

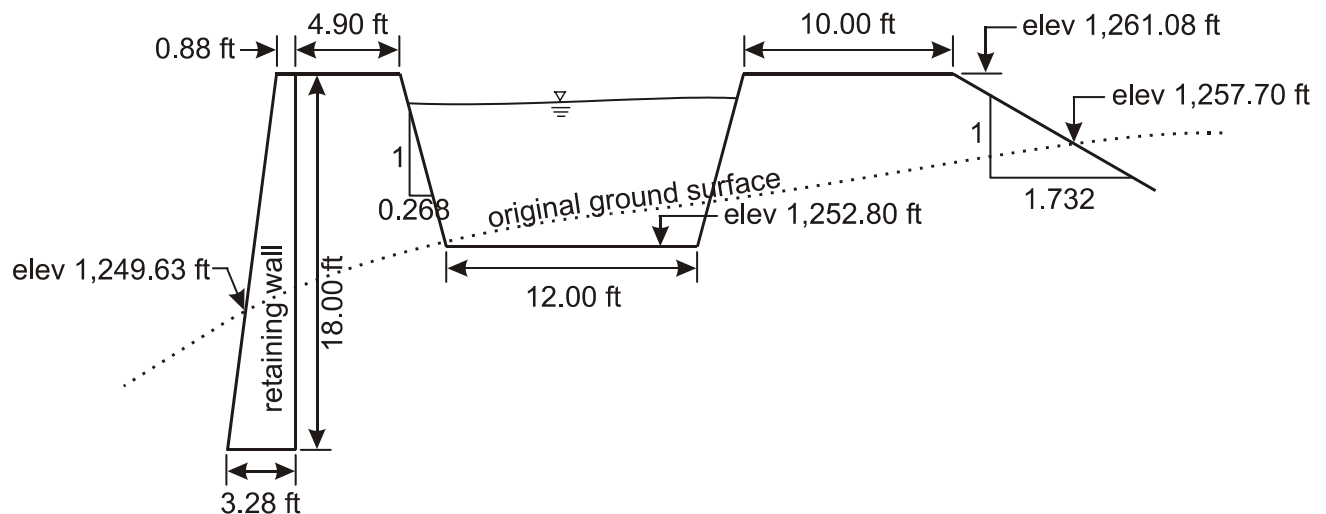
BIE 5300/6300 Assignment #8 Culvert Design

16 Nov 04 (due 23 Nov 04)

Show your calculations in an organized and neat format. Indicate any assumptions or relevant comments.

Given:

- A culvert is to be designed to carry cross-drainage water under a new irrigation canal (see the drawing below).
- The outlet of the culvert will protrude through the retaining wall on the downhill side.
- The canal will be concrete lined, with a lining thickness of 2.5 inches.



- The natural channel (a gulch) which carries the cross-drainage flow has a well-defined and fairly stable cross-section.
- The alignment of the gulch is orthogonal to the canal alignment.
- The design flow rate for the culvert will be 100 cfs.
- Circular concrete pipe will be used for the culvert barrel, and it comes with inside diameters of 2.0 and 3.0 ft.
- Let the upper top of the inlet to the culvert barrel be located at or just below elevation 1,257.70 ft (this will require some excavation work just upstream of the culvert inlet, but you don't have enough information here to know how much excavation will be needed).
- Let the upper top of the outlet from the culvert barrel be located at or just below elevation 1,249.63 ft.

Required:

- Design a culvert for cross-drainage under the canal.
- Follow USBR design guidelines, as given in the “Small Canal Structures” book.
- Use English units for this design.
- Attempt to make the design so that an energy dissipation structure is not required at the culvert outlet. Don’t have supercritical flow at the outlet.
- Determine the number of culvert barrels (in parallel) for this design.
- Determine the slope(s) of the culvert barrel from inlet to outlet.
- Specify collar size and locations.
- Specify the total length of concrete pipe required for the barrel in your design.
- Specify a standard USBR design for the inlet & outlet transitions.
- Make a drawing showing the location of the culvert barrel relative to the canal cross section and retaining wall, and the location of collars.
- Show your calculations and units, indicate any important assumptions, and provide any important comments you might have about the design.

Solution:

1. Determine the Required Pipe Size

- According to USBR design guidelines, use a maximum average barrel velocity of 10.0 fps
- Then, for the design discharge of 100 cfs:

$$D = \sqrt{\frac{4Q}{\pi V}} = \sqrt{\frac{4(100)}{\pi(10)}} = 3.57 \text{ ft} \quad (1)$$

- The available pipe sizes are 2 and 3 feet, inside diameter.
- Try two 2-ft pipes:

$$V = \frac{0.5(100 \text{ cfs})}{\left(\frac{\pi(2)^2}{4}\right)} = 15.9 \text{ fps} \quad (2)$$

which is too high.

- Try two 3-ft pipes:

$$V = \frac{0.5(100 \text{ cfs})}{\left(\frac{\pi(3)^2}{4}\right)} = 7.07 \text{ fps} \quad (3)$$

which is acceptable. Therefore, use two 3-ft pipes for this culvert design, giving two barrels.

2. Determine the Energy Loss Gradient

- With the full pipe flow impending, the energy loss gradient can be estimated by the Manning equation for open-channel flow, in which $h = D$
- Use a Manning n value of 0.015 for new concrete pipe, with a slight safety factor for aging:

$$W_p = \pi D = \pi(3.0) = 9.425 \text{ ft} \quad (4)$$

$$A = \frac{\pi D^2}{4} = \frac{\pi(3.0)^2}{4} = 7.069 \text{ ft} \quad (5)$$

$$S_f = \left(\frac{Qn}{1.49} \right)^2 \left(\frac{W_p^{4/3}}{A^{10/3}} \right) = \left(\frac{(50)(0.015)}{1.49} \right)^2 \left(\frac{(9.425)^{4/3}}{(7.069)^{10/3}} \right) = 0.00744 \quad (6)$$

where half of the design flow rate is used per barrel.

3. Determine the Critical Slope

- For critical flow, the Froude number is equal to unity:

$$F_r^2 = \frac{Q^2 T_c}{g A_c^3} = 1.0 \quad (7)$$

- For circular pipes, the following definitions apply:

$$\beta_c = 2 \cos^{-1} \left(1 - \frac{2h_c}{D} \right) \quad (8)$$

$$T_c = D \sin \left(\frac{\beta_c}{2} \right) \quad (9)$$

$$A_c = \frac{D^2}{8} (\beta_c - \sin \beta_c) \quad (10)$$

- Solve for depth, h , such that $F_r^2 = 1.0$ for $Q = 50$ cfs and $D = 3.0$ ft (for English units, $g \approx 32.2 \text{ ft/s}^2$)

- Using the Newton method, $\beta_c = 4.268$ rad, and $h_c = 2.301$ ft
- Calculate the energy loss gradient (critical slope) corresponding to this depth
- For a depth of 2.301 ft, the flow cross-sectional area is 5.818 ft^2 , and the wetted perimeter is 6.402 ft
- Applying the Manning equation:

$$(S_f)_{\text{crit}} = \left(\frac{(50)(0.015)}{1.49} \right)^2 \left(\frac{(6.402)^{4/3}}{(5.818)^{10/3}} \right) = 0.00850 \quad (11)$$

- If the slope of the pipe is 0.00850 or greater, critical flow can occur

4. Determine the Minimum Upstream Pipe Slope

- According to USBR guidelines, the top of the culvert barrel (pipe) should clear the bottom of the canal by at least 0.5 ft
- Note that if more information were provided about the uphill topography, it would also be possible to move the culvert inlet uphill, away from the canal berm
- The elevation of the inside top of the barrel at the culvert inlet is 1,257.70 ft, as specified above
- Assume a pipe thickness of 2 inches
- Recall the 2.5-inch canal lining thickness (specified)
- The elevation of the inside top of the barrel at the right canal base:

$$1,252.80 - (2.5+2.0)/12 - 0.50 = 1,251.93 \text{ ft} \quad (12)$$

- The horizontal distance of the steep descending part of the culvert barrel:

$$1.732(1,261.08 - 1,257.70) + 10.00 + 0.268(1,261.08 - 1,252.80) = 18.07 \text{ ft} \quad (13)$$

- The minimum slope of the steep descending part of the culvert barrel:

$$\text{slope} = \frac{1,257.70 - 1,251.93}{18.07} = \frac{5.77}{18.07} = 0.319 \quad (14)$$

- It is also necessary to check that the slope of the downstream pipe does not exceed the critical slope

5. Determine the Downstream Pipe Slope

- The flatter downstream part of the culvert barrel would traverse a horizontal distance of:

$$\text{Length} = 12.00 + 0.268(1,261.08 - 1,252.80) + 4.90 + 0.88 +$$

$$(1,261.08 - 1,249.63)(3.28 - 0.88)/18.00 = \underline{21.53 \text{ ft}}$$

- The change in elevation over this distance will be $1,251.93 - (1,249.63 - 2/12) = 1,251.93 - 1,249.46 = 2.47 \text{ ft}$ (where the 2/12 value is the assumed 2 inches of pipe wall thickness)
- Then, the slope of the flatter downstream part of the barrel would be $2.47/21.53 = 0.115$
- Also, the total horizontal distance is, then: $18.07 + 21.53 = 39.60 \text{ ft}$
- This slope is greater than the critical slope, and is not acceptable because it would cause supercritical flow throughout, from inlet to outlet, causing erosion downstream (unless erosion protection is used)
- Use the USBR-recommended downstream slope of 0.005 (0.5%), which is less than the calculated critical slope of 0.850%
- To accomplish this, the upstream (steep) portion of the culvert pipe can be extended further in the downstream direction (to the left)
- Linear equations can be written for the inside tops of the upstream & downstream barrel segments:

$$\text{Upstream: } y = 0.319x + 1,245.07$$

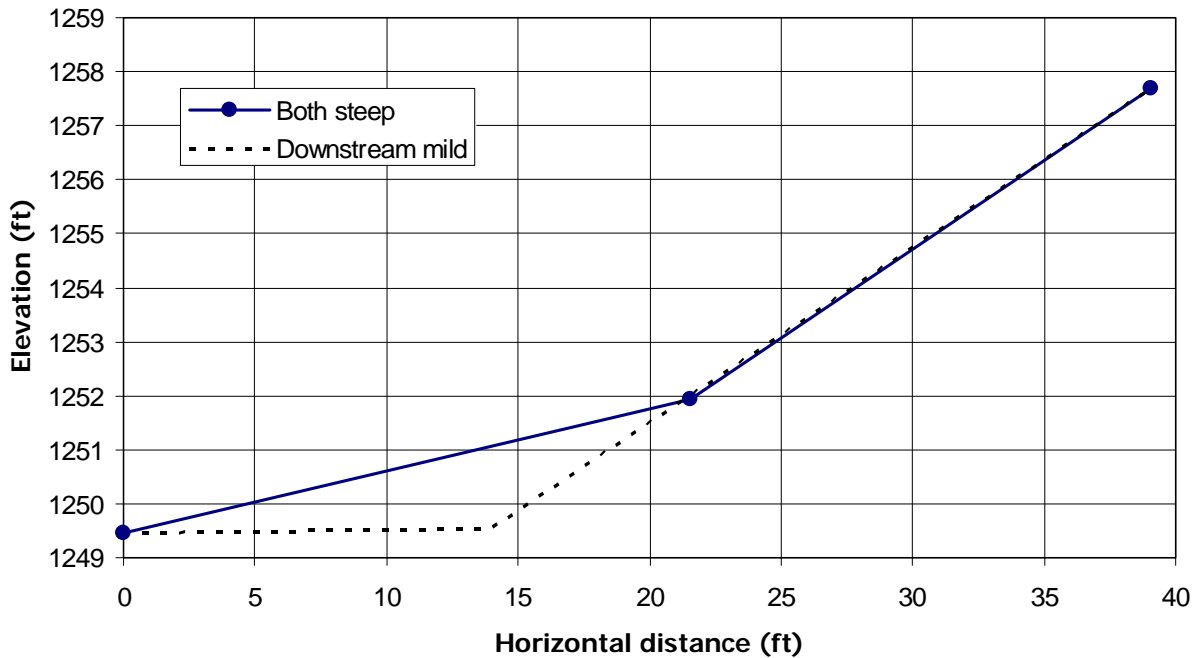
$$\text{Downstream:..... } y = 0.005x + 1,249.46$$

where the intercept in the upstream equation is calculated as $1,257.70 - (0.319)(39.60) = 1,245.07 \text{ ft}$

- Solving the two linear equations for distance:

$$x = \frac{1,249.46 - 1,245.07}{0.319 - 0.005} = \frac{4.39}{0.314} = 13.98 \text{ ft} \quad (15)$$

- This is the distance from the outlet at which the inside top of the upstream pipe intersects the inside top of the downstream pipe
- The elevation of the intersection point is $y = 0.319(13.98) + 1,245.07 = 1,249.53 \text{ ft}$, and the steep part of the barrel has the same slope as before
- Below, a profile of the inside top of the culvert barrel is shown



6. Determine the Pipe Length

- The approximate length of the upstream (steep) pipe is:

$$L_{US} = \sqrt{(39.60 - 13.98)^2 + (1,257.70 - 1,249.53)^2} = 26.89 \text{ ft} \quad (16)$$

- The approximate length of the downstream (mild) pipe is:

$$L_{DS} = \sqrt{(13.98)^2 + (1,249.53 - 1,249.46)^2} = 13.98 \text{ ft} \quad (17)$$

- A total length of $2(26.89 + 13.98) \approx \underline{82 \text{ ft}}$ of 3-ft diameter pipe is needed

7. Specify Inlet and Outlet Types

- The inlet and outlet can be USBR Type 1 (well-defined earthen section)
- The capacity of the downstream (mild) part of the barrel at impending full pipe flow (but assuming open-channel flow) is approximated as:

$$Q = \frac{1.49 (7.069)^{5/3}}{0.015 (9.425)^{2/3}} \sqrt{0.005} = 41 \text{ cfs} \quad (18)$$

- Then, at the design capacity of 50 cfs (per barrel), the downstream portion of the barrel would flow full and there would be a hydraulic jump inside the upstream (steep) part of the barrel
- The outlet velocity would be approximately 7.07 fps (see Eq. 3 above)
- An energy dissipation structure at the outlet is not needed (because the outlet velocity will be < 15 fps)

8. Specify Collar Placement and Size

- The standard USBR culvert design, calling for two collars under the downhill canal bank, and one collar under the uphill bank, is not appropriate in this design because of the downstream retaining wall
- Use a single collar under the upstream canal bank, with $Y = \frac{1}{2}D = 1.5$ ft, and a thickness of 6 inches
- Note that some excavation will be required at the downhill side of the retaining wall because the top of the culvert barrel has been set at the elevation of 1,249.63 (the inside top is about 2 inches lower, in this design)

9. Side View Drawing

