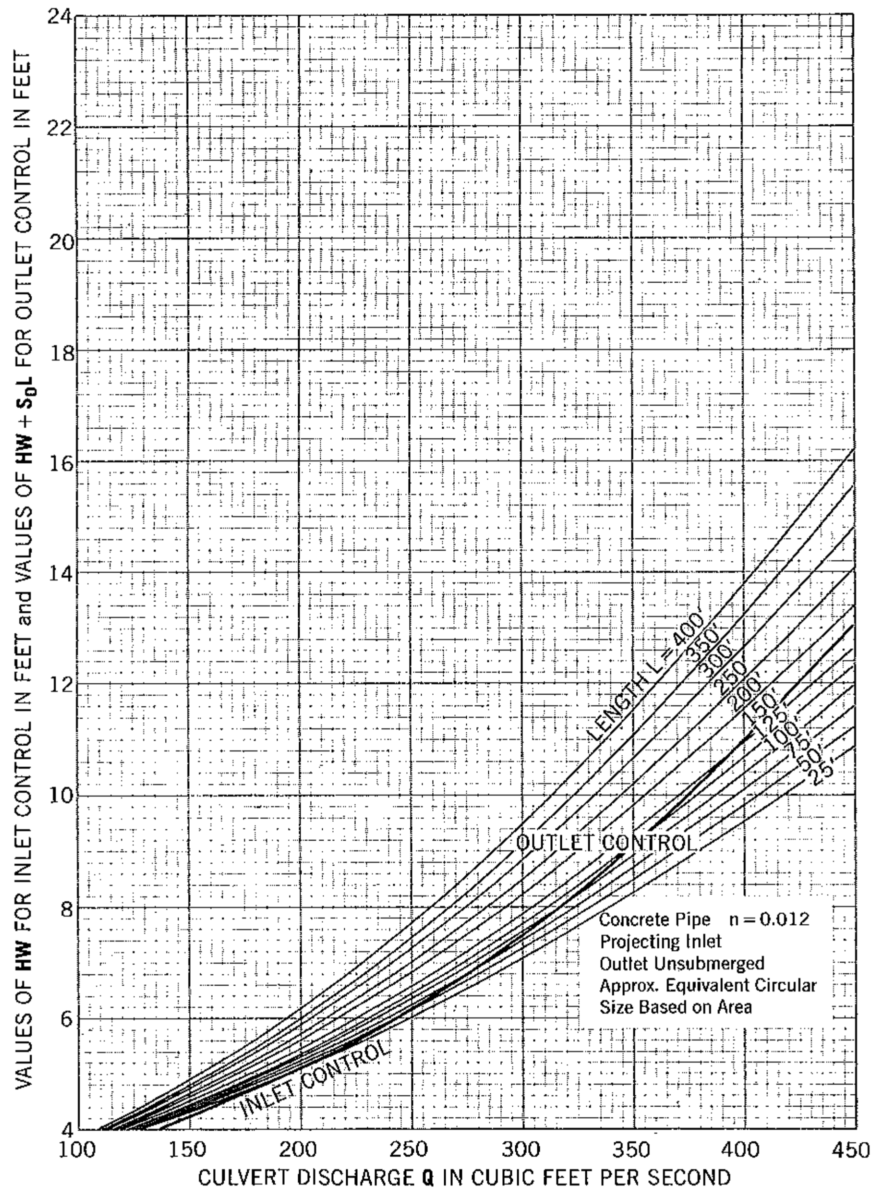
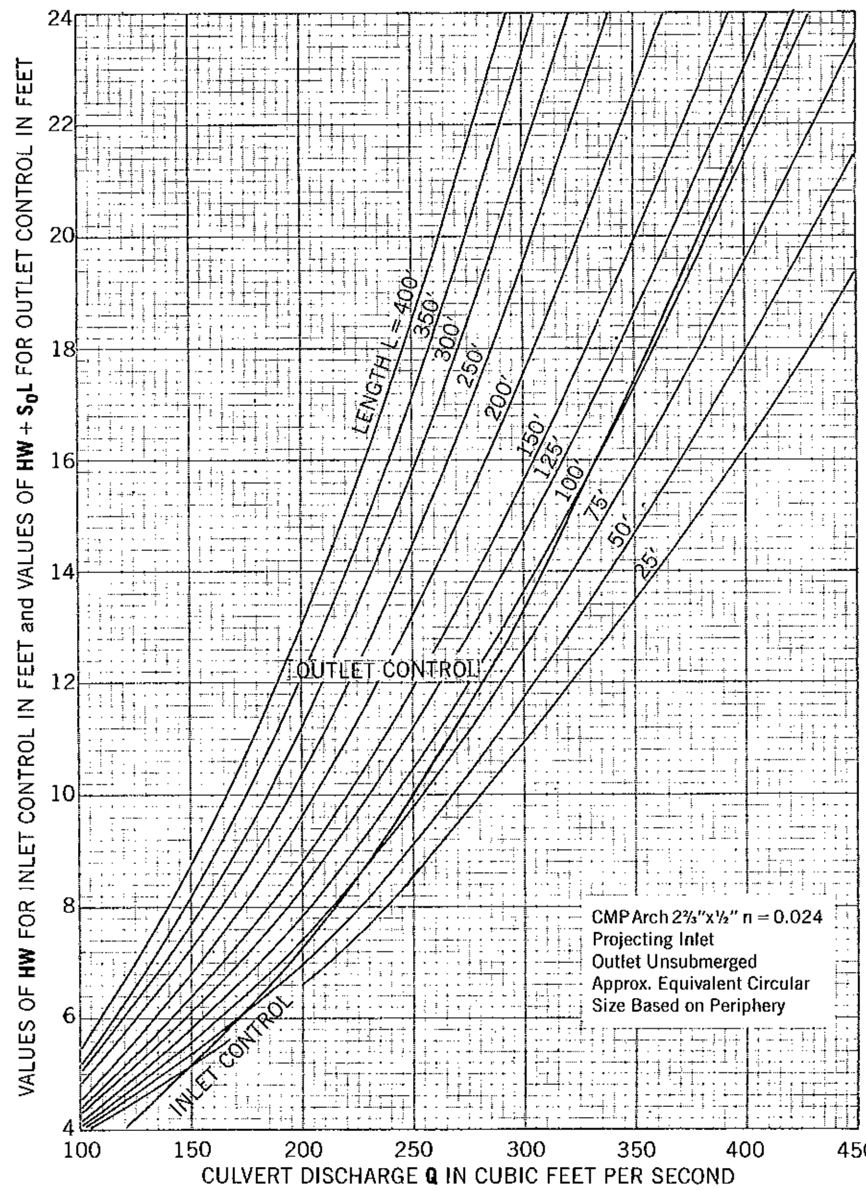


FIGURE 20: 49 x 79-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths

72-INCH CIRCULAR

FIGURE 21: 58 x 91-Inch Horizontal Elliptical Concrete Pipe

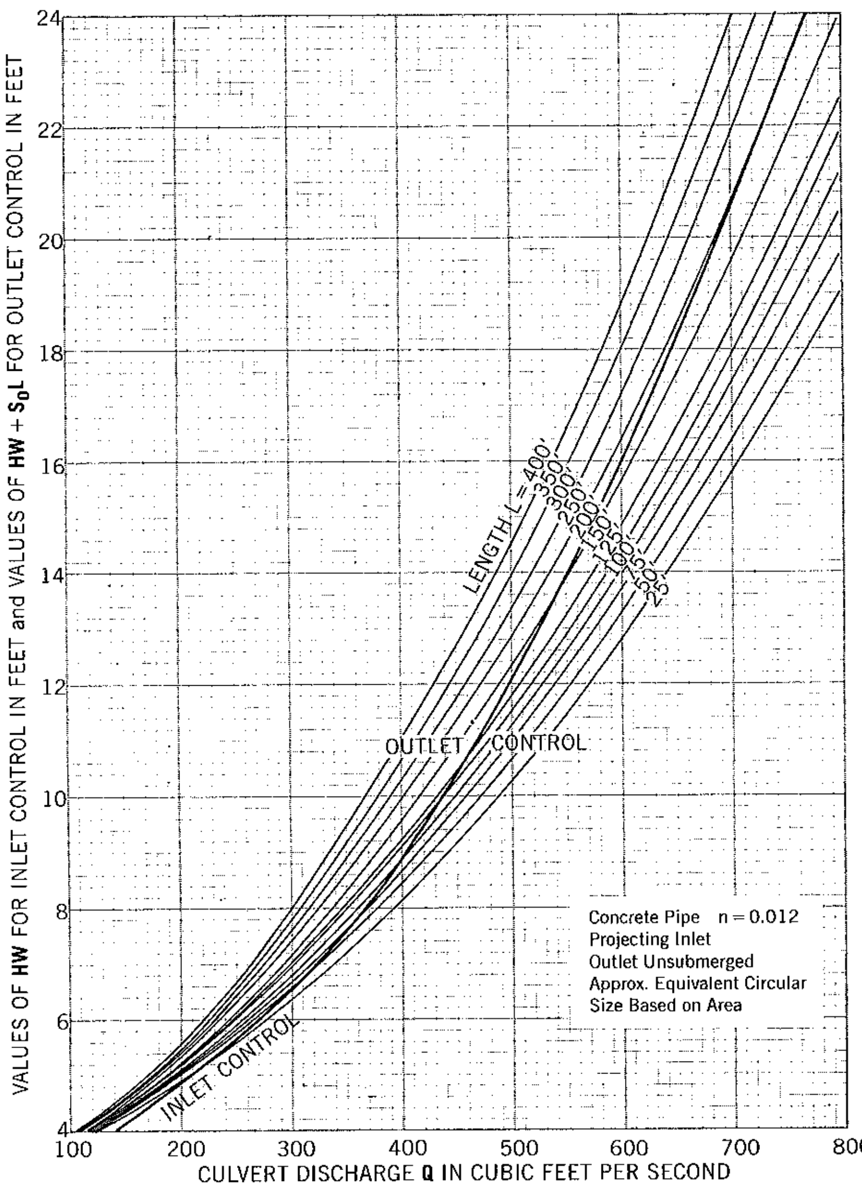
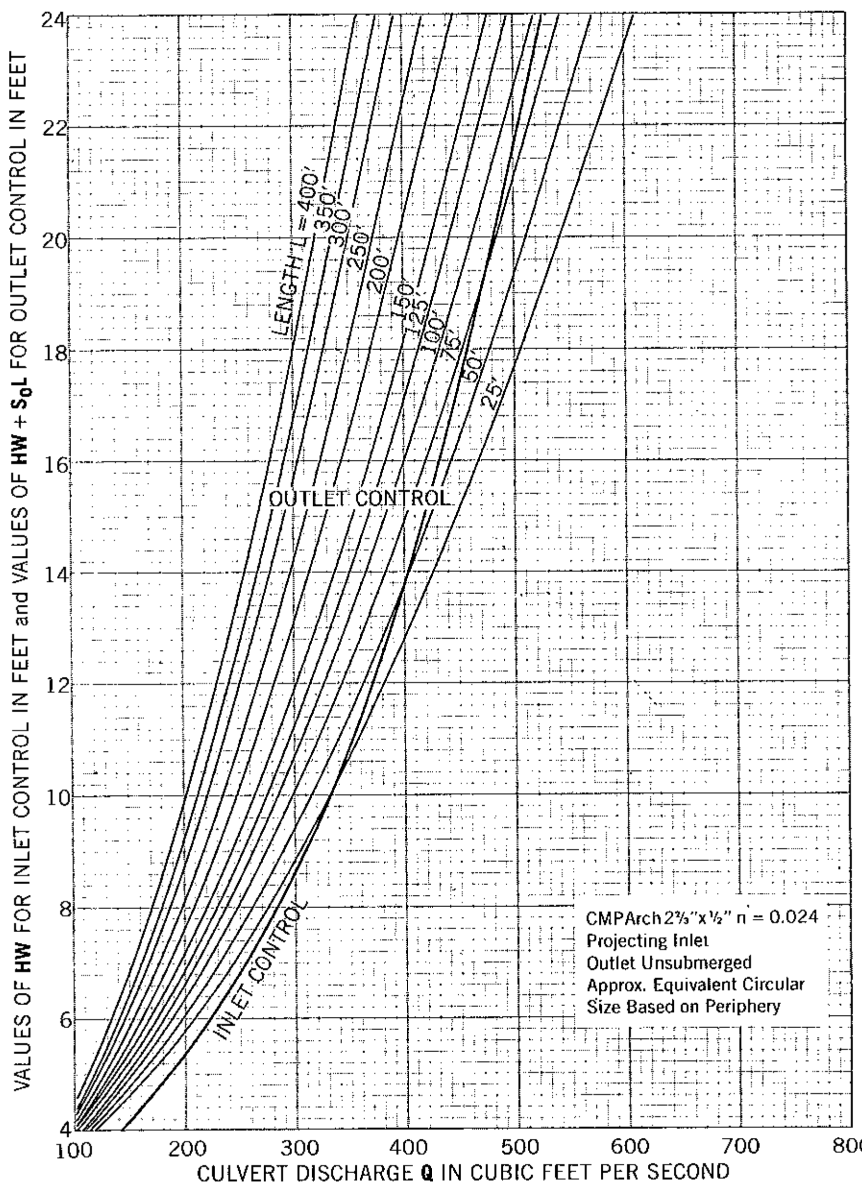


FIGURE 22: 54 x 85-Inch Corrugated Metal Pipe Arch



Interpolate for intermediate culvert lengths