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design data 8

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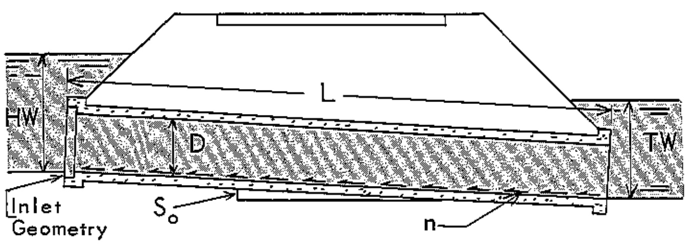
HYDRAULICS OF CULVERTS: 12-Inch Through 21-Inch Diameter Pipe

Culvert structures represent a significant portion of total highway construction costs. If each culvert installation is considered separately, a proper perspective of relative costs may not be readily apparent. However, if the overall highway drainage field is considered, it is found that drainage facilities represent 17.5 percent of the total $8 billion annual expenditure for new highway construction. Over one-third of all funds for highway drainage facilities, including bridges, is spent on culverts. This represents an annual culvert expenditure of approximately $500 million. Expenditures of this magnitude demand the application of modern engineering technology to assure that an efficient structure consistent with economy, adequacy and installation requirements is obtained. To accomplish this, all culvert designs should include an analysis based on sound hydraulic principles. The analysis should evaluate all of the factors which influence the flow of water through a culvert.

The major 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:

a. Geometry of the inlet;
b. Combined influence of size, shape, slope and surface roughness of the culvert pipe;
c. Tailwater conditions at the outlet.

FIGURE 1: Factors Affecting Culvert Capacity



D = inside diameter for circular 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

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 pass through the culvert at a greater rate than water can enter through the inlet. Since the control section is at the inlet, the capacity is not affected by any hydraulic factors beyond the culvert entrance such as pipe slope, length or surface roughness. Culverts operating under inlet control will always flow part full.

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. Culverts operating under outlet control can flow either part full or full.

An important consideration in the hydraulic design of culverts flowing part full is *critical slope.* Critical slope is the minimum slope at which maximum discharge will be realized without causing the culvert to flow full. Culverts installed on slopes less than critical will approach full flow at relatively low headwater depths and require correspondingly higher headwater depths to carry the same amount of water as culverts placed on slopes greater than critical slope. The classification of culverts by steep slope or flat slope is dependent on whether the actual slope is greater or less than critical slope.

The general operating characteristics of culverts are illustrated in *Figure 2* for culverts installed on relatively steep slopes and in *Figure 3* for culverts installed on relatively flat slopes. The breakpoint between steep and flat slopes, as related to critical slope, varies with discharge, pipe diameter and pipe roughness. However, for smooth-walled pipe, such as concrete, the critical slope is relatively flat and varies between 1.0 percent and 1.8 percent. For rough-walled pipe such as corrugated metal, the critical slope is much steeper, with the usual range between 4 percent and 7 percent.

As illustrated in *Figure 2a,* culverts installed on steep slopes will operate under inlet control with the inlet unsubmerged. As the headwater builds up and submerges the entrance, the culvert will continue to operate under inlet control (*Figure 2b*) because of the contracted flow. The degree of contraction is determined by the inlet geometry. When the depth of flow increases to the point where the culvert flows full (*Figure 2c*) the culvert will then operate with outlet controlled flow.

As illustrated in *Figure 3a,* culverts installed on flat slopes can operate under either inlet control or outlet control with the inlet unsubmerged. If the slope is insufficient to compensate for the resistant friction of the pipe wall, the culvert will operate with outlet control. If the slope of the culvert is steep enough to compensate for the frictional losses, the culvert will operate with inlet control. If inlet control governs, as the headwater builds up and submerges the entrance (*Figure 3b*), the culvert will continue to operate with inlet control at higher discharges. Inlet control will continue to exist until the frictional forces along the pipe wall become large enough to overcome the contracted flow at the entrance (*Figure 3c*) resulting in an outlet controlled type of flow. If outlet control governs, with the inlet unsubmerged, the culvert will continue to flow under outlet control (*Figure 3c*) at larger headwater depths and discharges.

The type of control a culvert will operate under for any given set of conditions can be definitely estab-

FIGURE 2: Operating Sequence of Culverts Installed on Relatively Steep Slopes

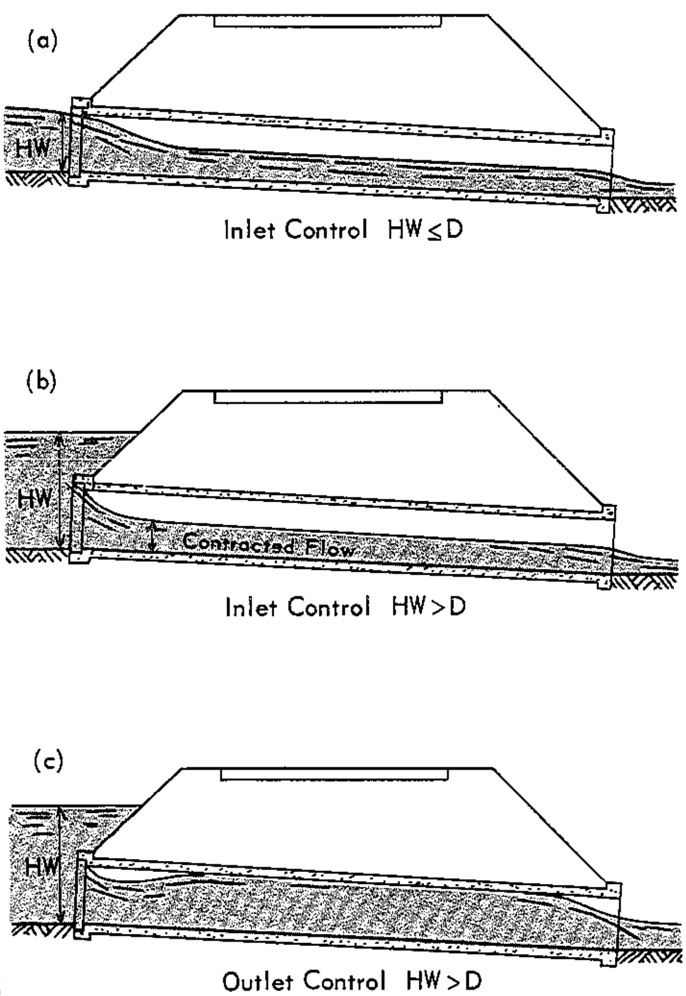
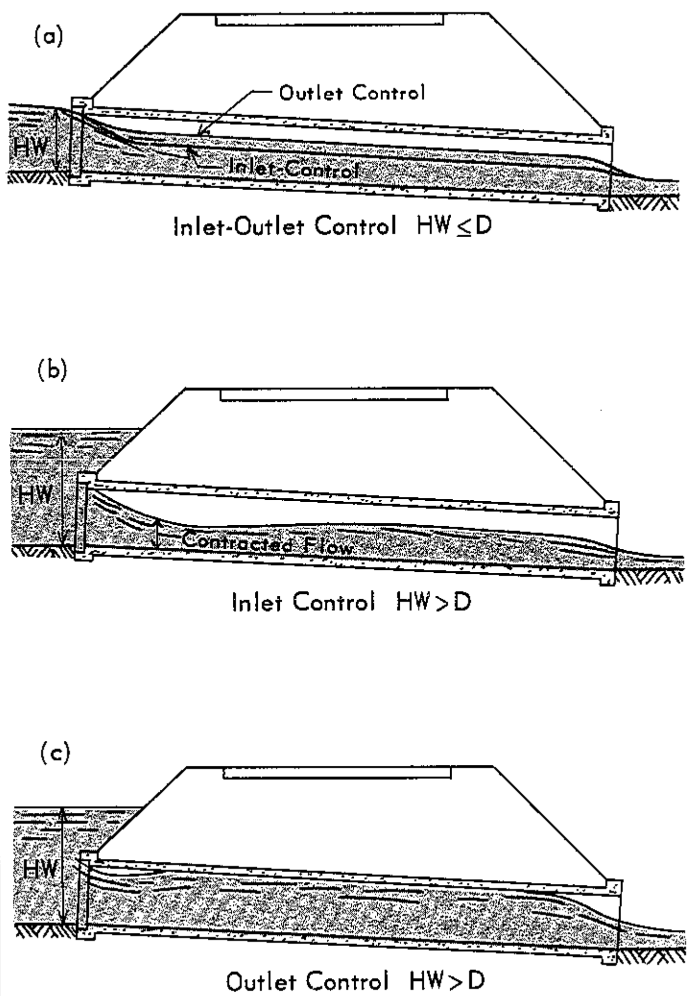


FIGURE 3: Operating Sequence of Culverts Installed on Relatively Flat Slopes



lished through detailed analysis. 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 can greatly reduce the time consuming mathematical calculations. Performance curves given in *Figures 4 through 11* enable the selection of required pipe size within the practical ranges of allowable headwater depths and design discharges. By determining the headwater depth for both inlet control and outlet control, the higher value can be used to indicate the type of control. *Figures 4 through 11* are based on monographs included in *Hydraulic Engineering Circular Number 5,* prepared by the Hydraulics Branch, Bridge Division, Office of Engineering, Federal Highway Administration.

The headwater depths for inlet controlled flow are read directly from the performance curves. For outlet controlled flow it is necessary to subtract the product of the culvert length and slope from the headwater depth. The following examples illustrates the proper use of the curves:

EXAMPLE 1

Given: A 25-foot-long drive culvert is to be installed on 0.5 percent slope. The culvert will be required to carry a discharge of 5.0 cubic feet per second within an allowable headwater depth of 2.0 feet.

Find: Size of concrete pipe and corrugated metal pipe required and type of control.

Solution: Enter *Figure 4, 12-Inch Diameter Concrete Pipe,* and project a vertical line from Q=5.0 to the inlet control curve and outlet control curve representing L=25 feet. Read headwater depth of 1.92 for inlet control and 2.11 for outlet control. Subtract $S_0 \times L$ from the outlet control figure 2.11-(0.005×25)=1.98 feet.

Enter *Figure 7, 15-Inch Diameter Corrugated Metal Pipe,* and project a vertical line from Q=5.0 to the inlet control curve and outlet control curve representing L=25 feet. Read headwater depth of 1.64 for inlet control and 2.10 for outlet control. Subtract $S_0 \times L$ from the outlet control figure 2.10-(0.005×25) =1.97 feet.

Diameter	Type of Pipe	Required HW Inlet Control	Required HW Outlet Control	Control Condition	Control Headwater	Comment
12"	Concrete	1.92	1.98	Outlet	1.98	OK
15"	CMP	1.64	1.97	Outlet	1.97	OK

Answer: A 12-inch diameter concrete pipe or a 15-inch diameter corrugated metal pipe will carry the design discharge within the allowable headwater depth of 2.0 feet.

Since the outlet control headwater depths for both pipes are larger than the inlet control headwater depths, outlet control governs in both cases.

EXAMPLE 2

Given: A 100-foot long highway culvert is to be installed on a 1.0 percent slope. The culvert will be required to carry a discharge of 12.0 cubic feet per second within an allowable headwater depth of 5.0 feet.

Find: Size of concrete pipe and corrugated metal pipe required.

Solution: The following table gives required pipe sizes and corresponding headwater depths.

Diameter	Type of Pipe	Required HW Inlet Control	Required HW Outlet Control	Control Condition	Control Headwater	Comment
15"	Concrete	4.0	6.0-1.0=5.0	Outlet	5.0	OK
18"	CMP	3.2	7.3-1.0=6.3	Outlet	6.3	N.G.
21"	CMP	2.5	4.3-1.0=3.3	Outlet	3.3	OK

Answer: A 15-inch diameter concrete pipe or a 21-inch diameter corrugated metal pipe will carry the design discharge within the allowable headwater depth of 5.0 feet.

From the above examples it is seen that even for small diameter pipe a concrete pipe size up to two sizes smaller in diameter than a corrugated metal pipe is warranted.

FIGURE 4: 12-Inch Diameter Concrete Pipe

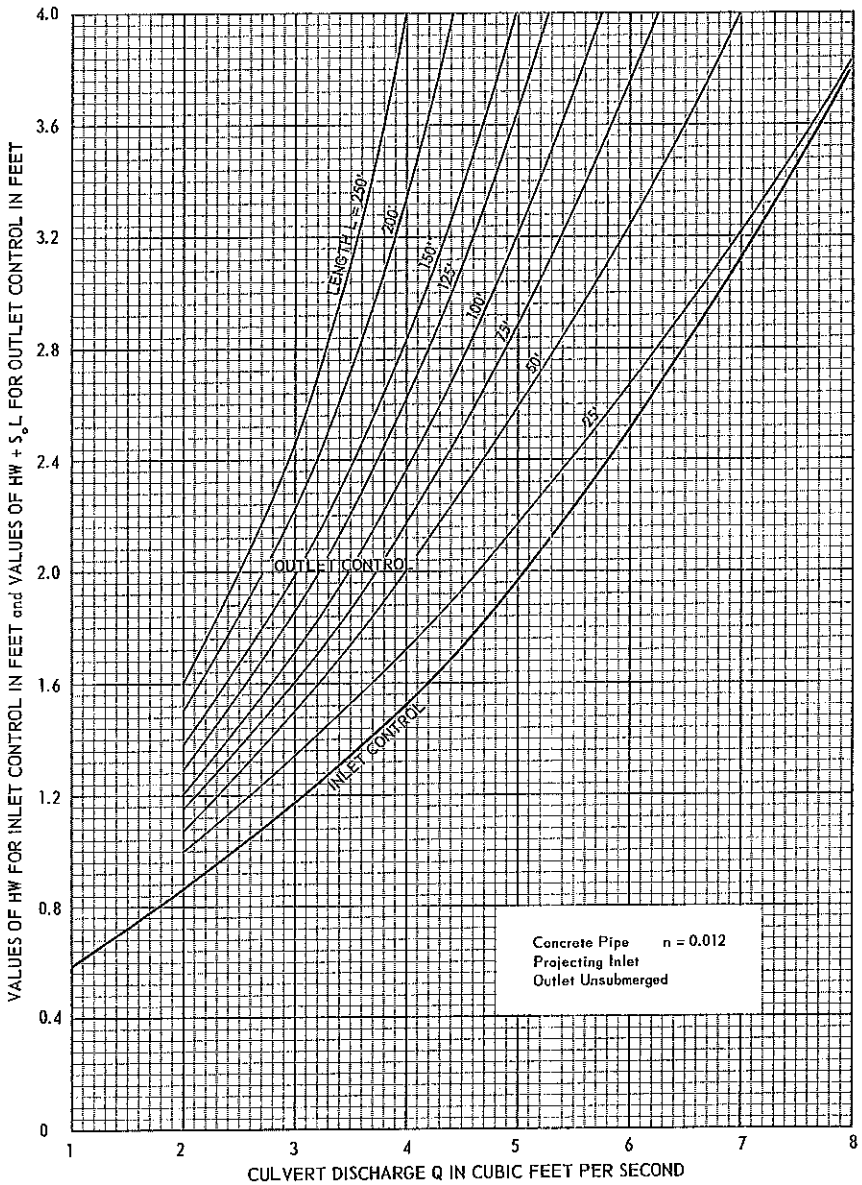
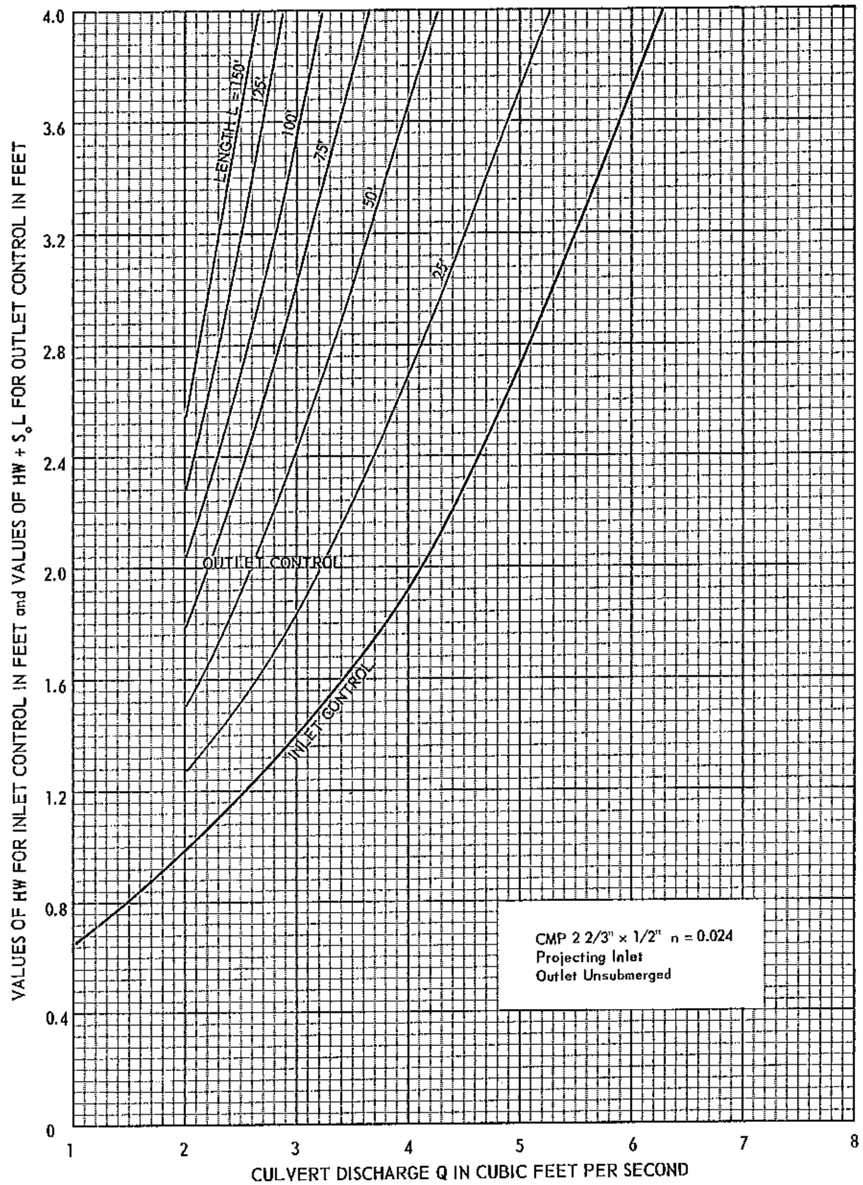


FIGURE 5: 12-Inch Diameter Corrugated Metal Pipe



Interpolate for intermediate culvert lengths

FIGURE 6: 15-Inch Diameter Concrete Pipe

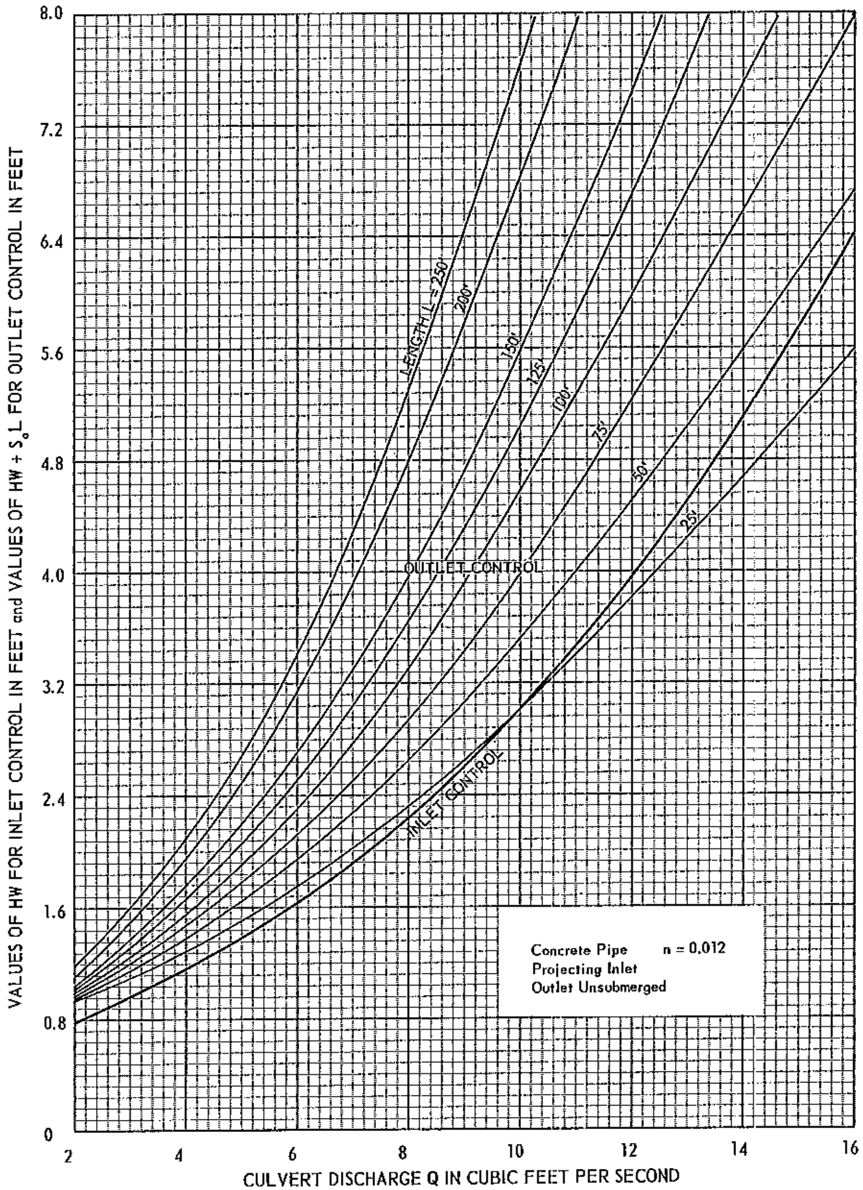
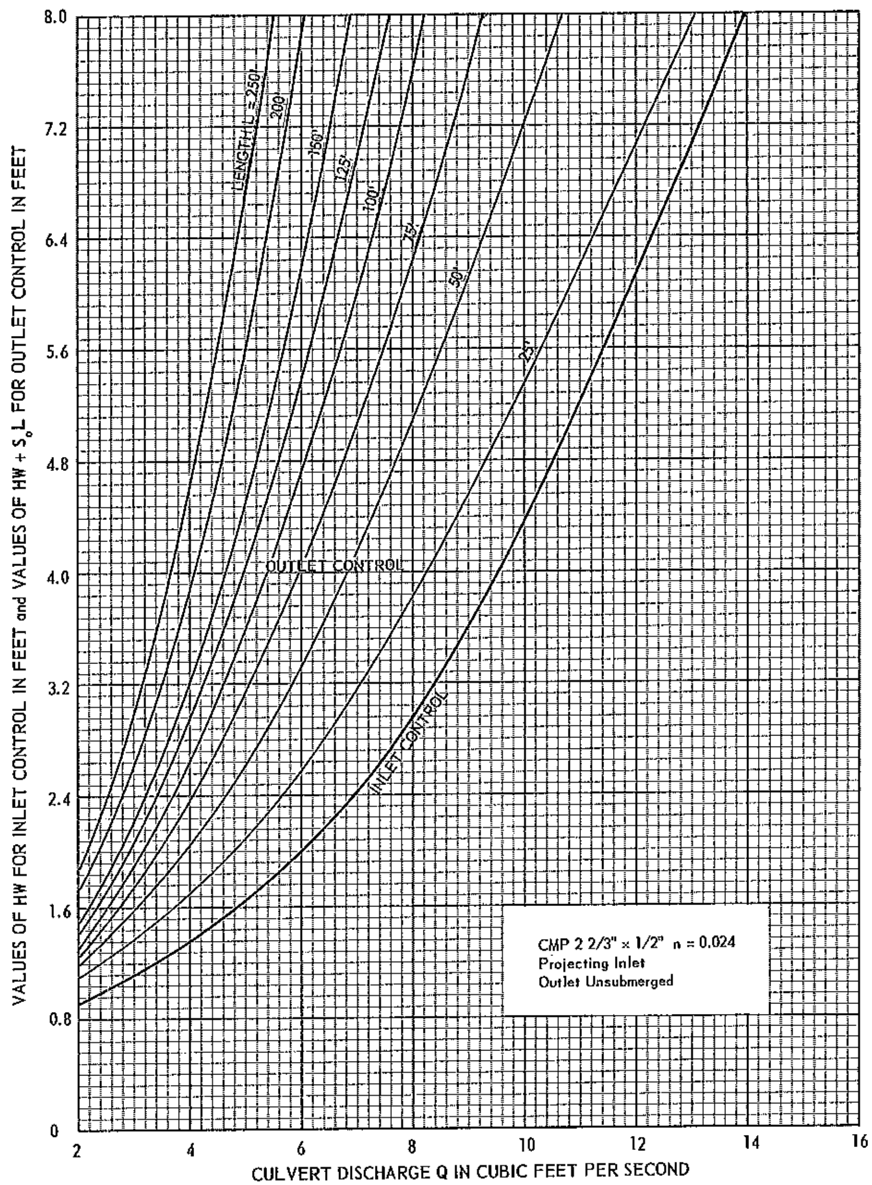


FIGURE 7: 15-Inch Diameter Corrugated Metal Pipe



Interpolate for intermediate culvert lengths

FIGURE 8: 18-Inch Diameter Concrete Pipe

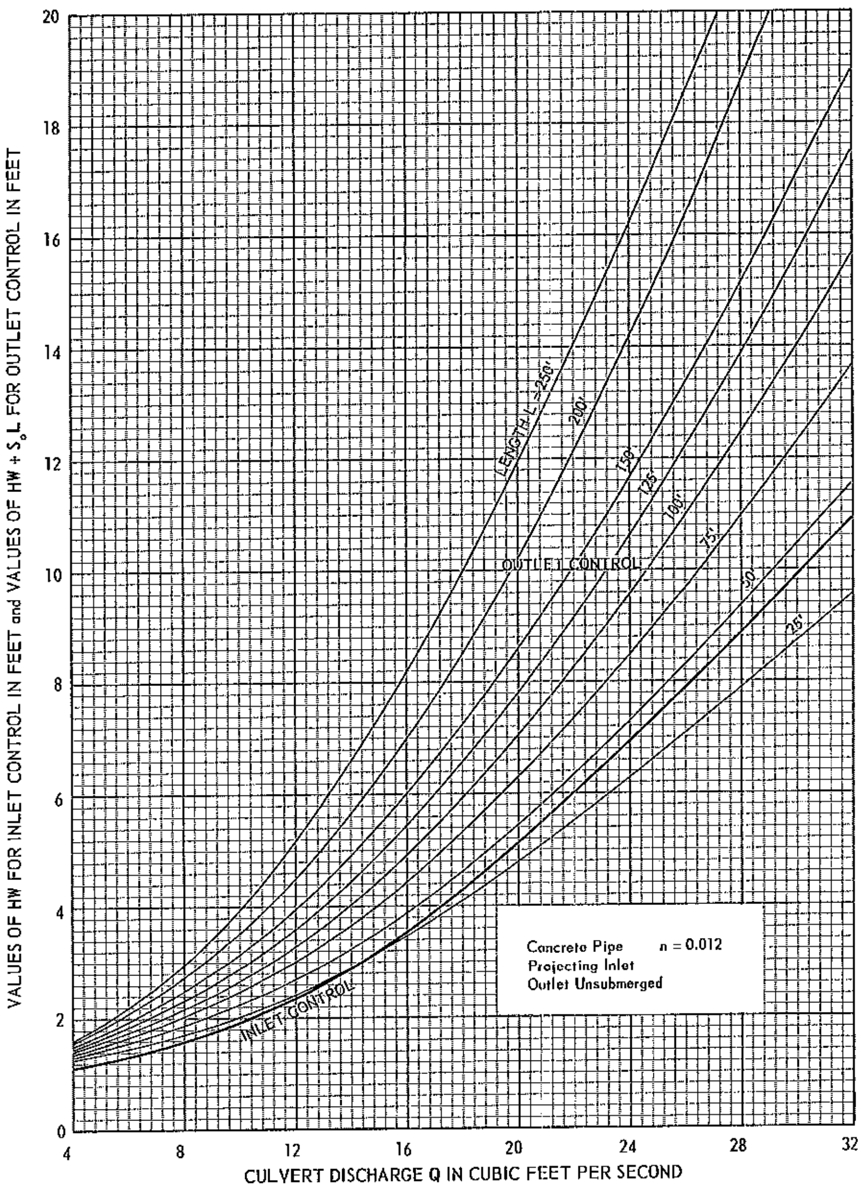
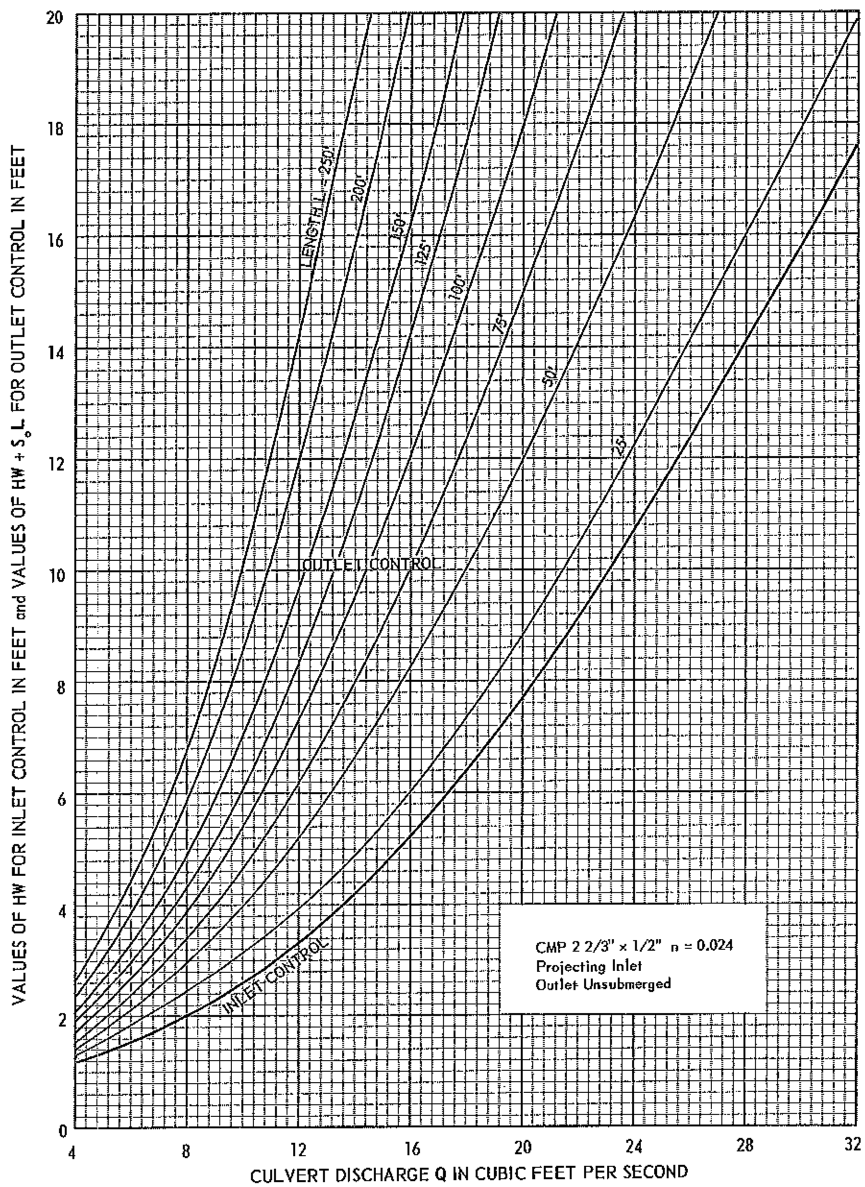


FIGURE 9: 18-Inch Diameter Corrugated Metal Pipe



Interpolate for intermediate culvert lengths

FIGURE 10: 21-Inch Diameter Concrete Pipe

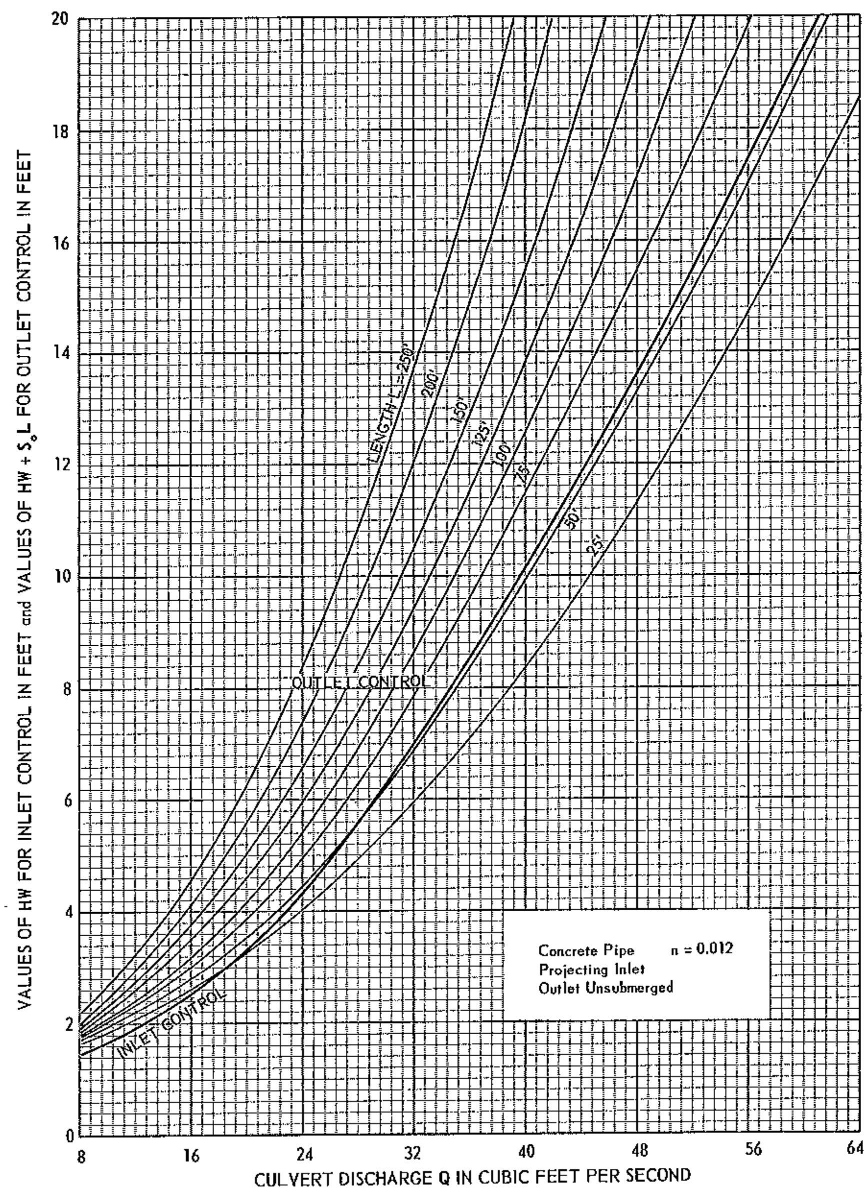
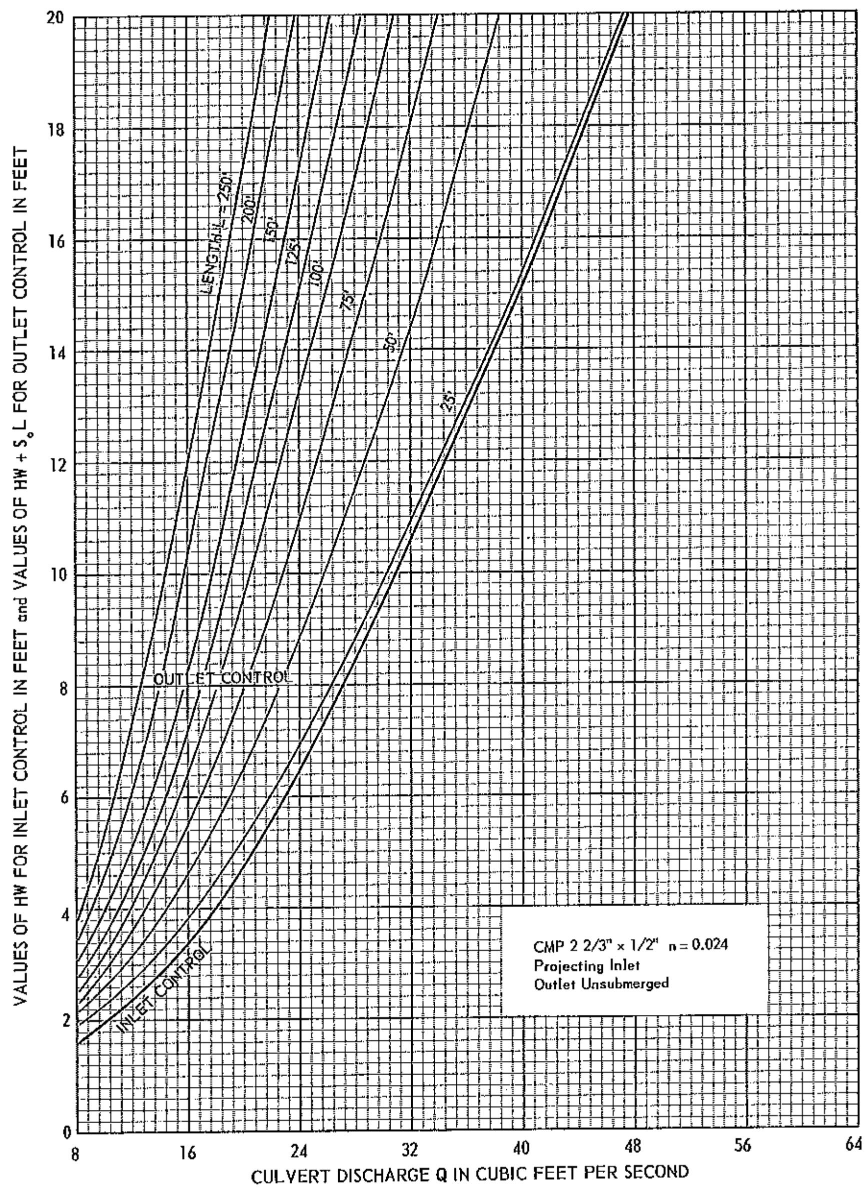


FIGURE 11: 21-Inch Diameter Corrugated Metal Pipe



Interpolate for intermediate culvert lengths