Design of Vertical Sheet-Pile walls and Bulkheads

Function
Seawalls are shore-parallel structures designed to protect upland installations such as houses and roads, port facilities or artificially filled land areas. The term "bulkhead" is sometimes used interchangeably with seawall; however, structures intended as docks, wharves, or boat landings are almost always referred to as bulkhead structures. Sheet piles are one of the most common types of earth retention structures.

The most common materials for seawalls and bulkheads are steel, concrete and timber.

1. Steel Piles:
   a. Steel sheet-piling is the most widely used bulkhead material.
   b. Steel piles can be driven into the foundation without extensive excavation. It can be driven into hard, dense soils and even soft rock.
   c. They are suitable for structures requiring deep penetration, large water depth, free standing or the combinations.
   d. Sections of various Geometries and sizes are available on the market from different manufacturers.
   e. The interlocking feature of the sheet-pile sections provides a relatively sand- or soil-tight fit that generally precludes the need for filters. This close fit may also be essentially water-tight, so regularly spaced weep holes are recommended. These and lifting holes in the piling should be backed with a proper filter to preclude loss of backfill material.
   f. In marine environment, the material is susceptible to corrosion, particularly in warm climates. The splash zone (between mean low water and the upper limit of wave contact) and areas near mud line are most vulnerable to corrosion. Protective coatings such as bitumen or concrete encasement are recommended.
Cathodic protection or coatings can be employed to prevent underwater corrosion. Pilings of corrosion resistance material are also available at added cost. However, some corrosion resistant materials only work well when the oxygen supply is adequate and are ineffective in regions where the oxygen supply is poor, such as near the mudline.

g. Steel piles are usually heavy and require heavy equipment for installation.

2. **Concrete Piles**:
   a. Concrete pile is suitable for temperate climate.
   b. Steel reinforced concrete is the most common construction material for small to modest sized structures, such as those used for residential and condominium protection.
   c. Prefabricated panels of 5 to 8 m (16 to 24 ft) deep with tongue-and-groove joint can be installed with high efficiency. A dense concrete of rich mix is recommended with a water to cement ratio of 0.44 to 0.40.
   d. Reinforcing steel should be covered with at least three inches of concrete to prevent sea water seepage which induces corrosion.
   e. For larger depths pre-stressed concrete piles are recommended. This limits the above-mudline length to less than 8 to 10 meters under most of the circumstances.
   f. Concrete piling costs considerably less than steel piling but is somewhat limited in depth. Material strength limits the concrete sheet piles to about 15 to 18 meters long. Concrete pile is also difficult to handle and impractical to drive with common equipment.

3. **Timber Piles**:
   a. Timber is only suitable for minor structures. The advantage of timber is that construction is simplified, requiring little or no excavation and no heavy equipment.
   b. Because of its rigidity and its high resistance to tension stress, timber piles often require no anchors or wales. Supporting posts can be driven at adequate spaces with cross members directly fastened to them.
   c. Timber is particularly suitable in cold region because it will not become brittle or crack due to low temperature.
   d. In warm weather, timber is subject to attack by marine borers such as ship worm, teredo or other crustacean spieces. To protect timber from marine borers or fungus attack, it can be impregnated with a creosote-coal tar solution or other chemical solutions. However, environmental concerns have vastly limited the types of solutions permitted for marine usage.
   e. The performance of timber as a seawall material is not uniform and hard to control. Some timber structures lasted for decades or even centuries; many, however, failed within few years.
Typical layout for sheet pile structures
Typical layout for sheet pile structures
Design Procedure

1. Solve for depth of embedment ($D_n$) by moment balance → moment about anchor point (i.e. moment from $T = 0$). Depth of embedment is the sheet pile penetration depth below the sea bottom. 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.

$$L = H + D_n$$

**Force Balance Diagram on a Vertical Wall Panel**

Beam Diagram

- $M_s$: active moment from the section
- $M_R$: resistance or passive moment from the section

**Equations**

$$M_R > SF \times M_a$$

- $SF = 1.5$, normal conditions
- $SF = 1.2$, special conditions, e.g. Earthquake…
  - design to larger load but rarer occurrence
Design of Wall Section \textarrow \text{Determine design force for pile}

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 so that,

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

and

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

where q, V and M are force, shear and moment, respectively. Fig. 9 shows an example of the q-, V- and M-diagram on a wall section. The values of maximum M and V are used to determine the required cross-section of the wall.

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.

For steel pile moment reduction is allowed since the material is elastic and it will deflect under lateral loading. The effect of the wall deflection is known to reduce the moment on the pile due to stress redistribution in the soil. This reduction could be substantial if the deflection is large. Therefore, the rigid beam solution given above will result in over design which could be by a large margin at times. The reduction factor, \( \eta_d \), defined as the ratio of the reduced moment to the theoretical moment under rigid condition is determined empirically with the aid of a design diagram. Since the moment...
reduction and the deflection are mutually dependent, the design cross-section is not unique.

A Multiple number of cross-sections can all satisfy the stress criterion. A lighter cross-section generally costs less but deflects more than a heavier cross-section. An optimum design selection is then determined by the allowable deflection.

2. Anchor design

![Anchor diagram]

a. Set Anchor Point -
   i. Optimum is above residue water line (may be on pile cap)
   ii. Minimum above MHHW
   iii. Higher anchor $\rightarrow$ larger anchor block $\rightarrow$ larger tension

b. Solve for anchor force $\sum F = 0$

The following criteria are to be observed in the anchor block design:

a. The anchor should be located as close to the bulkhead as possible but should be far enough that the full passive earth pressure can be utilized to resist the anchor pull.

b. 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.

c. The anchor should be located far enough so that it will not add loading to the wall.

The zone of optimal anchor location is shown in Fig.11. The effective penetration level, or the maximum depth where active pressure exists, is first determined. This level is taken as the level of maximum moment beneath the dredge line. Beyond this level counter resistance begins to manifest. If there is no maximum moment level the effective penetration is taken as taken to be the end of the pile. The anchor must be situated in the passive wedge zone as shown to fully utilize the earth resistance.
Optimum Location for anchor block

For the anchor to not add any loading to the wall, it must located in the zone of no added pressure. The critical angle $\alpha_c$ could be determined by the Culman method.

We first express the wedge of weight of $W$ behind the wall in terms of the wedge angle $\alpha$ as shown in Fig 12-A. The free body diagram is given in Fig.12-B. The horizontal force acting on the wall due to this wedge is the quantity $Q_h$. This quantity clearly varies with angle $\alpha$. Thus, a $Q_h$-$\alpha$ diagram can be constructed as shown in Fig.12-C. In this diagram a maximum value of $Q_h$ exists. The $\alpha_c$ is determined so that the combined earth loading and the anchor reaction will not exceed the $Q_h$ maximum.

Culman’s diagram for determining anchor location

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

$$\frac{F_R}{S.F.} = \gamma_s (K_p - K_a) \left( h + \frac{D}{2} \right) D$$
where $F_R$ = 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 as shown in Fig. 13 the connection of the tie rod to the block should pass the centroid of pressure distribution to minimize anchor rotation.

Finally, the section of anchor block is designed against the stress induced by anchor rod and earth pressure. Again, the shear stress can be neglected considering only the bending stress. In this case, 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, therefore,

$$M_h = \frac{TL}{I_2}$$

$$M_v = \frac{TD}{8}$$

**Tie Rod and Wale Design**

Some standard wale and tie rod arrangement for sheet pile structures are shown in Fig. 14. The tie rod is designed for allowable pull, $f_a$. Additional allowance of about 1/4 in. (About 0.65 cm) in diameter is recommended for salt water applications. The connections of rod to wall and anchor block are designed for 1.2 to 1.4 times the allowable pull. The rods are usually protected by wrapping, painting, or encasement. For long rods, intermediate vertical supports and/or turn buckles are used to eliminate sag.

The wale structure usually composes of two channels set back to back or I-beam section to provide needed rigidity of wall panels between tie rods. It is designed as a continuous beam of uniform load supported by tie rods. The bending moment experienced by the wale section is then determined by,
\[ M = \frac{TL}{10} \]

where \( T \) is the tension in tie rod and \( L \) is the spacing between tie rods. For tie rod set at an angle, the tension is computed by:

\[ T = F_r \sec \theta \]

where \( \theta \) = tie rod angle with respect to horizontal.

**Backfill and Drainage**

Backfill in the anchor zone should be compacted to achieve the desired resistance. Near the wall, however, the material should be sufficient porous to allow adequate drainage. Drain holes should be tapped on the wall with adequate frequency. The location of the drain hole should be above the mean high water line. If the material behind the wall contains fine soil filter cloth might have to be installed to prevent excessive leaching of material. For seawall of inadequate elevation, it is advisable to install a drain field using pebbles or gravel field. A hard surface made of reinforced concrete also could prove to be effective against erosion caused by overtopping. Such hard surface must be constructed on adequate and well-drained foundation to be effective.