HYDRAULICS OF CULVERTS: HORIZONTAL ELLIPTICAL CONCRETE PIPE STRUCTURAL PLATE PIPE ARCH

The hydraulic design of culverts establishes the minimum pipe size which has sufficient capacity to discharge a required flow within an allowable headwater depth. In the hydraulic design of culverts where the outlet is not submerged, the two principal types of flow that must be considered are flow under inlet control and flow under outlet control.

For any given headwater depth and pipe size, the capacity of a culvert operating under inlet control is dependent entirely on the inlet geometry. Since the geometric shape of the socket end of a concrete pipe results in less contraction of the flow at the entrance than the sharp edge of a corrugated metal pipe, with or without a headwall, greater and more efficient capacity is realized with concrete pipe.

Under outlet control the primary factor limiting culvert capacity is surface roughness. The relative smoothness of concrete pipe enables concrete pipe to handle substantially greater flow than the same size corrugated metal pipe.

The significance of these hydraulic advantages of concrete pipe is illustrated by the performance curves presented in Figures 1 through 22. The curves correlate headwater-discharge and are based on nomographs included in Hydraulic Engineering Circular Number 5, Hydraulics Branch, Bridge Division, Office of Engineering and Operations, Bureau of Public Roads.

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 \( S_0 \) from the headwater depth.

<table>
<thead>
<tr>
<th>Pipe Size</th>
<th>Equiv. Circular</th>
<th>HW Inlet Control</th>
<th>HW Outlet Control</th>
<th>Control Condition</th>
<th>Control HW</th>
</tr>
</thead>
<tbody>
<tr>
<td>59 x 81</td>
<td>72</td>
<td>15.50</td>
<td>42.2 - 20.0 - 40.20</td>
<td>Outlet</td>
<td>40.2</td>
</tr>
<tr>
<td>60 x 87</td>
<td>70</td>
<td>15.50</td>
<td>28.6 - 20.0 - 40.20</td>
<td>Outlet</td>
<td>42.6</td>
</tr>
<tr>
<td>67 x 99</td>
<td>74</td>
<td>10.10</td>
<td>22.7 - 20.0 - 30.70</td>
<td>Outlet</td>
<td>20.7</td>
</tr>
<tr>
<td>71 x 103</td>
<td>90</td>
<td>8.90</td>
<td>17.8 - 20.0 - 15.80</td>
<td>Outlet</td>
<td>15.8</td>
</tr>
<tr>
<td>75 x 112</td>
<td>96</td>
<td>7.80</td>
<td>14.1 - 20.0 - 12.10</td>
<td>Outlet</td>
<td>12.1</td>
</tr>
<tr>
<td>79 x 117</td>
<td>102</td>
<td>7.40</td>
<td>11.5 - 20.0 - 9.30</td>
<td>Outlet</td>
<td>9.8</td>
</tr>
</tbody>
</table>

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

Enter Figure 14: 83 x 128-Inch Corrugated Metal Pipe Arch and project a vertical line from \( Q = 400 \) on the horizontal scale to the INLET CONTROL curve and the OUTLET CONTROL curve representing \( L = 400 \) feet. At the intersecting points, read \( HW = 8.75 \) feet and \( HW + S_0 = 10.40 \) feet on the vertical scale.

The Inlet control headwater depth is equal to 8.75 feet. To obtain the outlet control headwater depth, subtract \( S_0 \cdot L \) from the outlet control figure.

\[ 10.40 - (0.005 \times 400) = 8.40 \]

Since the outlet control headwater depth of 8.40 feet is larger than the inlet control headwater depth of 6.75 feet, outlet control governs.

Answer: A 59 x 81-inch horizontal elliptical concrete pipe (equivalent 72-inch circular) or a 83 x 128-inch corrugated metal pipe arch (equivalent 108-inch circular) will carry the design discharge within an allowable headwater depth of 9 feet. Both pipes are operating under outlet control.

The difference in required headwater depths between 59 x 81-inch horizontal elliptical concrete pipe and corrugated metal pipe arch in sizes 59 x 81-inch through 83 x 128-inch is illustrated in the accompanying figure. This example shows that a corrugated metal pipe six sizes larger than concrete pipe is necessary to meet the allowable headwater requirements. Comparing the 59 x 81-inch corrugated metal and the 58 x 91-inch concrete pipe sizes indicates that the same size corrugated metal pipe arch must operate at a headwater depth 44% greater than horizontal elliptical concrete pipe.

![Comparative Headwater Depths](image-url)
**FIGURE 13:** 87 x 136-Inch Horizontal Elliptical Concrete Pipe

VALUES OF HW FOR INLET CONTROL IN FEET and VALUES OF HW + SL FOR OUTLET CONTROL IN FEET

Interpolate for intermediate culvert lengths

**FIGURE 14:** 83 x 128-Inch Corrugated Metal Pipe Arch

VALUES OF HW FOR INLET CONTROL IN FEET and VALUES OF HW + SL FOR OUTLET CONTROL IN FEET

Concrete Pipe $n = 0.012$
Projected Inlet
Outlet Unsubmerged
Approx. Equivalent Circular
Size Based on Area

CMPI Arch Str. Plate $n = 0.033$
Projected Inlet
Outlet Unsubmerged
Approx. Equivalent Circular
Size Based on Periphery

CULVERT DISCHARGE $Q$ IN CUBIC FEET PER SECOND

CULVERT DISCHARGE $Q$ IN CUBIC FEET PER SECOND
120-INCH CIRCULAR

FIGURE 17: 97 x 151-Inch Horizontal Elliptical Concrete Pipe

FIGURE 18: 91 x 142-Inch Corrugated Metal Pipe Arch

VALUES OF HW FOR INLET CONTROL IN FEET and VALUES OF HW + Sf FOR OUTLET CONTROL IN FEET

CULVERT DISCHARGE Q IN CUBIC FEET PER SECOND

Concrete Pipe n = 0.012
Projecting Inlet
Outlet Unsubmerged
Approx. Equivalent Circular
Size Based on Area

CMP Arch Str. Plate n = 0.033
Projecting Inlet
Outlet Unsubmerged
Approx. Equivalent Circular
Size Based on Periphery

Interpolate for intermediate culvert lengths
132-INCH CIRCULAR

FIGURE 19: 106 x 166-Inch Horizontal Elliptical Concrete Pipe

FIGURE 20: 100 x 154-Inch Corrugated Metal Pipe Arch

Interpolate for intermediate culvert lengths.
**FIGURE 21: 116 x 180-Inch Horizontal Elliptical Concrete Pipe**

- Concrete Pipe $n = 0.012$
- Projecting Inlet
- Outlet Unsubmerged
- Approx. Equivalent Circular Size Based on Area

**FIGURE 22: 107 x 171-Inch Corrugated Metal Pipe Arch**

- CMP Arch Str. Plate $n = 0.033$
- Projecting Inlet
- Outlet Unsubmerged
- Approx. Equivalent Circular Size Based on Periphery

Interpolate for intermediate culvert lengths.