Seawalls, Revetments & Bulkheads
Seawalls & Dikes

- massive structure
- primarily designed to resist wave action & prevent inland flooding from major storm events along high value coastal property
- key functional element in design is the crest elevation → minimize the overtopping from storm surge and wave runup
- either gravity- or pile-supported structures (weight providing stability against sliding forces and overturning moments)
- concrete or stone.
- variety of face shapes
Typical Seawalls

1. Curved-Face
2. Combination Stepped and Curved-Face
3. Stepped-Face
4. Rubble
Typical Seawalls

**Figure V-3-4.** Different types of seawalls and dikes (from Pilarczyk 1990)
Virginia Beach opted for a low-crest elevation, sheet-pile, concrete cap seawall that also serves as a new boardwalk.
Revetments

• facing of erosion resistant material (stone or concrete)
• built to protect a scarp, embankment, or other shoreline feature against erosion
• major components: armor layer, filter, and toe
  • armor layer provides the basic protection against wave action
  • filter layer supports the armor,
    – allows water to pass through the structure
    – and prevents the underlying soil from being washed through the armor
  • toe protection prevents displacement of the seaward edge of the revetment
Revetment & Riprap

- The design practice same as for rubble mound breakwaters.
- More care should be exercised in filter design.
- Application of geotextile filter is common.
- Prevent toe scouring, piping, bank instability and other hydraulically related failure modes.
- Grading of the stone must be more tightly controlled than for breakwater
Typical Revetment
Typical Revetments

Figure V-3-8. Summary of revetment alternatives (continued)
Typical Revetment
Typical Revetment
Figure 1, Typical layer arrangement of block revetment

Loose Block

Articulated Mat
<table>
<thead>
<tr>
<th>COMPARATIVE PROPERTIES</th>
<th>TYPES OF POLYMER</th>
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<td>Polyester</td>
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<td>Strength</td>
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<td>Elastic modulus</td>
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<td>RESISTANCE TO:</td>
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<td>Alkalis</td>
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<td>Fungus, vermin, insects</td>
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<td>Fuel</td>
<td>M</td>
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<tr>
<td>Detergents</td>
<td>H</td>
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H = High, M = Medium, L = Low
(A) Fabric sections being sewn together

(B) Fabric being pinned in place

(c) In situ heat welding operation
Armoflex blocks and mat construction

Terrafix interlocking blocks
(A) Interlocking concrete grids serve as base for plants

(B) Salt water resistance grass planted on top
Bulkheads

• Vertical retaining walls (hold or prevent soil from sliding seaward).
• Reduce land erosion vice mitigate coastal flooding and wave damage.
  – For eroding bluffs and cliffs → increase stability by protecting the toe from undercutting.
• Cantilever bulkheads
  – derive their support from ground penetration;
  – effective embedment length must be sufficient to prevent overturning.
  – Toe scour results in a loss of embedment length → threatens the stability of such structures.
• Anchored bulkheads
  – gain additional support from anchors embedded on the landward side or from structural piles placed at a batter on the seaward side.
  – corrosion protection at the connectors is particularly important to prevent failures.
• Gravity structures (rock-filled timber cribs and gabions)
  – eliminate the expense of pile driving
  – can often be used where subsurface conditions support their weight or bedrock is too close to the surface to allow pile driving.
  – require strong foundation soils to adequately support their weight,
  – normally do not sufficiently penetrate the soil to develop reliable passive resisting forces on the offshore side → depend primarily on shearing resistance along the base of the structure to support the applied loads.
  – cannot prevent rotational slides in materials where the failure surface passes beneath the structure.
Bulkhead Types

Figure V-3-7. Typical bulkhead types
Typical Sheet-Pile Bulkhead with Anchor

A splash apron may be added next to coping channel to reduce damage due to overtopping.

Dimensions and details to be determined by particular site conditions.

- Coping channel
- Top of bulkhead
- Former ground surface
- Tie rod
- Timber block
- Round timber pile
- Tide Range
- Timber wale
- Steel sheet piles
- Sand fill
Bulkhead Alternatives
Functional Design

• The functional design of coastal armoring structures involves calculations of
  – wave runup,
  – wave overtopping,
  – wave transmission, and reflection.

• These technical factors together with economic, environmental, political (social), and aesthetic constraints all combine to determine the crest elevation of the structure.
Vertical Wall Height Considerations

- Freeboard ($F$)
- Reflected wave height ($H$)
- Wave set-up ($\delta_w$)
- Storm surge ($\delta_s$)
- Mean high spring tide ($\delta_t$)
- Chart Datum ($D$)
- Dredge line ($S$)
- Scouring depth

$h_e$
General Design Procedure

1. Determine water level range
2. Determine wave heights
3. Determine run-up
4. Determine overtopping for low structures
5. Set the crest elevation
6. Select suitable armor & Select armor unit size
7. Design under-drainage features if they are required.
8. Provide for local surface runoff and overtopping runoff, and make any required provisions for other drainage facilities such as culverts and ditches.
9. Consider end conditions to avoid failure due to flanking
10. Design toe protection
11. Design filter and underlayers
12. Provide for firm compaction of all fill and backfill materials.
13. Develop cost estimate for each alternative.
Forces on Vertical Bulkhead Structures

main consideration with respect to structural stability, the stability of water front retaining walls is concerned with back side earth pressure and above ground surcharge
Forces on Vertical Bulkhead Structures

Static forces:
• active soil and water pressures from the backfill
• water and passive soil pressures on the seaward side
• anchor forces (when applicable)

Dynamic forces:
• wave action and seepage flow within the soil. (Wave impacts increase soil pressure in the backfill and require larger resisting passive earth pressures and anchor forces to ensure stability)
• berthing and mooring forces (when applicable).
Forces on Vertical Bulkhead Structures

Design Low Water condition concerns:
- active earth pressure
- passive earth pressure
- residue water pressure
- surcharge
- scour

Design High Water condition concerns:
- overtopping
- wave impact loading on structural components
Lateral Earth Pressures

• Active earth pressure
  – wall moves away from the embankment a wedge of soil will expand
  – horizontal pressure exerted on the wall under this state is known as active pressure, $P_A$
  – $K_a$ is the active pressure coefficient ($= \sigma_h / \sigma_v$) and $\sigma_z$ is the effective normal stress at elevation $z$

$$K_a = \tan^2 (45^\circ - \phi/2)$$

$$P_A = K_a \sigma_z - 2c \sqrt{K_a}$$
Lateral Earth Pressures

• Passive earth pressure
  – wall moves towards the embankment a wedge of soil will compress
  – horizontal pressure exerted on the wall under this state is known as passive pressure, $P_p$
  – $K_p$ is the active pressure coefficient ($= \sigma_h / \sigma_v$)

\[ K_p = \tan^2 \left( 45^\circ + \phi/2 \right) \]

\[ P_p = K_p \sigma_z + 2c \sqrt{K_p} \]
Lateral Earth Pressures

\[ \sigma_z = \gamma_a z + \sigma_s \]

\( \sigma_s \) is the added stress due to surcharge.
\( \gamma_a \) is the effective specific weight of soil,
- varies with soil properties, water content and degree of compaction
- computed by

\[ \gamma_a = \frac{W}{V} = \frac{1+w}{1+e} G \gamma_w \]
Soil Properties

- \( W \) = weight of soil dry soil specific weight, about
- \( V \) = volume of soil = water specific weight.
- \( e \) = void ratio = \( V_w / V_s \).
- \( w \) = \( W_w / W_s \) = water content.
- \( G \) = specific gravity of dry soil = \( \gamma_s / \gamma_w \).
- \( \gamma_s \) = approximately 165 lb/ft\(^3\), or 2.65 ton/m\(^3\).
- \( \gamma_w \) = 62.4 lb/ft\(^3\), or 1.0 ton/m\(^3\).
Multi-layer Soil & Sloped Wall

Sloped Wall Multi-layer Condition

Simple Multi-layer Condition

Rupture Angle, $\zeta = 90 - (45 - \phi/2)$
Sloped Wall

\[ P_a = K_{ai} \left[ \Sigma \gamma_i h_i + \frac{w \cos \alpha}{\cos(\alpha - \beta)} \right] \cos \alpha \]

\[ K_{ai} = \frac{\cos^2(\phi - \alpha)}{\left( \cos^2 \alpha \right) \cos(\delta + \alpha) \left[ 1 + \sqrt{\frac{\sin(\phi_i - \beta) \sin(\phi_i + \delta)}{\cos(\alpha + \delta) \cos(\alpha - \beta)}} \right]^2} \]

\[ P_p = K_{pi} \left[ \Sigma \gamma_i h_i + \frac{w \cos \alpha}{\cos(\alpha - \beta)} \right] \cos \alpha \]

\[ K_{pi} = \frac{\cos^2(\phi - \alpha)}{\left( \cos^2 \alpha \right) \cos(\delta + \alpha) \left[ 1 + \sqrt{\frac{\sin(\phi_i + \beta) \sin(\phi_i - \delta)}{\cos(\alpha + \delta) \cos(\alpha - \beta)}} \right]^2} \]
Sloped Wall

$\phi_i =$ internal soil friction angle in layer $i$.
$\alpha =$ bulkhead angle.
$\delta =$ friction angle between soil and wall.
$\beta =$ surcharge angle.
$C_i =$ soil cohesion strength (undrained shear strength).
$h_i =$ soil layer thickness.
$\gamma_i =$ effective specific weight in layer $i$. 
Sheet-pile Design, Force Balance

(a) Sandy material

(b) Hard clay material

\[ L = H + D_n \]

\[ H_A \]

\[ D_0 \]

\[ D_n \]

\[ D_A \]

\[ B_n \]

\[ A_p \]

\[ P_1 \]

\[ P_2 \]
Sheet-pile Design, Force Balance

• Solve for depth of embedment \((D_n)\) by moment balance \(\Rightarrow\) moment about anchor point (i.e. moment from \(T = 0\)).

• If scouring is anticipated the reference level should be set at the scouring line instead of the intersect of the original ground with the seawall.

\[ M_R > SF \times M_a \]

- \(SF = 1.5\), normal conditions
- \(SF = 1.2\), special conditions, e.g. Earthquake…
  design to larger load but rarer occurrence

\(M_a\): active moment from the section

\(M_R\): resistance or passive moment from the section
Determine design force for pile

\[ V(z) = \int_0^z q(z) \, dz \]
\[ M(z) = \int_0^z v(z) \, dz \]

- The shear and moment distributions on the wall can be constructed from the force diagram first by assuming the wall is rigid with no deflection.
- \( q, V \) and \( M \) are force, shear and moment, respectively.
Determine design force for pile

- Under ordinary situation, the shear stress can be neglected.
- The required section modulus of the wall section is then determined by,

\[ Z = \frac{M}{\sigma_a} \]

where \( \sigma_a \) is the allowable tensile strength of the wall material.
Anchor Design

Set Anchor Point -

- Optimum is above residue water line (may be on pile cap)
- Minimum above MHHW
- Higher anchor $\rightarrow$ larger anchor block $\rightarrow$ larger tension

[Diagram showing anchor on cap and anchor not on cap, with anchor block and reinforcing required noted.]
Anchor Design

Anchor block design criteria:

1. Located as close to the bulkhead as possible

2. Far enough that the full passive earth pressure can be utilized to resist the anchor pull.

3. The vertical position should be above ground water level but with sufficient overburden. This is particularly important when the anchor pull is not horizontal such as the practice of tying the anchor rod to the cap of the wall.

4. The anchor should be located far enough so that it will not add loading to the wall.
Figure 5-8. Minimum anchor-wall spacing for full passive anchor resistance in homogeneous soil.
Anchor Design

Sand, $c = 0$

Clay, $\phi = 0$
Anchor Design

The depth of the anchor block, $D$, is determined by equating the allowable anchor pull to the anchor resistance:

$$\frac{F_R}{S.F.} = \gamma_s (K_p - K_a) \left( h + \frac{D}{2} \right) D$$

$F_R$ = horizontal anchor pull, or the anchor tension at the set point at the wall;
$h$ = embedment depth at the top of the anchor block.;
S.F. is the safety factor and a value of about 2 or larger is used to account for the uncertainty of the soil properties.

Since the pressure distribution on the anchor block is trapezoidal, the connection of the tie rod to the block should pass the centroid of pressure distribution to minimize anchor rotation.
Anchor Design

- the section of anchor block is designed against the stress induced by anchor rod and earth pressure
- the shear stress can be neglected considering only the bending stress
- it is common practice to treat the anchor block as continuous beam in the horizontal direction and cantilever in the vertical direction.
- The corresponding bending moments are

\[ M_h = \frac{TL}{12} \quad M_v = \frac{TD}{8} \]
Failure Modes

Figure 5-1. Deep-seated failure
Failure Modes

Figure 5-2. Rotational failure due to inadequate penetration

a. Cantilever wall

b. Anchored wall
Failure Modes

Figure 5-3. Flexural failure of sheet piling

a. Cantilever wall

b. Anchored wall
Failure Modes

a. Anchor passive failure

b. Tie rod failure
Failure Modes

c. Wale system failure