Design of Pipe Culverts

Professional Development Hours (PDH) or Continuing Education Hours (CE)

Online PDH or CE course

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References

The main reference for this chapter is:

The book is available in the Books page on the course website and is downloadable free on usbr.gov.
Overview

- Objectives
- Introduction
- Design Criteria
- Design Example

Objectives

The objective is to design pipe culverts according to USBR guidelines including all the necessary parts and appurtenances.
You Will Need

- **Lecture notes** can be taken in class, copied from notes given to students representatives, or printed from the course website.
- The following **charts and tables** the following are necessary for the design procedure.

Transitions details (5 pages)
Erosion Protection works (2 pages)
Table 21 and 22 (2 pages)

Introduction

Culvert in cross-drainage works
**Design Criteria**

1. **Alinement**

Location of culvert is to use the natural channel. If a canal crosses a natural channel with a skew, it is better to locate the culvert on a skew with the canal.

![Diagram of Culvert Alinement](image1.png)

**Figure 4-26. Plan and profile of typical culvert, 103-0-1303**

2. **Profile**

- \( S_1 \) should be much steeper than critical slope.
- \( S_2 \) is usually 0.005 to facilitate dissipation of energy by hydraulic jump in the pipe without being flat enough to permit sedimentation in the pipe. The pipe should be under canal prism with at least 2 feet below the invert of an earth section canal, and at least 0.5 foot below the lining of concrete lined canal.

![Diagram of Culvert Profile](image2.png)
Design Criteria
3. Conduit

Culverts may be single or multi barreled and may consist of the following types:
- Precast reinforced concrete pressure pipe (PCP),
- Precast reinforced concrete culvert pipe (RCCP),
- Asbestos-cement pressure pipe (AC),
- Reinforced plastic mortar pressure pipe (RPM), or
- Rectangular concrete box section.

Design Criteria
3. Conduit (continued)

Selection of the type of culvert conduit depends on:
- The project life.
- Life expectancy of the pipe.
- Loading conditions to be imposed on the pipe.
- The cost of each type.
- Its availability at the site.
Design Criteria
4. Inlet

Several types of transitions are used as culvert inlets namely type 1 through type 4. The best choice for any particular situation is dependent upon the hydraulics, the topographic character of the site, and the relative elevations of the canal and drainage channel.

See details P337-341 “Small Canal structures”

![Image 1](image1.png)  
*Figure 4-7. Type 4 inlet concrete transition, P-328-701-9300*

![Image 2](image2.png)  
*Figure 4-23. Precast concrete pipe culvert with precast concrete inlet transition, P-328-701-6507*

Design Criteria
4. Inlet (Continued)

Benefits of concrete transitions:

- A greater capacity is provided by good transitioning.
- The required length of pipe may be shortened by the length of the concrete transitions.

*continued on next slide*
Hydraulic Structures

Design Criteria
4. Inlet (Continued)

Benefits of concrete transitions (Continued):

- Reduction in erosion. Reduces the threat to the canal bank.
- The cutoff walls of concrete transitions reduce the danger of piping by percolation.

Note: Freeboard from inlet water surface to the top of bank should be at least 2 feet.

Figure 4.22. Precast concrete pipe culvert with type 3 inlet transition. F482-417-524

Design Criteria
5. Outlet

Its function is to release water to the outlet channel without excessive erosion.

a. Concrete transitions

In case of concrete transitions, the culvert conduit is sized on the basis of maximum full pipe velocity of 10 ft/sec. There are two types of concrete transitions:

- Type 1 concrete transition is used for well-defined outlet channel.
- Type 2 concrete transition is used for poorly defined outlet channel.

Figure 7.1. Type 1 concrete transition. F33-D-25693
**Design Criteria**

5. Outlet (Continued)

b. Outlet energy dissipators

- Baffled outlet performs well in dissipating excess energy, provided clogging by weeds or other debris can be avoided. The culvert pipe should be sized on full pipe velocity of 12 ft/sec; the theoretical velocity should not exceed 50 ft/sec.

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**Design Criteria**

5. Outlet (Continued)

- Other types of energy dissipators.
  
  Example baffled apron drop.
Design Criteria
6. Hydraulics

a. Design capacity
Generally, for small irrigation structures, cross drainage are sized on the basis of storm runoff for a 25-years flood frequency.

b. Pipe velocity
The culvert should be designed for a maximum pipe velocity of 10 ft/sec if a concrete transition is used at outlet, and for a maximum full pipe velocity of 12 ft/sec if an energy dissipator is used.

Design Criteria
6. Hydraulics

c. Pipe diameter

\[ Q = AV \]
\[ = \pi D^2 V \]

\[ D = 1.13 \frac{Q}{V} \]

The minimum pipe diameter permitted is 24 inches. Precast concrete pipe is widely supplied in increments of 3 inches of diameter.
Design Criteria
6. Hydraulics (Continued)

d. Hydraulic control

- **Inlet control**: if the upstream water surface is not influenced by flow conditions d.s. from inlet, it is said to have inlet control.
- **Outlet control**: if the water surface is influenced by downstream flow conditions, it is said to have outlet control.

Design Criteria
6. Hydraulics (Continued)

e. Determination of inlet or outlet control

1. Inlet control hydraulics

Where inlet control exists, the head required at culvert inlet is computed from the orifice equation:

\[ Q = CAV \]

\[ = CA \sqrt{2gh} \]

\[ h = \frac{Q^2}{2gC^2A^2} \]

\[ C = 0.6V = \frac{Q}{A} \cdot g = 32.2 \text{ ft/sec}^2 \]

\[ h = 0.0433V^2 \]
Design Criteria
6. Hydraulics (Continued)

2. Outlet control hydraulics
   i. Inlet losses
      \[ h_i = k_i \Delta h_i \]
   ii. Pipe losses
      The pipe losses consist of friction losses and bend losses.
   iii. Outlet losses
      \[ h_o = k_o \Delta h_o \]

Design Criteria
7. Pipe Collars

It is customary to locate collars on the pipe as follows: one collar below the centerline of the uphill bank, two collars under downhill bank, with one under the inside edge and one located 2 ft downstream the outside edge.

Figure 4-21. Concrete box culvert with concrete percolation collars, F328-701 3743
**Design Criteria**

7. Pipe Collars (Continued)

A "short path" between collars will occur if the resistance to percolation through the soil is less than the resistance to percolation along concrete surface of the pipe and collars.

\[
K_1 X = K_2 X + 2K_3 Y \\
2X = 0.33X + 2(1+Y)
\]

Solving for \(X\) in terms of \(Y\)

\[
2X - 0.33X = 2Y \\
1.67X = 2Y
\]

\[X_{(\text{min})} = 1.2Y\]

*Figure 4-27. Weighted-creep method. 103-D-1304*

---

**Design Example**

Assume that a precast concrete pipe culvert is needed to convey storm runoff water under a canal at its intersection with the natural channel.
Design Example
A. Assumptions
1. Properties of the canal section are:
   \[ b = 8\text{ft}, \ h_b = 6\text{ft}, \ ss = 1\frac{1}{2}H : W, \ d_a = 4\text{ft}, W_1 = 6\text{ft} \text{ and } W_2 = 12\text{ft} \text{ to accommodate an operating road.} \]
2. The cross drainage channel is wide, shallow and poorly defined both at inlet and outlet. It is estimated that the outlet channel will support a depth of \(1\text{ft}\) and a velocity of \(1\text{ft/sec}\) for the design flow.
3. The outside bank heights \(h_{o_1} = 4\text{ft, } h_{o_2} = 9\text{ft}\).
4. It has been determined that the 25-year flood could yield a discharge of \(45\text{ cfs}\).

Use \(n = 0.013\) for concrete.

![Figure 4-28. Culvert--typical profile, 103-D-1395](image)

Design Example
B. Design
1. Pipe velocity
   \[ V = 10\text{ft/ sec} \]
2. Pipe diameter
   \[ D = 1.13\sqrt{\frac{Q}{V}} = 1.13\sqrt{\frac{45}{10}} = 2.38\text{ft} \]
   \[ D = 2\times12 + 0.38\times12 = 28.56\text{in} \]
   Provide 30 inches diameter = 2.5 ft

\[ A = \frac{\pi}{4}(2.5)^2 = 4.91\text{ft}^2 \]
\[ V = \frac{Q}{A} = \frac{45}{4.91} = 9.17\text{ft/sec} \]
Design Example

Inlet Type

3. Inlet type

As the drainage channel is poorly defined and the upper canal bank is only 4 ft higher than channel invert, a type 3 or 4 inlet transition will be good.

Use type 3 transition (Fig. 7.5).

Design Example

Pipe Friction Slope

4. Pipe friction slope

\[ V = \frac{1.486}{n} R^{2/3} S^{1/2} \]

using \( n = 0.013 \)

\[ R = \frac{A}{P} = \frac{D}{4} = \frac{2.5}{4} = 0.625 \text{ ft} \]

\[ S_f = \left[ \frac{V n}{1.486 R^{2/3}} \right]^2 = \left[ \frac{9.17 \times 0.013}{1.486 (0.625)^{2/3}} \right] \]

\[ S_f = 0.012 \]
Design Example
Critical Slope

5. Critical Slope

\[
D^{5/2} = (2.5)^{5/2} = 9.882
\]

\[
D^{8/3} = (2.5)^{8/3} = 11.51
\]

\[
\frac{Q}{D^{5/2}} = \frac{45}{9.882} = 4.55
\]

Using Table 22

\[
d_c = 0.89
\]

\[
d_c = 0.89 \times D = 0.89 \times 2.5 = 2.22 ft
\]

---

Design Example
Critical Slope (Continued)

From Table 21 get

\[
\frac{Q_s}{D^{9/2}S_c^{1/2}} = 0.491
\]

<p>| Table 21.—Uniform flow in circular sections flowing partly full |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>(d)</th>
<th>(A)</th>
<th>(R)</th>
<th>(Q_n)</th>
<th>(Q_n)</th>
<th>(Q_n)</th>
<th>(Q_n)</th>
<th>(Q_n)</th>
<th>(Q_n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.2450</td>
<td>0.1935</td>
<td>0.1285</td>
<td>2.89</td>
<td>0.85</td>
<td>0.7115</td>
<td>0.2033</td>
<td>0.477</td>
</tr>
<tr>
<td>0.38</td>
<td>0.2545</td>
<td>0.1978</td>
<td>0.1294</td>
<td>2.89</td>
<td>0.96</td>
<td>0.7106</td>
<td>0.2026</td>
<td>0.481</td>
</tr>
<tr>
<td>0.57</td>
<td>0.2942</td>
<td>0.2020</td>
<td>0.1351</td>
<td>1.915</td>
<td>0.87</td>
<td>0.7254</td>
<td>0.2018</td>
<td>0.485</td>
</tr>
<tr>
<td>0.89</td>
<td>0.2759</td>
<td>0.2062</td>
<td>0.1420</td>
<td>1.875</td>
<td>0.88</td>
<td>0.7230</td>
<td>0.2002</td>
<td>0.488</td>
</tr>
</tbody>
</table>

\[
\frac{Q_s}{D^{9/2}S_c^{1/2}} = 0.491
\]

\[
S_c = \left[ \frac{45 \times 0.013}{11.51 \times 0.491} \right]^2 = 0.0107
\]
**Design Example**

**Invert Slope**

6. Invert slope

Assume class B-25 pipe with thickness $t = 3.5$ inches. Provide a minimum cover of 2 ft over concrete pipe.

$$y_1 = D + t + 2 + h_h - h_h - B$$

$$= 2.5 + 3.5 = 3.8 \text{ft}$$

---

**Design Example**

**Invert Slope (Continued)**

$$L_1 = 1.5h_h + W_1 + 1.5 \left( h_h + B - H \right) + t_v - 0.5$$

$$= 1.5 \times 6 + 6 + 1.5 \left( 4 + 3 - 6 \right) + 0.5 - 0.5 = 16.5 \text{ft}$$
**Design Example**

Invert Slope (Continued)

![Diagram of a pipe culvert with equations and measurements]

\[ S_i = \frac{y}{L_i} = \frac{3.8}{16.5} = 0.23 \]

\[ \alpha_i = \tan^{-1}(S_i) = 12.95^\circ \text{ say } 13^\circ \]

\[ S_i \gg S_y \]

\[ 0.23 \gg 0.0107 \]

This permits free flow at pipe inlet with inlet control.

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**Design Example**

Invert Slope (Continued)

![Diagram of a pipe culvert with measurements]

\[ L_2 = 41 \text{ ft} \]
Design Example
Outlet type

7. Outlet type

As outlet channel is poorly defined, use type 2 transition. From Fig. 7.4, with \( D = 30 \text{ inches} \)

\[
L = 6\text{ft 9 inches}, E = 4\text{ft 6 inches}, e = 24\text{ inches}, B = 6\text{ft 6 inches},
\]

\( C = 4\text{ ft 2 inches}, t = 6\text{ inches} \)

Concrete (Cubic yds.) = 2.2, Reinforcement steel (lbs) = 180

Design Example
Inlet Hydraulics

8. Inlet Hydraulics

\[
h = 0.0433V^2
\]

\[
= 0.0433(9.17)^2 = 3.64\text{ ft}
\]

Where \( h \) is the head to discharge the design flow.
Design Example
Inlet Freeboard

9. Inlet freeboard
   For type 3 transition,
   \[ d_1 = h + \frac{D'}{2} - B \]
   \[ \cos(\alpha_1) = \frac{D/2}{D'/2} \]
   \[ D' = \frac{D}{\cos(\alpha_1)} \]
   \[ D' = \frac{2.5}{\cos(13^\circ)} = 2.56 \text{ft} \]
   \[ d_1 = 3.64 + \frac{2.56}{2} - 3 = 1.9 \text{ft} \]

   \[ f_{b1} = h_b - d_1 = 4 - 1.9 = 2.1 > 2 \text{ft (Minimum freeboard) O.K.} \]

Design Example
Collars

10. Collars
   Provide 1 collar under upper bank of canal and 2 collars under lower bank.
11. Erosion Protection

Erosion protection is not required at culvert inlet.

For $Q = 45$ cfs use type 2 protection at outlet (12 inches of coarse gravel for outlet length = 12 ft).

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7-14. Cross-drainage Structures.—The following protection is considered minimum for cross-drainage structures with concrete transitions.

<table>
<thead>
<tr>
<th>$Q$, cfs</th>
<th>Type of protection</th>
<th>Outlet length, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 30</td>
<td>None</td>
<td>Type 2</td>
</tr>
<tr>
<td>30 to 60</td>
<td>None</td>
<td>Type 3</td>
</tr>
<tr>
<td>60 to 120</td>
<td>Type 1</td>
<td>Type 2</td>
</tr>
</tbody>
</table>

Where the velocity at the conduit is greater than 15 feet per second at the outlet, use the protection type for the next higher discharge stage as minimum. Where baffled outlets are provided at the outlet of a structure the protection should be a thickness of $W$ with the minimum diameter of rock equal to $W$ and extending a distance $W$ (5 feet minimum) beyond the baffled outlet. $W$ is the inside width of the baffled outlet box.

---

Design Example

Verification of Hydraulics

C. Verification of hydraulics by Bernoulli's method

1. Energy balance at outlet

$$E_{11} = d_4 + \frac{V_4^2}{2g}$$

$$= 1 + \frac{(1)^2}{2 \times 32.2} = 1.02 \text{ ft}$$
**Design Example**
Verification of Hydraulics

At section (1)
\[
d_l \frac{D}{D} = 0.89, \quad d_c = 2.22\text{ ft}
\]
\[
\frac{A_c}{D^2} = 7.384 \text{ (Table 21)}
\]
\[
\frac{A_c}{(2.5)} = 0.738, \quad A_c = 4.62\text{ ft}^2
\]

\[
V_c = \frac{Q}{A_c} = \frac{45}{4.62} = 9.74\text{ ft/s}
\]
\[
h_c = \frac{V_c^2}{2g} = \frac{9.74^2}{2 \times 32.2} = 1.48\text{ ft}
\]
\[
E_c = d_c + h_c = 2.22 + 1.48 = 3.7\text{ ft} > 1.02\text{ ft}
\]
If \(E_c > E_s\), the structure is inlet controlled.

---

**Design Example**
Verification of Hydraulics

2. Specific energy at section (2)

Try \(d_2 = 1.2\text{ ft}\)
\[
\frac{d_2}{D} = \frac{1.2}{2.5} = 0.48
\]
\[
\frac{A_2}{D^2} = 0.3727 \text{ (Table 21)}
\]
\[
A_2 = 0.3727 (2.5)^2 = 2.33\text{ ft}^2
\]
\[
V_2 = \frac{Q}{A_2} = \frac{45}{2.33} = 19.3\text{ ft/s}
\]
\[
h_{2c} = \frac{V_2^2}{2g} = \frac{(19.3)^2}{2 \times 32.2} = 5.8\text{ ft}
\]
Design Example
Verification of Hydraulics

\[ \frac{Q}{D} \left( \frac{S_{i1}}{n} \right)^{1/2} = 0.216 \quad (\text{Table 22}) \]

\[ \frac{45 \times 0.013}{11.51 \left( \frac{S_{i1}}{n} \right)^{1/2}} = 0.216 \]

\[ S_{i1} = 0.0554 \]

\[ h_{i1} = \left( \frac{S_{i1} + S_{i2}}{2} \right) L_3 \]

\[ = \left[ \frac{0.0107 + 0.0554}{2} \right] \times 16.5 \]

\[ = 0.54 \text{ ft} \]

\[ 1.48 + 2.22 + 3.8 = 0.54 + 5.8 + 1.2 \]

\[ 7.50 = 7.54 \text{ O.K.} \]

---

Design Example
Verification of Hydraulics

3. Specific energy and velocity at section (3)

\[ y_2 = 0.005 \times 41 = 0.2 \text{ ft} \]

Try \( d_v = 1.4 \text{ ft} \)

\[ d_3 = \frac{1.4}{2.5} = 0.56 \]

\[ A_3 = \frac{d_3^2}{4} = 0.4526 \]

\[ A_3 = 0.4526 (2.5)^2 = 2.83 \text{ ft}^2 \]

\[ V_3 = \frac{Q}{A_3} = \frac{45}{2.83} = 15.9 \text{ ft} / \text{sec} \]

\[ h_{v_3} = \frac{V_3^2}{2g} = \frac{15.9^2}{2 \times 32.2} = 3.9 \text{ ft} \]

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Design Example
Verification of Hydraulics

\[ \frac{Q \cdot n}{D^{4/3} \left( S_{h} \right)^{1/3}} = 0.279 \text{ (Table 21)} \]

\[ 45 \times 0.013 = 0.279 \]

\[ 11.51 \left( S_{h} \right)^{1/3} = 0.279 \]

\[ S_{h} = 0.033 \]

\[ h_{f} = \frac{S_{f} + S_{l}}{2} L_{2} \]

\[ = \frac{0.055 + 0.033}{2} \times 41 = 1.8 \text{ ft} \]

\[ 5.8 + 1.2 + 0.2 = 1.8 + 3.94 + 1.4 \]

\[ 7.20 = 7.14 \]

Therefore, \( V_{s} = 15.9 \text{ ft/sec} \)

Design Example
Erosion Protection (Revisited)

4. Outlet protection
Since the velocity is 15.9 ft/sec exceeding 15 ft/sec, type 3 protection (12 inches of riprap on 6 inches sand and gravel bedding for protection outlet length = 16 ft)

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Pipe Culverts