Chapter 3

Water Structures

3-1 Introduction:

Water structures are the constructions used for irrigation and drainage projects. Figure (3-1) shows a general layout for different water structures for an irrigation and drainage project.

Figure (3-1): A General Layout for different Water Structures for Irrigation and Drainage Projects.
Water structures are divided into crossing structures and heading-up (control) structures.

1- Crossing Structures:

A- Intersection of a water channel with a road:
   (1) Bridge.
   (2) Culvert.

B- Intersection of two water channels:
   (1) Syphon.
   (2) Aqueduct.

2- Heading-up (Control) Structures:

A- Diversion Structures:
   (1) Weir.
   (2) Barrage and Regulator.
   (3) Escape.

B- Navigation Structures:
   Lock.

C- Storage Structures:
   Dam.

3-2 Elements of a Water Structure:

Any water structure consists of three main parts:

1- Superstructure: It includes reinforced concrete (R.C.) slabs and girders, masonry arches, rolled steel joists with timber flooring.

2- Substructure: It includes the supports(mainly abutments and piers) and the retaining walls.

3- Foundations.

3-3 Retaining Walls:

The retaining walls are constructed to withstand the earth pressure. The retaining walls are made of different materials such as brick or stone masonry for residential areas and parks, as shown in figures (3-2) and (3-3).

Concrete is used also for making the retaining walls for industrial areas and adjacent to bridges and dams. Plain concrete (P.C.) is easy to form and does not require steel but large quantities may be needed, as shown in figure (3-
4). Reinforced concrete (R.C.) is economical for large structures, as shown in figures (3-5), (3-6) and (3-7).

Figure (3-2): A Stepped Brick Wall.

Figure (3-3): A Stepped Brick Abutment with a Wall.

Figure (3-4): P.C. Gravity Retaining Walls.

Figure (3-5): R.C. Cantilever Retaining Walls.
3-4 Safety of a Water Structure:

1- The Superstructure: It has to be safe or stable against all existed forces such as dead loads, live loads and traffic loads.

2- The Substructure:
(1) Overturning. \[ F.O.S. = \left( \frac{M_{st.}}{M_{ov.}} \right) > 2 \]
(2) Stresses. \[ f_{1\&2} = \left( - \frac{N}{A} \right) \left( 1 \pm 6 \frac{e}{B} \right) \]
(3) Sliding. \[ F.O.S. = \left( \frac{\mu N}{H} \right) > 2 \]
Where, \( \mu \) is a coefficient of friction that depends on the soil type and ranges from 0.2 to 0.6.
3- The Foundation:

(1) Percolation:
Percolation occurs in the underlying permeable soil due to the head of water between both the upstream (US) and the downstream (DS). It causes undermining for the pervious soil which may lead to the collapse of the whole structure.

The length of the foundation floor (or apron) has to be enough to be stable against the percolation.

(2) Uplift Pressure:
The floor of the water structure is forced upwards due to the uplift pressure of the water filtering through the pervious soil under the foundation.

A net uplift diagram has to be established to check the stability against the uplift pressure.

(3) Downstream Erosion:
The soil downstream the water structure has to be protected against the erosive (scour) action of the falling water (such as the water falling over the sill of a weir).

End sill and/or stone pitching may be used.

The following figures from (3-10) till (3-17) show sketches for different water structures.

![Figure (3-10): Sectional Elevation for a R.C. Bridge.](image)

![Figure (3-11): Sectional Elevation for a R.C. Culvert.](image)
Figure (3-12): Sectional Elevation for a R.C. Syphon.

Figure (3-13): Sectional Elevation for a R.C. Aqueduct.

Figure (3-14): A Sketch for a Weir.

Figure (3-15): A Sketch for a Regulator.

Figure (3-16): A Sketch for a Lock.  Figure (3-17): A Sketch for a Dam.
3-5 Bridges:
A bridge is constructed at the intersection of a water channel (canal or drain) with a road. It is built to continue the road across the water channel.

3-6 Types of Bridges:
1- Reinforced Concrete (R.C.) Bridges:
   (1) Slab bridges: For short spans, 4 - 6 m.
   (2) Girder bridges: For spans up to 20 m.
   (3) Prestressed bridges: For large spans, 50 - 60 m.

![Figure (3-18): Isometric View for Reinforced Concrete RC Bridge.](image)

2- Arch Bridges:
They are built of stones, bricks, plain concrete (PC).
The most common types in Egypt are:
   (1) 90° - segmental arches: For spans up to 5 m.
   (2) Semi - circular arches: For small drains, where they are built directly on P.C. foundation without abutments.

![Figure (3-19): Isometric View for Arch Bridge.](image)
3- Rolled Steel Joist Bridges:
They are built of rolled steel joists either embedded in concrete or covered with timber flooring. They are used for:
   (1) Light traffic with spans 6 - 12 m.
   (2) Over deep mechanically cleaned drains.
   (3) Over channels of poor soils.

![Isometric View for Rolled Steel Joist Bridge](image)

4- Timber Bridges: For foot path.

5- Metallic Bridges: As the railway bridges.

3-7 Reinforced Concrete (R.C.) Bridges:

1) Hydraulic Design:
\[ v_{ch} = \frac{Q}{A_{ch}} \]
Where,
\[ v_{ch} \]: Velocity through the channel, m/sec
\[ Q \]: Discharge through the channel, m³/sec
\[ A_{ch} \]: Cross sectional area of the channel, m²

2) \[ v_v = (1 - 2) v_{ch} \]
Where,
\[ v_v \]: Velocity through the vent(s) of the bridge, m/sec

- \[ v_v \leq 1.5 - 2 \text{ m/sec for pitching or concrete lining.} \]
- \[ v_v \leq 0.9 \text{ m/sec for earth soils.} \]

3) \[ A_v = \frac{Q}{v_v} = n S y \]
Where,
\[ A_v \]: Cross sectional area of the vent(s) of the bridge, m².
\[ n \]: Number of the vents of the bridge.
\[ S \]: Span of each vent of the bridge, m.
\[ y \]: Depth of the water, m.
**Check:** \[ A_v \geq 0.6 \ A_{ch} \]

.: The design is --- vents, each vent has a span of --- m.

4- \[ v_v(\text{act}) = \frac{Q}{A_v(\text{act})} \]

Where, \( v_v(\text{act}) \): Actual velocity through the vent(s) of the bridge, m/sec

\[ A_v(\text{act}) = n \ S_{\text{act}} \ y \]: Actual cross sectional area of the vent(s) of the bridge, m².

(2) **Check of Heading Up (h):**

<table>
<thead>
<tr>
<th>One Vent</th>
<th>Multi Vents</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ h = \left( \frac{v_{ch}^2}{2gC^2} \right) \times \left( \frac{A_{ch}}{A_v} \right)^2 - 1 ]</td>
<td>[ h = \alpha \beta \ \frac{v_{ch}^2}{2g} ]</td>
</tr>
</tbody>
</table>

C : Coefficient of contraction, according to the span (\( S_{\text{act}} \)).

- \( S_{\text{act}} < 2 \text{ m} \), \( C = 0.72 \)
- \( 2 \text{ m} < S_{\text{act}} < 4 \text{ m} \), \( C = 0.82 \)
- \( S_{\text{act}} > 4 \text{ m} \), \( C = 0.92 \)

\( \alpha = (A_{ch} - A_v) / A_{ch} \)

\( \beta \): Coefficient according to the pier.

- \( \beta = 0.68 \) for semi-circular pier.

(3) **Empirical Design:**

As shown in figure (3-19), consider that the bridge consists of the three main items: the superstructure (reinforced concrete slab and girders), the substructure (abutments and piers) and the foundations.

![Empirical Design of R.C. Bridge](image-url)
1- Superstructure:
   - **The girders:**
     Spacing between the girders: \( l = (1 - 3) \text{ m} \)
     Effective span of the girder: \( L_{\text{eff}} = 1.05 \text{ S} \)
     Thickness of the girder: \( t_g = L_{\text{eff}} / (7 - 10) \)
     Width of the girder: \( b_g = (30 - 40) \text{ cm} \)
   - **The Slab:**
     Thickness of the slab: \( t_s = 1 / (8 - 12) \geq 20 \text{ cm} \)

2- Substructure:
   - **The Abutment:**
     Usually for \( H < 4 \text{ m} \), either P.C. gravity wall or R.C. cantilever wall can be used.
     When \( H \geq 4 \text{ m} \), R.C. wall with Counterforts is preferred.

   **R.C. Abutment with Counterforts:**
   - Top width: \( b = S / 10 \)
   - Bottom width: \( B = (0.4 - 0.66) \text{ H} = B_1 + B_2 \)
   - Width of the toe: \( B_1 = B / 3 \)
   - Width of the heel: \( B_2 = 2 B / 3 \)
   - Thickness of the stem: \( t_s' = 1 / (8 - 10) \geq 15 \text{ cm} \)
   - Spacing of Counterforts: \( = (H / 3 - H / 2) \)
   - **The Pier:**
     R.C. Pier: Top width: \( E = S / (3 - 4) \geq 1 \text{ m} \)
     Thickness: \( t_p = S / (6 - 12) \)
     P.C. Pier: Width: \( E = S / (3 - 4) \geq 1 \text{ m} \)

3- Foundations:
   - Thickness of R.C. foundation: \( t_{\text{R.C.}} = 1 / 6 \)
   - Thickness of P.C. foundation: \( t_{\text{P.C.}} \geq 25 \text{ cm} \)

---

Figure (3-22): R.C. Bridge.
Example (1):
It is required to construct R.C. bridge at the intersection of a road with a canal. The road width over the bridge is 7 m with 2 footpaths, each of 1.5 m.

Data for the canal:
The water slope is 8 cm/km, the roughness coefficient is 0.025 and the bed width is 18 m, as shown in the figure.

a) Design the bridge, where heading up is not to exceed 5 cm?
b) Design empirically the different elements of the bridge?
c) Draw a plan (H.E.R.) and a sectional elevation for the bridge?

Solution:

(1) Hydraulic Design:
1- \( v_{ch} = \frac{Q}{A_{ch}} \)
\[
A = by + z y^2 = (18*3) + (1*(3)^2) = 63 \text{ m}^2
\]
\[
P = b + 2 (y^2 + z^2 y^2)^{1/2} = 18 + 2 (3^2 + 1^2 3^2)^{1/2} = 26.49 \text{ m}
\]
\[
R = \frac{A}{P} = \frac{63}{26.49} = 2.38 \text{ m}
\]
\[
Q = A x v_{ch} = (1/0.25) x (2.38)^{2/3} x (8*10^{-5})^{1/2} = 0.64 \text{ m/sec}
\]
\[
v = (1 - 2) v_{ch} = (1 - 2) * 0.64 = 0.64 - 1.28 \text{ m/sec} \approx 1 \text{ m/sec}
\]

2- \( v = n S y \)
\[
A_v = \frac{Q}{v} = n S y
\]
\[
n S y = (63*0.64) / 1 = 40.32 \text{ m}^2
\]
\[
S = 40.32 / (2*3) = 6.72 \text{ m} \approx 7 \text{ m}
\]
\[
\therefore \text{ The design is 2 vents; each vent has a span of 7 m.}
\]

3- \( v_{v(act)} = \frac{Q}{A_{v(act)}} \)
\[
A_{v(act)} = n S_{(act)} y = 2*7*3 = 42 \text{ m}^2
\]
\[
\therefore v_{v(act)} = (63*0.64) / 42 = 0.96 \text{ m/sec}
\]

(2) Check of Heading Up (h):
\[
h = \alpha \beta \frac{v_{ch}^2}{2g}
\]
\[
h = 0.33 * 0.68 * \frac{0.64}{2*9.81}^2
\]
\( \alpha = (A_{ch} - A_v) / A_{ch} = (63 - 42) / 63 = 0.33 \quad \therefore h = 0.0047 \text{ m} = 0.5 \text{ cm} < 5 \text{ cm} \)

\( A_v \geq 0.6 \text{ Ach} \quad (2 \times 7 \times 3 = 42) \geq (0.6 \times 63 = 37.8) \)

(3) **Empirical Design:**

1- **Superstructure:**

- The girders:
  - Spacing between the girders: \( l = (1 - 3) \text{ m} = 1 \text{ m} \)
  - Effective span of the girder: \( L_{eff} = 1.05 \times S = 1.05 \times 7 = 7.35 \text{ m} \)
  - Thickness of the girder: \( t_g = L_{eff} / (7 - 10) = 75 \text{ cm} \)
  - Width of the girder: \( b_g = (30 - 40) \text{ cm} = 35 \text{ cm} \)

- The Slab:
  - Thickness of the slab: \( t_s = l / (8 - 12) = (20 - 30) \text{ cm} = 20 \text{ cm} \)

2- **Substructure:**

- The Abutment:
  - \( H > 6 \text{ m} \), R.C. wall with Counterforts is preferred.
    - Top width: \( b = S / 10 = 70 \text{ cm} \)
    - Bottom width: \( B = (0.4 - 0.65) \times H = (0.4 - 0.65) \times 5 = 2.1 \text{ m} = B_1 + B_2 \)
    - Width of the toe: \( B_1 = B / 3 = 0.7 \text{ m} \)
    - Width of the heel: \( B_2 = 2B / 3 = 1.4 \text{ m} \)
    - Thickness of the stem:\( t_s' = l / (8 - 10) = 15 \text{ cm} \)
    - Spacing of Counterforts: \( = (H / 3 - H / 2) = 2 \text{ m} \)

- The Pier: R.C. Pier:
  - Top width: \( E = S / (3 - 4) = 2 \text{ m} \)
  - Thickness: \( t_p = S / (6 - 12) = 70 \text{ cm} \)

3- **Foundations:**

- \( t_{R.C.} = 1 / 6 = 20 \text{ cm} \)
- \( t_{P.C.} = 30 \text{ cm} \)
3-8 Culvert:

Figure (3-23): Isometric View for R.C. Box Culvert.

Figure (3-24): Types of Culvert.

Figure (3-25): Arch Culvert.
Figure (3-26): Pipe Culvert.

Figure (3-27): R. C. Box Culvert.
(1) **Hydraulic Design:**

1. \( v_{ch} = \frac{Q}{A_{ch}} \)
2. \( v_c = (2 - 3) v_{ch} \)
3. \( A_c = \frac{Q}{v_c} = n S^2 \)
4. \( O R A_c = \frac{Q}{v_c} = n \pi d_i^2 / 4 \)

(2) **Check of Heading Up (h):**

\[
h = (v_{c_{act}}^2 / 2g) * (C_{en} + C_f + C_{sc} + C_{exit})
\]
\[ C = a \left( 1 + \frac{b}{R} \right) \frac{L}{R} \]

<table>
<thead>
<tr>
<th></th>
<th>R.C.</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.003</td>
<td>0.004</td>
</tr>
<tr>
<td>b</td>
<td>0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>

\( C = C_f \)

L: length of culvert.

\( R = A/P \) Hydraulic Radius.

\[ C_{sc} = \phi \left( \frac{t}{b} \right)^{\frac{4}{3}} \sin \alpha \]

For circular steel bar \( \phi \) 16 mm, \( \phi = 1.77 \), \( t = 1.6 \) cm, \( b = 10 \) cm, \( \alpha = 60^\circ \)

\[ C_{sc} = 0.13 \]

\[ C_2 = 1.0 \]

\[ C_2 = 0.3 \]

\[ C_2 = 0.8 \]
Example (2):
Given: \( AS_c = 16,000 \) Feddan \( WD_c = 80 \text{ m}^3/\text{Fed/day} \) \( h \leq 20 \text{ cm} \)

**Canal Data:**

![Canal Diagram]

**Road Data:**

![Road Diagram]

**Solution:**

1. **Hydraulic Design:**
   \[
   v_{ch} = \frac{Q}{A_{ch}}
   \]
   \[
   A_{ch} = b y + z y^2 = (7.5 \times 2.25) + (1.5 \times (2.25)^2) = 24.5 \text{ m}^2
   \]
   \[
   Q = \frac{(16,000 \times 80)}{(24 \times 60 \times 60)} = 14.8 \text{ m}^3/\text{sec}
   \]
   \[
   v_{ch} = \frac{Q}{A_{ch}} = 0.6 \text{ m/sec}
   \]

2. \[
   v_c = (2 - 3) v_{ch} = (2 - 3) \times 0.6 = 1.2 - 1.8 \text{ m/sec} \approx 1.2 \text{ m/sec}
   \]

3. \[
   A_c = \frac{Q}{v_c} = n S^2
   \]
   \[
   12.3 = n S^2
   \]

<table>
<thead>
<tr>
<th>( n )</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S )</td>
<td>3.5</td>
<td>2.48 \approx 2.5</td>
</tr>
</tbody>
</table>

![Table Diagram]

XXX | OK
The design is 2 vents; each vent has a span of 2.5 m.

4. \( v_{c(\text{act})} = \frac{Q}{A_{c(\text{act})}} \)

\( A_{c(\text{act})} = n S_{(\text{act})}^2 = 2 \times 2.5^2 = 12.5 \text{ m}^2 \)

\( v_{c(\text{act})} = \frac{14.8}{12.5} = 1.18 \text{ m/sec} \)

\[ (2) \text{ Check of Heading Up (h):} \]

\[ h = \left(\frac{v_{c(\text{act})}^2}{2g}\right) \times (C_{\text{en}} + C_f + C_{\text{sc}} + C_{\text{exit}}) \]

\( C_{\text{en}} = 0.2 \)  Rounded wall

\[ C = a\left(1 + \frac{b\ L}{R}\right) \]

\( R = \frac{A}{P} = \frac{S^2}{4} = \frac{S}{4} = \frac{2.5}{4} = 0.63 \text{ m} \)

\( C = 0.003\left(1 + \frac{0.03}{0.63}\right) \times \frac{18.5}{0.63} \)

\( C_f = 0.1 \)

For circular steel bar \( \phi \) 16 mm, \( \phi = 1.77, t = 1.6 \text{ cm}, b = 10 \text{ cm}, \alpha = 60^\circ \)

\( C_{\text{sc}} = 0.13 \)

\( C_{\text{exit}} = 1 \)  Box wall

\[ h = \left\{ \left(\frac{1.18}{2 \times 9.81}\right) \right\} \times (0.2 + 0.1 + 0.13 + 1) = 0.1015 \text{ m} \]

\[ = 10.15 \text{ cm} < 20 \text{ OK} \]

For Pipe Culvert:
3-9 Syphon:

(1) Hydraulic Design: As the culvert.
(2) Check of Heading Up (h):

\[ h = \left( \frac{v_{c_{act}}^2}{2g} \right) \times \left( C_{en} + C_f + C_{sc} + C_{\text{bend/angle}} + C_{\text{exit}} \right) \]

<table>
<thead>
<tr>
<th>Bend</th>
<th>Elbow</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{\text{bend}} = C_3 \times (\theta / 90) )</td>
<td>( C_{\text{elbow}} = \sin^2 \frac{\theta}{2} + 2 \sin^4 \frac{\theta}{2} )</td>
</tr>
<tr>
<td>( r/R )</td>
<td>( \theta )</td>
</tr>
<tr>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>0.3</td>
<td>40</td>
</tr>
<tr>
<td>0.4</td>
<td>60</td>
</tr>
<tr>
<td>0.5</td>
<td>80</td>
</tr>
<tr>
<td>0.6</td>
<td>90</td>
</tr>
<tr>
<td>( C_3 \text{Pipe} )</td>
<td>0.14</td>
</tr>
<tr>
<td>( C_3 \text{Box} )</td>
<td>0.18</td>
</tr>
<tr>
<td>0.4</td>
<td>0.464</td>
</tr>
</tbody>
</table>

r: radius of pipe or (Height/2) for box
R: radius of curvature for syphon

\( C_{\text{elbow}} \) is neglected for \( \theta < 20^\circ \)
Figure (3-28): Cases of loading for the Syphon.

Figure (3-29): Arch Syphon.
Example (3):

<table>
<thead>
<tr>
<th></th>
<th>Drain</th>
<th>Canal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge, Q, m³/sec</td>
<td>7</td>
<td>---</td>
</tr>
<tr>
<td>W.L., m</td>
<td>(4.50)</td>
<td>(6.00)</td>
</tr>
<tr>
<td>Bed L., m</td>
<td>(2.50)</td>
<td>(4.50)</td>
</tr>
<tr>
<td>Bed Width, m</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Bank L., m</td>
<td>---</td>
<td>(7.50)</td>
</tr>
<tr>
<td>Bank Width, m</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Side Slope, channel</td>
<td>3:2</td>
<td>1:1</td>
</tr>
<tr>
<td>Side Slope, bank</td>
<td>2:1</td>
<td>2:1</td>
</tr>
</tbody>
</table>

\[ C_f + C_{sc} = 0.65 \]

**Solution:**

(1) **Hydraulic Design:**

1- \[ v_d = \frac{Q}{A_d} \]

\[ A_d = b y + z y^2 = (3 \times 2) + (1.5 \times (2)^2) = 12 \text{ m}^2 \]

\[ v_d = \frac{Q}{A_d} = 7 / 12 \approx 0.6 \text{ m/sec} \]

2- \[ v_{sy} = (2 - 3) v_d = (2 - 3) \times 0.6 = 1.2 - 1.8 \text{ m/sec} \approx 1.2 \text{ m/sec} \]

3- \[ A_{sy} = \frac{Q}{v_{sy}} = n S^2 \]

\[ 7 / 1.2 = 5.83 = n \pi d_i^2 / 4 \]

\[ \therefore 7.42 = n \times d_i^2 \]

<table>
<thead>
<tr>
<th>n</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_i</td>
<td>2.72 ≈ 2.7</td>
<td>1.93 ≈ 1.9</td>
</tr>
</tbody>
</table>

\[ 2 \times 1.9 = 3.8 \geq 3 \]

OK | XXX
The design is 1 vent; which has a diameter of 2.25 m.

4- \[ v_{sy(\text{act})} = \frac{Q}{A_{sy(\text{act})}} \]
\[ A_{sy(\text{act})} = n \pi d_{(\text{act})}^2 / 4 = 1 * \pi * 2.25^2 / 4 = 4 \text{ m}^2 \]
\[ \therefore v_{sy(\text{act})} = (7 / 4) = 1.75 \text{ m/sec} \]

(2) Check of Heading Up (h):
\[ h = \left( \frac{v_{sy(\text{act})}^2}{2g} \right) * (C_{\text{en}} + C_{f} + C_{sc} + C_{\text{bend/elbow}} + C_{\text{exit}}) \]

\[ C_{\text{en}} = 0.2 \quad \text{Rounded wall} \]

\[ C_{\text{exit}} = 1 \quad \text{Box wall} \]

\[ \tan \theta = 0.27 / 11.25 = 0.024 \quad \therefore \theta = 1.4^\circ < 20^\circ \]

\[ C_{\text{bend/elbow}} = 0 \quad \text{(neglected)} \]

\[ C_{f} + C_{sc} = 0.65 \]

\[ h = \left( \frac{v_{sy(\text{act})}^2}{2g} \right) * (C_{\text{en}} + C_{f} + C_{sc} + C_{\text{bend/elbow}} + C_{\text{exit}}) \]
\[ = \{1.75^2 / (2*9.81)\} * (0.2 + 0.65 + 1) \]
\[ = 0.2888 \text{ m} > 20 \text{ cm} \quad \text{Unsafe} \]

Take \[ C_{\text{exit}} = 0.3 \quad \text{(Box with expanding)} \]

\[ \therefore h = \{1.75^2 / (2*9.81)\} * (0.2 + 0.65 + 0.3) \]
\[ = 0.1795 \text{ m} < 20 \text{ cm} \quad \text{OK} \]