8.3 Anchored Bulkheads

Description

Anchored bulkheads are used at waterfront areas to prevent soil erosion and to provide areas suitable for docking. Bulkheads range from 2 inches or 3 inches thick tongue and groove timber sheet pile construction, to 12 inches deep steel "Z" piles. This application computes net pressures on the bulkhead, required depth of embedment of the sheet piles, maximum bending moment and the bending moment at the tie rod anchor point, the total active soil and water pressure, the net passive earth pressure reaction, and the tie rod anchor force using the "free earth" method.

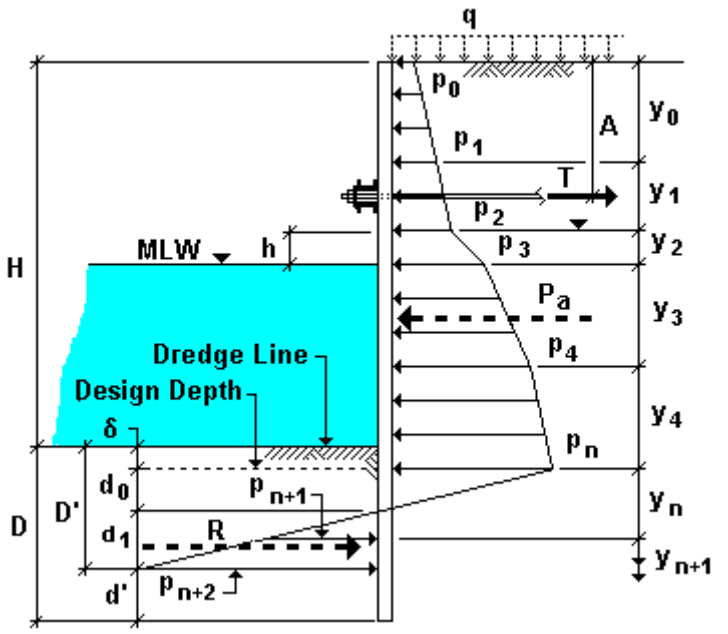
The soil acting on the bulkhead must be divided into segments with linearly varying pressure within each segment. This application provides for entry of any number of segments between the top of the bulkhead and the design depth and for two segments below the design depth. The user must enter the height from the top of the bulkhead to the design depth, the depth of the soil segments, the active soil pressure coefficients for each segment, the passive soil pressure coefficients for the segments below the design depth, embedment increase for safety against toe failure, the dry or submerged unit weight of the soil within each segment, the unit weight of fresh or salt water, the water head above mean low water and a uniform surcharge load.

A summary of input and calculated values is shown on pages 11 and 12.

Reference: "Design Manual Soil Mechanics, Foundations, and Earth Structures, NAVFAC DM-7."
Alexandria, VA: Department of the Navy, Naval Facilities Engineering Command, March 1971

Input

Notation



Input Variables

Uniform surcharge load: $q := 0 \cdot psf$

Depths of soil segments above design depth: $y := [3 \;\; 4 \;\; 1 \;\; 2 \;\; 2]^{T} \cdot ft$

Unit weight of soils (dry weights above water or submerged weights below water): $\gamma := [100 \;\; 100 \;\; 60 \;\; 60 \;\; 60 \;\; 60 \;\; 60]^{T} \cdot pcf$

Active soil pressure coefficients for all soil segments: $k_a := [0.30 \;\; 0.30 \;\; 0.30 \;\; 0.30 \;\; 0.30 \;\; 0.30 \;\; 0.30]^{T}$

Definitions of n and range variable i: $n := \text{length}(y) \qquad n = 5 \qquad i := 0 \,..\, n-1$

Note ⇒ Range variable i and variable n are computed from the number of segments.

Passive soil pressure

coefficients below design depth: $k_{p_n} := 5.0 \qquad k_{p_{n+1}} := 5.0$

Tie rod depth below top of bulkhead: $A := 3 \cdot ft + 0 \cdot in$

Allowance for scour and over dredging: $\delta := 1 \cdot ft$

Unit weight of fresh or salt water: $\gamma_w := 64 \cdot pcf$

Water head behind bulkhead at MLW: $h := 1 \cdot ft$

Index at top of water head behind bulkhead: $s := 2$

Required percentage increase in embedment for safety against toe failure: $Per\_d := 40\%$

Depth of soil segments below design depth: $y_n := 3 \cdot ft \qquad y_{n+1} := 25 \cdot ft$

Computed Variables

H	height of bulkhead above dredge line
H_d	height of bulkhead above design depth
y_w	depth from top of bulkhead to top of water behind bulkhead
p	net pressures on bulkhead
d_0	depth from design depth to the point of zero net pressure on bulkhead
P_a	total net force on bulkhead due to active soil pressures and water head
d_1	depth from the point of zero net pressure to develop passive soil reaction R
d'	required additional embedment depth for safety against toe failure
D'	minimum embedment depth to develop passive reaction force R

D	required embedment depth below dredge line
R	net reaction force developed by passive soil pressures below the design depth
T	tie rod anchor force per unit length of bulkhead
M_A	bending moment in the sheet piling at the tie rod
Yo	depth from top of bulkhead to point of zero shear and maximum moment
M_{max}	maximum bending moment in sheet piling

Calculations

Height of bulkhead above design depth:

$H_d := \sum_i y_i$ $\quad H_d = 12\ ft$

Height of bulkhead above dredge line:

$H := H_d - \delta$ $\quad H = 11\ ft$

Depth to top of water head:

$y_w := \sum_i \left((i < s) \cdot y_i \right)$ $\quad y_w = 7\ ft$

Net active soil pressures + water head acting on bulkhead above design depth:

$p_0 := k_{a_0} \cdot q$ $\quad p_{i+1} := p_i + k_{a_i} \cdot \gamma_i \cdot y_i + (i = s) \cdot \gamma_w \cdot h$

$p^{\mathrm{T}} = [0 \ \ 90 \ \ 210 \ \ 292 \ \ 328 \ \ 364]\ psf$

Net passive pressure increases per unit of depth in first and second strata below design depth:

$w_{p1} := \left(k_{p_n} - k_{a_n} \right) \cdot \gamma_n$ $\quad w_{p1} = 282\ \frac{psf}{ft}$

$w_{p2} := \left(k_{p_{n+1}} - k_{a_{n+1}} \right) \cdot \gamma_{n+1}$ $\quad w_{p2} = 282\ \frac{psf}{ft}$

Net soil pressure at bottom of first strata below design depth (+ indicates a net active pressure and - indicates a net passive pressure):

$p_{n+1} := p_n - w_{p1} \cdot y_n$ $\quad p_{n+1} = -482\ psf$

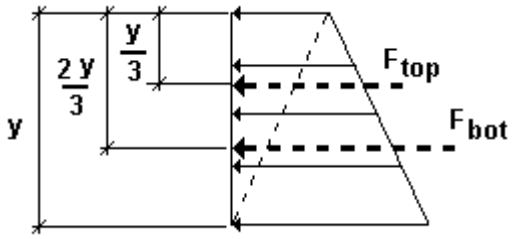
Embedment depth from design depth to point of zero pressure:

$d_0 := \text{if}\left(w_{p1} \cdot y_n \geq p_n, \frac{p_n}{w_{p1}}, y_n + \left(\frac{p_n - w_{p1} \cdot y_n}{w_{p2}} \right) \right)$ $\quad d_0 = 1.291\ ft$

Forces acting on each segment above design depth:

$$F_{top_i} := \frac{1}{2} \cdot p_i \cdot y_i \cdot ft$$

$$F_{bot_i} := \frac{1}{2} \cdot p_{i+1} \cdot y_i \cdot ft$$



$$F := F_{top} + F_{bot}$$

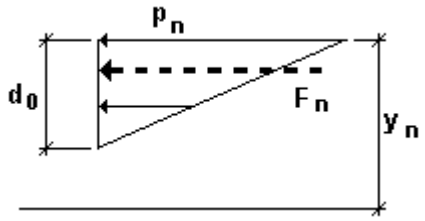
$$F_{top}^{T} = [0 \;\; 180 \;\; 105 \;\; 292 \;\; 328] \; lbf$$

$$F_{bot}^{T} = [135 \;\; 420 \;\; 146 \;\; 328 \;\; 364] \; lbf$$

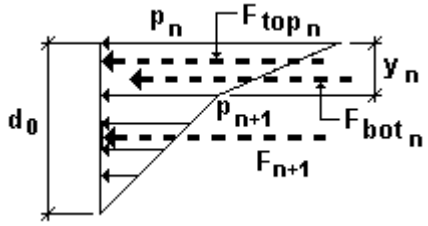
$$F^{T} = [135 \;\; 600 \;\; 251 \;\; 620 \;\; 692] \; lbf$$

Forces acting outward on the bulkhead below design depth:

Case 1: $d_0 < y_n$:



Case 2: $d_0 > y_n$



$$F_{top_n} := \text{if}\left(d_0 \le y_n, \frac{1}{2} \cdot p_n \cdot d_0 \cdot ft, \frac{1}{2} \cdot p_n \cdot y_n \cdot ft\right) \qquad F_{top_n} = 234.922 \; lbf$$

$$F_{bot_n} := \text{if}\left(d_0 \le y_n, 0 \cdot lbf, \frac{1}{2} \cdot p_{n+1} \cdot y_n \cdot ft\right) \qquad F_{bot_n} = 0 \; lbf$$

$$F_n := F_{top_n} + F_{bot_n} \qquad F_n = 234.922 \; lbf$$

$$F_{n+1} := \text{if}\left(d_0 \le y_n, 0 \cdot lbf, \frac{1}{2} \cdot p_{n+1} \cdot \left(d_0 - y_n\right) \cdot ft\right) \qquad F_{n+1} = 0\ lbf$$

Total net force on bulkhead due to active soil pressures and water pressure:

$$P_a := \sum F \qquad P_a = 2533\ lbf$$

Distance from top of bulkhead to top of each segment above design depth:

$$k := 0..n \qquad S_k := \sum_i \left((i < k) \cdot y_i\right) \qquad S^{\mathrm{T}} = [0\ \ 3\ \ 7\ \ 8\ \ 10\ \ 12]\ ft$$

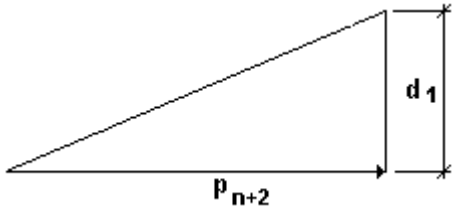
Summation of moments due to net active soil pressure forces about tie rod:

$$M_T := \sum_i \left[F_{top_i} \cdot \left[\left(\frac{y_i}{3} + S_i - A\right)\right] + F_{bot_i} \cdot \left[\left(\frac{2}{3} \cdot y_i + S_i - A\right)\right]\right] + \text{if}\left[d_0 \le y_n, F_n \cdot \left[\left(\frac{d_0}{3} + S_n - A\right)\right], F_{top_n} \cdot \left[\left(\frac{y_n}{3} + S_n - A\right)\right] + F_{bot_n} \cdot \left[\left(\frac{2}{3} \cdot y\right.\right.\right.$$

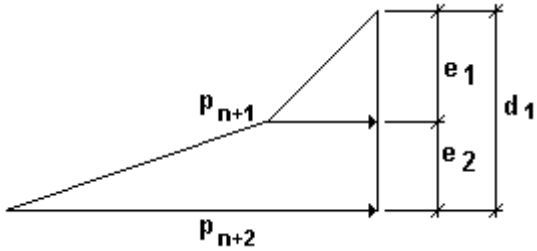
$$M_T = 13857\ lbf \cdot ft$$

Embedment d_1 depth below point of zero net pressure to develop reaction force R

Case 1: depth d_1 entirely within the first strata below design depth
Case 3: depth d_1 entirely within the second strata below design depth



Case 2: top of first soil strata below design depth within depth d_1



Depth d_1 for Case 1 or Case 2 as a function of w_p:

Guess value of d1: $d_1 := 2 \cdot d_0$ $d_1 = 2.582\ ft$

$$f(w_p) := \text{root}\left(\frac{1}{2} \cdot w_p \cdot d_1^{\,2} \cdot ft \cdot \left(H_d - A + d_0 + \frac{2}{3} \cdot d_1\right) - M_T, d_1\right)$$

Embedment depth e1: (e1 is zero for Case 1 or 3)

$$e_1 := \text{if}\left(d_0 \geq y_n, 0 \cdot ft, y_n - d_0\right) \qquad e_1 = 1.709\ ft$$

Embedment depth e2 for Case 2:

Guess value of e2: $e_2 := 2 \cdot d_0 - e_1$ $e_2 = 0.872\ ft$

$$g(e_2) := \frac{1}{2} \cdot \left(w_{p1} \cdot e_1^{\,2} \cdot ft \cdot \left(H_d - A + d_0 + \frac{2}{3} \cdot e_1\right) + w_{p1} \cdot e_1 \cdot e_2 \cdot ft \cdot \left(H_d - A + d_0 + e_1 + \frac{1}{3} \cdot e_2\right) + \left(w_{p1} \cdot e_1 + w_{p2} \cdot e_2\right) \cdot e_2 \cdot$$

$$e_2 := \text{root}\left(g(e_2), e_2\right) \qquad e_2 = 1.131\ ft$$

Embedment depth d1:

$$d_1 := \text{if}\left(d_0 \geq y_n, f(w_{p2}), \text{if}\left(d_0 + f(w_{p1}) \leq y_n, f(w_{p1}), e_1 + e_2\right)\right) = 2.84\ ft$$

$d_1 = 2.84\ ft$

Embedment depth to develop passive reaction force R:

$D' := \delta + d_0 + d_1$ $D' = 5.131\ ft$

Additional embedment depth required for safety against toe failure:

$d' := Per\_d \cdot (d_0 + d_1)$ $d' = 1.652\ ft$

Embedment depth below dredge line:

$D := \delta + d_0 + d_1 + d'$ $D = 6.783\ ft$

Net reaction force developed by passive soil pressures below design depth:

$$R := \frac{1}{2} \cdot \text{if}\left(d_0 \geq y_n, w_{p2} \cdot d_1^{\,2}, \text{if}\left((d_0 + d_1) \leq y_n, w_{p1} \cdot d_1^{\,2}, w_{p1} \cdot e_1^{\,2} + w_{p2} \cdot e_1 \cdot e_2 + \left(w_{p1} \cdot e_1 + w_{p2} \cdot e_2\right) \cdot e_2\right)\right) \cdot ft$$

$R = 1137\ lbf$

Anchor rod tension for a unit length of the bulkhead:

$T := P_a - R$ $\quad T = 1396\ lbf$

Index at top of segment containing the tie rod:

$t_0 := \text{match}(A, S)$ $\quad t := |t_0|$ $\quad t = 1$

Net soil pressure at top of segment containing the tie rod:

$p_{top} := p_t$ $\quad p_{top} = 90\ psf$

Net pressure at tie rod (if the tie rod is at a segment ptop = pbot):

$p_{bot} := p_{top} + k_{a_t} \cdot \gamma_t \cdot \left(A - S_t\right)$ $\quad p_{bot} = 90\ psf$

Bending moment in the sheet piling at the tie rod:

$$M_A := \frac{1}{2} \cdot \left(\sum_i \left((i < t) \cdot \left(p_i \cdot y_i \cdot \left(\frac{2}{3} \cdot y_i + A - S_{i+1} \right) + p_{i+1} \cdot y_i \cdot \left(\frac{1}{3} \cdot y_i + A - S_{i+1} \right) \right) \right) + \frac{2 \cdot p_{top} + p_{bot}}{3} \cdot \left(A - S_t \right)^2 \right) \cdot ft$$

$M_A = 135\ lbf \cdot ft$

Location of point of zero shear and maximum moment from top of bulkhead.

Index of segment where shear passes through zero:

$Sum\_F_k := \sum_i \left((i < k) \cdot F_i \right)$

$$u := \begin{array}{l} j \leftarrow 0 \\ \text{while } T > Sum\_F_j \\ \quad j \leftarrow j + 1 \\ \text{return } j - 1 \end{array}$$

$u = 3$

Shear at top of segment where shear passes through zero:

$V_u := T - Sum\_F_u$ $\quad V_u = 409.647\ lbf$

Shear as a function of distance y' from top of segment where shear passes through zero:

$$f(y') := V_u - \left(p_u \cdot y' + \frac{1}{2} \cdot k_{a_u} \cdot \gamma_u \cdot y'^2 \right) \cdot ft$$

Guess value of v': $u' := \frac{y_u}{}$ $\quad u' = 1\ ft$

Guess value of y': $y' := \frac{}{2}$ $y' = 1\ ft$

$y' := \mathbf{root}(f(y'), y')$ $y' = 1.347\ ft$

Check (should approach zero):

$$V_u - p_u \cdot y' \cdot ft - \frac{1}{2} \cdot k_{a_u} \cdot \gamma_u \cdot y'^2 \cdot ft = -1.054 \cdot 10^{-12}\ lbf$$

Net soil pressure at point of zero shear:

$p_o := p_u + k_{a_u} \cdot \gamma_u \cdot y'$ $p_o = 316.246\ psf$

Distance Y_o from top of bulkhead to point of zero shear and maximum moment:

$Y_o := S_u + y'$ $Y_o = 9.347\ ft$

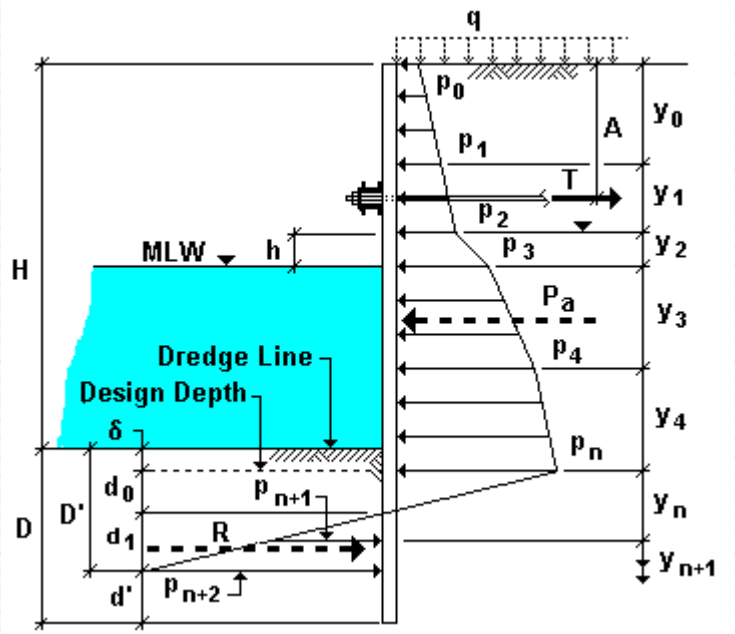
$$M_{max} := \left[T \cdot (Y_o - A) + \sum_i \left[(i < u) \cdot \left[F_{top_i} \cdot \left[S_i + \frac{y_i}{3} - Y_o \right] + F_{bot_i} \cdot \left[S_i + \frac{2}{3} \cdot y_i - Y_o \right] \right] \right] \right] - \frac{1}{6} \cdot y'^2 \cdot (2 \cdot p_u + p_o) \cdot ft$$

$M_{max} = 4689\ lbf \cdot ft$

The maximum moment may be reduced for flexible bulkheads penetrating medium compact and compact coarse-grained soils (Rowe's Moment Reduction). The calculation of the possible moment reduction is not within the scope of this application.

Summary

Input



Uniform surcharge load:	$q = 0\ psf$
Water head behind bulkhead at mean low water:	$h = 1\ ft$
Unit weight of fresh or salt water:	$\gamma_w = 64\ pcf$
Depth below dredge line to allow for scour and over dredging:	$\delta = 1\ ft$
Specified percentage increase in embedment depth for safety against toe failure:	$Per\_d = 40\ 1\%$
Depth of tie rod below top of bulkhead:	$A = 3\ ft$
Segment depths:	$y^{T} = [3\ \ 4\ \ 1\ \ 2\ \ 2\ \ 3\ \ 25]\ ft$
Unit weights of soil:	$\gamma^{T} = [100\ \ 100\ \ 60\ \ 60\ \ 60\ \ 60\ \ 60]\ pcf$
Active soil pressure coefficients:	$k_a{}^{T} = [0.3\ \ 0.3\ \ 0.3\ \ 0.3\ \ 0.3\ \ 0.3\ \ 0.3]$

Computed Variables

Height of bulkhead above dredge line: $H = 11\ ft$

Required embedment depth below dredge line: $D = 6.78\ ft$

Tie rod tension per unit length of bulkhead: $T = 1396\ lbf$

Bending moment at tie rod: $M_A = 135\ lbf \cdot ft$

Maximum bending moment: $M_{max} = 4689\ lbf \cdot ft$