

WOLLO UNIVERSITY
Kombolcha Institute of Technology
Department of Hydraulic and Water RESOURCES engineering
HWRE-3132- Hydraulic Structures II

Examples – Cross Drainage Structure

1. *Design a suitable cross-drainage work, given the following data at the crossing of a canal and drainage.*

Canal

<i>Full supply discharge</i>	<i>= 32 m³/s</i>
<i>FSL</i>	<i>= RL 213.5m</i>
<i>Canal bed level</i>	<i>= RL 212.0 m</i>
<i>Canal bed width</i>	<i>= 20.0 m</i>
<i>Trapezoidal canal section with 1.5 H: 1 V side slopes</i>	
<i>Canal water depth</i>	<i>= 1.5 m</i>

Drainage

<i>High flood discharge</i>	<i>= 300 m³/s</i>
<i>HFL</i>	<i>= 210.0 m</i>
<i>High flood depth</i>	<i>= 2.5 m</i>
<i>General ground level</i>	<i>= 212.5 m</i>

Solution

Since the drainage is of large size, work of type III will be adopted. Further, because the canal bed level (212 m) is much above the HFL of drainage (210 m) an aqueduct will be constructed. The earthen bank of the canal will be discontinued and the canal water taken in concrete trough. For effecting economy, the canal shall be flumed.

Step 1. Design of drainage waterway

Lacey's regime perimeter, $P = 4.75 \sqrt{Q} = 4.75 \sqrt{300} = 82.3 \text{ m}^3/\text{s}$

Taking the clear span between piers to be 9 m and pier thickness = 1.5 m, there will be 8 bay
→ clear waterway = $8 \times 9 = 72 \text{ m}$

Using 7 piers of 1.5 m thickness each, length occupied by piers = $7 \times 1.5 = 10.5 \text{ m}$

Total length of waterway = $72 + 10.5 = 82.5 \text{ m}$

Step 2. Design of canal waterway

Bed width of canal = 20.0 m

Let the width be flumed to 10.0 m.

Providing a splay of 2:1 in contraction, the length of the contraction transition = $\left(\frac{20-10}{2}\right) \times 2 = 10.0 \text{ m}$

Providing a splay of 3:1 in expansion, the length of the expansion transition = $\left(\frac{20-10}{2}\right) \times 3 = 15.0$ m

Length of the flumed rectangular portion of the canal between abutments = 82.3 m (provided)

In transitions, the side slopes of the canal section will be warped in plan from the original 1.5H:1V to vertical.

Step 3. Head loss and bed levels at different sections

Section 4-4

At section 4-4, where the canal turns back to its normal section, we have

Area of trapezoidal canal section = $(B + 1.5 y) y = (20 + 1.5 \times 1.5) \times 1.5 = 33.375 \text{ m}^2$

Velocity, $V_4 = \left(\frac{Q}{A}\right) = \frac{32}{33.375} = 0.959 \text{ m/s}$

Velocity head = $\frac{V_4^2}{2g} = \frac{(0.959)^2}{2 \times 9.81} = 0.046 \text{ m}$

RL of bed at 4-4 = 212.0 m (given)

RL of water surface at 4-4 = $212.0 + 1.5 = 213.5 \text{ m}$

RL of TEL at 4-4 = $213.5 + 0.046 = 213.546 \text{ m}$

The known conditions at 4-4 shall be utilized for finding the bed levels at 3-3.

Section 3-3

Keeping the same depth of 1.5 m throughout the channel, we have at section 3-3;

Bed width = 10.0 m $\rightarrow$ Area of channel = $10 \times 1.5 = 15 \text{ m}^2$

Velocity, $V_3 = 32/15 = 2.13 \text{ m/s} \rightarrow$ Velocity head = $2.13^2 / (2 \times 9.81) = 0.232 \text{ m}$

Assuming that the head loss in expansion from section 3-3 to section 4-4 = $0.3 \left[\frac{V_3^2 - V_4^2}{2g} \right]$

$$= 0.3 (0.232 - 0.046) = 0.0558 \text{ m, say } 0.056 \text{ m}$$

RL of TEL at section 3-3 = RL of TEL at 4-4 + loss in expansion

$$= 213.546 + 0.056 = 213.602 \text{ m}$$

Therefore, RL of water surface at section 3-3 = RL of TEL at 3-3 - Velocity head

$$= 213.602 - 0.232 = 213.370 \text{ m}$$

RL of bed at 3-3 = $213.370 - 1.5 = 211.870 \text{ m}$

Section 2-2

From section 2-2 to section 3-3, the trough section is constant. Therefore, area and velocity at section 2-2 are the same as at 3-3. There is friction loss between 2-2 and 3-3 and may be computed by Manning's formula as;

$$H_L = \frac{n^2 V^2 L}{R^{4/3}}$$

Take $n = 0.016$ (concrete in trough section), and $L = 82.5$ m (length of trough – calculated)

Area of trough, $A = 10 \times 1.5 = 15 \text{ m}^2$, Wetted perimeter, $P = 10 + 2 \times 1.5 = 13 \text{ m}$

Hydraulic radius, $R = A/P = 15/13 = 1.16 \text{ m}$, Velocity in trough, $V = Q/A = 32/15 = 2.13 \text{ m/s}$

Therefore,

$$H_L = \frac{0.016^2 \times 2.13^2 \times 82.5}{1.16^{4/3}} = 0.0787 \text{ m ; say } 0.079 \text{ m}$$

RL of TEL at 2-2 = RL of TEL at 3-3 + friction loss in trough

$$= 213.602 + 0.079 = 213.681 \text{ m}$$

RL of water surface at 2-2 = $213.681 - 0.232 = 213.449 \text{ m}$

RL of bed at 2-2 = $213.449 - 1.5 = 211.949 \text{ m}$

Section 1-1

Loss of head in contraction transition from 1-1 to 2-2 = $0.2 \left(\frac{V_2^2 - V_1^2}{2g} \right) = 0.2 \left(\frac{2.13^2 - 0.947^2}{2 \times 9.81} \right) = 0.037 \text{ m}$

RL of TEL at 1-1 = RL of TEL at 2-2 + loss in contraction = $213.681 + 0.037 = 213.718 \text{ m}$

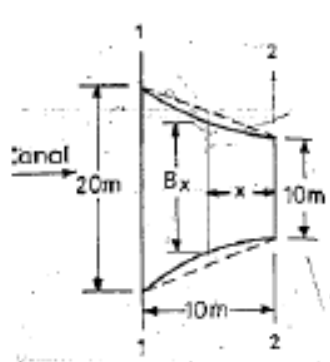
RL of water surface at 1-1 = $213.718 - 0.046 = 213.672 \text{ m}$

RL of bed at 1-1 = $213.672 - 1.5 = 212.172 \text{ m}$

Now, all the bed levels, FSL and TEL are plotted as shown below.

Step 4. Design of Transitions

- (a) *Contraction transition: Since the depth is kept constant, the transition can be designed as a Hyperbolic transition, given by*

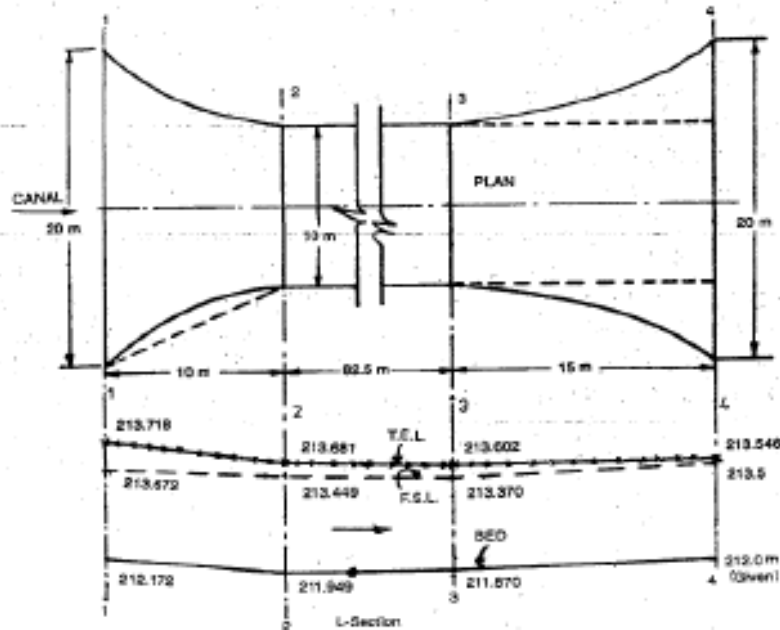


$$B_x = \frac{B_n B_f L_f}{L_f B_n - x(B_n - B_f)} = \frac{20 \times 10 \times 10}{10 \times 20 - x(20 - 10)} = \frac{2000}{200 - 10x}$$

$$B_f = 20 \text{ m}$$

$$B_n = 10 \text{ m}$$

$$L_f = 10 \text{ m}$$

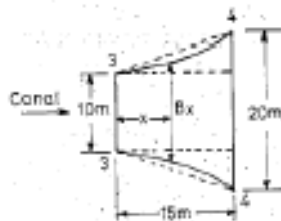


For various values of x lying between 0 and 10 m, values of B_x are worked out as shown below. The distance x is measured from flumed section;

x in metres	0	2	4	6	8	10
$B_x = \frac{2,000}{300 - 10x}$ in metres	10.0	11.11	12.5	14.29	16.67	20.0

(b) Expansion transition: In this case $B_n = 20$ m, $B_f = 10$ m and $L_f = 15$ m

$$B_x = \frac{B_n B_f L_f}{L_f B_n - x(B_n - B_f)} = \frac{20 \times 10 \times 15}{15 \times 20 - x(20 - 10)} = \frac{3000}{300 - 10x}$$



For various values of x lying between 0 and 15 m, values of B_x are worked out and plotted.

x in metres	0	2	4	6	8	10	12	14	15
$B_x = \frac{3,000}{300 - 10x}$ in metres	10.0	10.71	11.54	12.5	13.64	15.0	16.67	18.75	20.0

Step 5. Design of trough

A free board of 0.6 m is provided above the normal water depth of 1.5 m, giving 2.1 m depth (height of trough). The entire trough section will be constructed in monolithic R.C. and can be designed by usual structural methods.

2. Design a siphon aqueduct if the following data at the crossing of a canal and a drainage are given:

(i)	Discharge of canal	= 40 m ³ /s
(ii)	Bed width of canal	= 30 m
(iii)	Full supply depth of canal	= 1.6 m
(iv)	Bed level of canal	= 206.4 m
(v)	Side slopes of canal	1.5H:1V
(vi)	High flood discharge of drainage	= 450 m ³ /s
(vii)	HFL of drainage	= 207.0 m
(viii)	Bed level of drainage	= 204.5 m
(ix)	General ground level	= 206.5 m

Solution

Since the drainage is of a large size, work of type III will be adopted. The earthen banks of the canal will be discontinued and the canal water taken in concrete trough. For the sake of economy, the canal shall be flumed.

Step 1. Design of drainage waterway

$$\rightarrow \text{Lacey's regime perimeter, } P = 4.75 \sqrt{Q} = 4.75 \sqrt{450} = 100.8 \text{ m}$$

Taking the clear span between piers to be 8 m and pier thickness = 1.5 m, there will be 11 bay

$$\rightarrow \text{clear waterway} = 11 \times 8 = 88 \text{ m}$$

Using 10 piers of 1.5 m thickness each, length occupied by piers = 10 x 1.5 = 15 m

$$\rightarrow \text{Total length of waterway} = 88 + 15 = 103 \text{ m}$$

Limiting the velocity through the barrel to 2 m/s.

$$\rightarrow \text{Height of barrels required} = Q / (V \times \text{Clear waterway}) = 450 / (2 \times 88) = 2.56 \text{ m}$$

Hence, provide 11 rectangular barrels, each 8 m wide and 2.5 m high.

$$\rightarrow \text{Actual velocity through barrels} = 450 / (11 \times 8 \times 2.5) = 2.05 \text{ m/s}$$

Step 2. Design of canal waterway

Bed width of canal = 30.0 m

Let the width be flumed to 15.0 m.

$$\rightarrow \text{Providing a splay of 2:1 in contraction, the length of the contraction transition} = \left(\frac{30-15}{2} \right) \times 2 = 15.0 \text{ m}$$

$$\rightarrow \text{Providing a splay of 3:1 in expansion, the length of the expansion transition} = \left(\frac{30-15}{2} \right) \times 3 = 22.5 \text{ m}$$

Length of the flumed rectangular portion of the canal between abutments = 103 m (provided)

In transitions, the side slopes of the canal section shall be warped in plan from the original 1.5H:1V to vertical.

Step 3. Design of bed levels at different sections

Section 4-4

At section 4-4, where the canal turns back to its normal section, we have

$$\text{Area of trapezoidal canal section} = (B + 1.5 y) y = (30 + 1.5 \times 1.6) \times 1.6 = 51.84 \text{ m}^2$$

$$\text{Velocity, } V_4 = \left(\frac{Q}{A} \right) = \frac{40}{51.84} = 0.77 \text{ m/s}$$

$$\text{Velocity head} = \frac{V_4^2}{2g} = \frac{(0.77)^2}{2 \times 9.81} = 0.030 \text{ m}$$

$$\text{RL of bed at 4-4} = 206.4 \text{ m (given)}$$

$$\text{RL of water surface at 4-4} = 206.4 + 1.6 = 208.0 \text{ m}$$

$$\text{RL of TEL at 4-4} = 208.0 + 0.030 = 208.03 \text{ m}$$

Section 3-3

Keeping the same depth of 1.5 m throughout the channel, we have at section 3-3;

$$\rightarrow \text{Bed width} = 15.0 \text{ m} \rightarrow \text{Area of channel} = 15 \times 1.6 = 24 \text{ m}^2$$

$$\text{Velocity, } V_3 = 40/24 = 1.67 \text{ m/s} \rightarrow \text{Velocity head} = 1.67^2 / (2 \times 9.81) = 0.142 \text{ m}$$

$$\begin{aligned} \text{Assuming that the head loss in expansion from section 3-3 to section 4-4} &= 0.3 \left[\frac{V_3^2 - V_4^2}{2g} \right] \\ &= 0.3 (0.142 - 0.030) = 0.0336 \text{ m, say } 0.034 \text{ m} \end{aligned}$$

$$\begin{aligned} \text{RL of TEL at section 3-3} &= \text{RL of TEL at 4-4} + \text{loss in expansion} \\ &= 208.030 + 0.034 = 208.064 \text{ m} \end{aligned}$$

$$\begin{aligned} \text{Therefore, RL of water surface at section 3-3} &= \text{RL of TEL at 3-3} - \text{Velocity head} \\ &= 208.064 - 0.142 = 207.922 \text{ m} \end{aligned}$$

$$\text{RL of bed at 3-3} = 213.370 - 1.6 = 206.322 \text{ m}$$

Section 2-2

From section 2-2 to section 3-3, the trough section is constant. Therefore, area and velocity at section 2-2 are the same as at 3-3. There is friction loss between 2-2 and 3-3 and may be computed by Manning's formula as;

$$H_L = \frac{n^2 V^2 L}{R^{4/3}}$$

Take $n = 0.016$ (concrete in trough section), and $L = 103 \text{ m}$ (length of trough – calculated)

$$\text{Area of trough, } A = 15 \times 1.6 = 24 \text{ m}^2, \text{ Wetted perimeter, } P = 15 + 2 \times 1.6 = 18.2 \text{ m}$$

Hydraulic radius, $R = A/P = 24/18.2 = 1.32 \text{ m}$, Velocity in trough, $V = Q/A = 40/24 = 1.67 \text{ m/s}$
Therefore,

$$H_L = \frac{0.016^2 \times 1.67^2 \times 103}{1.32^{4/3}} = 0.051 \text{ m}$$

RL of TEL at 2-2 = RL of TEL at 3-3 + friction loss in trough
 $= 208.064 + 0.051 = 208.115 \text{ m}$

RL of water surface at 2-2 = $208.115 - 0.1422 = 207.973 \text{ m}$

RL of bed at 2-2 = $207.973 - 1.6 = 206.373 \text{ m}$

Section 1-1

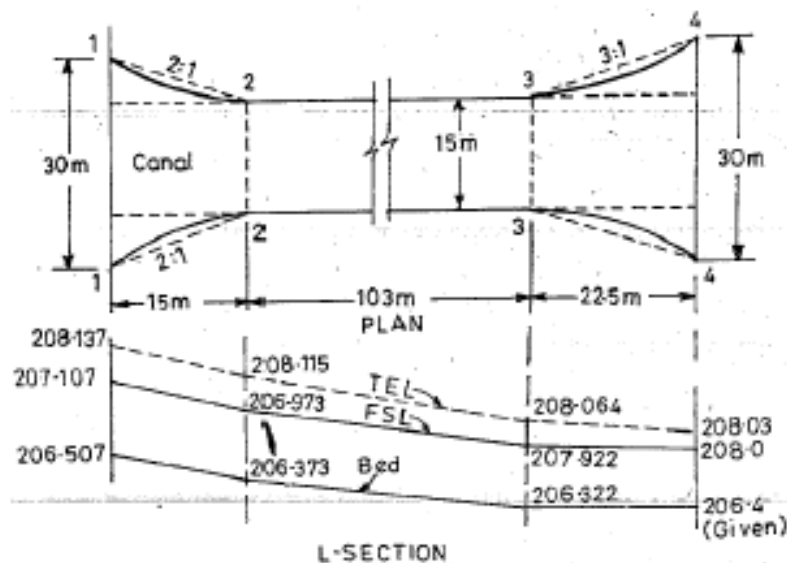
Loss of head in contraction transition from 1-1 to 2-2 = $0.2 \left(\frac{V_2^2 - V_1^2}{2g} \right) = 0.2 \left(\frac{1.67^2 - 0.77^2}{2 \times 9.81} \right) = 0.022 \text{ m}$

RL of TEL at 1-1 = RL of TEL at 2-2 + loss in contraction = $208.115 + 0.022 = 208.137 \text{ m}$

RL of water surface at 1-1 = $208.137 - 0.022 = 208.107 \text{ m}$

RL of bed at 1-1 required to maintain constant depth = $208.107 - 1.6 = 206.507 \text{ m}$

Now, all the bed levels, FSL and TEL are plotted as shown below.



Step 4. Design of Transitions

(a) Contraction transition: Since the depth is kept constant, the transition can be designed as a Hyperbolic transition, given by

$$B_x = \frac{B_n B_f L_f}{L_f B_n - x(B_n - B_f)} = \frac{30 \times 15 \times 15}{15 \times 30 - x(30 - 15)} = \frac{450}{30 - x}$$

$$B_f = 15 \text{ m}, B_n = 30 \text{ m}, L_f = 15 \text{ m}$$

For various values of x lying between 0 and 10 m, values of B_x are worked out as shown below. The distance x is measured from flumed section;

X (m)	0	2	4	6	8	10	12	14	15
B _x (m)	15.0	16.04	17.27	18.72	20.42	22.50	25.0	28.10	30.0

(b) Expansion transition: In this case $B_n = 30$ m, $B_f = 15$ m and $L_f = 22.5$ m

$$B_x = \frac{B_n B_f L_f}{L_f B_n - x(B_n - B_f)} = \frac{30 \times 15 \times 22.5}{22.5 \times 30 - x(30 - 15)} = \frac{675}{45 - x}$$

X (m)	0	2	4	6	8	10	12	14	16	18	20	22.5
B _x (m)	15.0	15.7	16.46	17.30	18.25	19.30	20.40	21.75	23.30	25.00	27.0	30.0

Step 5. Design of trough

The trough shall be divided into three equal compartments, each 5 m wide, separated by 0.3 m thick partition walls (2 in number). A 5 m wide inspection road shall be carried on the left compartment. A free board of 0.6 m is provided above the normal water depth of 1.6 m, giving 2.2 m depth (height of trough). The entire trough section will be designed as monolithic R.C. structure by the usual structural methods.

The tentative weights may be calculated taking the following dimensions:

Outer walls = 0.4 m thick;

Bottom slab of trough = 0.4 m thick

The intermediate walls shall be extended into transitions so as to provide the necessary clear width of 15 m.

Now, the overall outer width of trough (including walls)

$$= 15 + 2 \times 0.3 + 2 \times 0.4 = 16.4 \text{ m (} = \text{length of the siphon barrel)}$$

Step 6. Head Loss Through the Siphon Barrels

The head loss through the siphon barrels is given by

$$h = \left[1 + f_1 + f_2 \frac{L}{R} \right] \frac{V^2}{2g} - \frac{V_a^2}{2g}$$

$$f_2 = a \left(1 + \frac{b}{R} \right)$$

For cement plastered barrels, $a = 0.00316$, $b = 0.030$ (Table); Hydraulic radius,

$$R = A/P = (8 \times 2.5)/(2 \times (8 + 2.5)) = 0.953 \text{ m}$$

Length of barrels, $L = 16.4$ m

Substituting these values, we get

$$f_2 = 0.00326, \text{ and } h = \{1 + 0.505 + 0.00326 (16.4/0.953)\} 2.05^2 / (2 \times 9.81) = 0.333 \text{ m}$$

d/s HFL = 207.0 m (given)

Afflux (h) = 0.333 m

→ u/s HFL = d/s HFL + afflux (or loss of head)
= 207.0 + 0.333 = 207.333 m

Step 7. Uplift Pressure on Roof of Barrels

RL of bottom of trough = RL of canal bed – slab thickness = 206.4 – 0.4 = 206.0 m

Loss of head at entry of barrel = $0.505 \times V^2 / 2g = 0.505 \times 2.05^2 / 19.62 = 0.108$ m

Uplift on the roof = u/s HFL – Loss at entry – Level of underside of roof slab
= 207.333 – 0.108 – 206.0 = 1.225 m of water (=12.25 kN/m²)

The concrete trough slab is 0.4 m thick and will thus exert a downward load of $0.4 \times 24 = 9.6$ kN/m²

The balance of the uplift pressure, i.e. $12.25 - 9.6 = 2.56$ kN/m² has to be resisted by the reinforcement at the top in the roof slab. The roof slab has to be designed for full canal water load (1.6 m water) plus self weight, when the drainage water is low and not exerting any uplift. Suitable reinforcement at bottom of slab may be provided for this downward force.

Step 8. Design of roof of barrel

Uplift to be balanced by top reinforcement = 2.56 kN/m²

Downward water load acting when there is no uplift = 1.6 m of water = 16 kN/m²

Load due to self weight of slab = 9.6 kN/m²

Total downward load = $16 + 9.6 = 25.6$ kN/m²

The slab of the trough is designed for the above loads, considering both positive (due to downward loads) and negative (due to uplift from below) bending moments (reinforcement provided at bottom and top), and maximum shear.

Step 9. Uplift on the bottom of floor of barrel

(a) Static Head

RL of barrel floor = RL of trough bottom – height of barrel
= 206.0 – 2.5 = 203.5 m

Let a thickness of 0.8 m provided for the floor.

RL bottom of floor = $203.5 - 0.8 = 202.7$ m

Bed level of drain = 204.5 m (given)

Assuming that the water table has gone up to the bed level of the drain, the static uplift on the drain floor = $204.5 - 202.7 = 1.8$ m of water

b) *Seepage head*: The seepage head will be maximum when the canal is running full and the drain dry (empty).

Thus, the total seepage head = FSL of canal – bed level of drain

$$= 208.0 - 204.5 = 3.5 \text{ m}$$

The residual seepage head at point 'a' in the center of the first barrel has been calculated by Bligh's theory as

Assuming that the total length of the drainage floor = 30 m;

The seepage line *abc* will traverse creep length as follows:

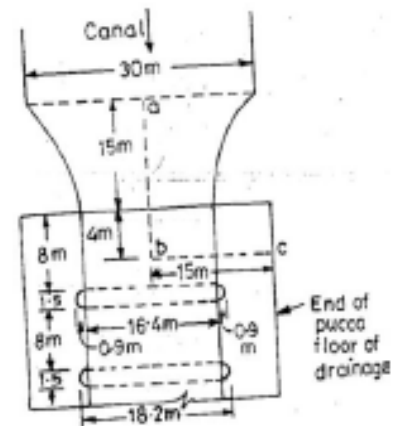
$$\begin{aligned} ab &= \text{length of u/s transition} + \text{half the barrel span} \\ &= 15 + 4 = 19 \text{ m} \end{aligned}$$

$$bc = 15 \text{ (half of the total length of 30 m)}$$

$$\text{Total creep length} = 19 + 15 = 34 \text{ m}$$

Residual seepage head at b

$$= 3.5 \left[1 - \frac{19}{34} \right] = 1.55 \text{ m}$$



$$\text{Total uplift} = \text{Static head} + \text{Seepage head} = 1.8 + 1.55 = 3.35 \text{ m of water}$$

The provided 0.8 m thickness of slab will resist due to its own weight, an uplift = $0.8 \times 24 = 19.2 \text{ kN/m}^2$

Therefore, balance to be resisted by reinforcement due to bending action = $3.35 \times 10 - 19.2 = 14.3 \text{ kN/m}^2$

Suitable reinforcement for this uplift has to be provided at the top of the culvert floor so as to counteract the bending action.

Total length of the floor:

- Length of floor required under barrel = 16.4 m
- Extra floor length required to accommodate pier noses on both sides = $2 \times 1.0 = 2.0 \text{ m}$
- Horizontal length of d/s ramp (5:1) = $5 (204.5 - 203.5)$ = 5.0 m
- Width of d/s cut-off beyond ramp = 0.6 m
- Length of extra floor provided on u/s side = 0.6 m

$$\text{Total length} = 30 \text{ m}$$

Step 10. Design of cutoffs and protection works for the drainage floor

Designed using the usual procedure adopted in previous chapters.

