



Example Abutment Calculations

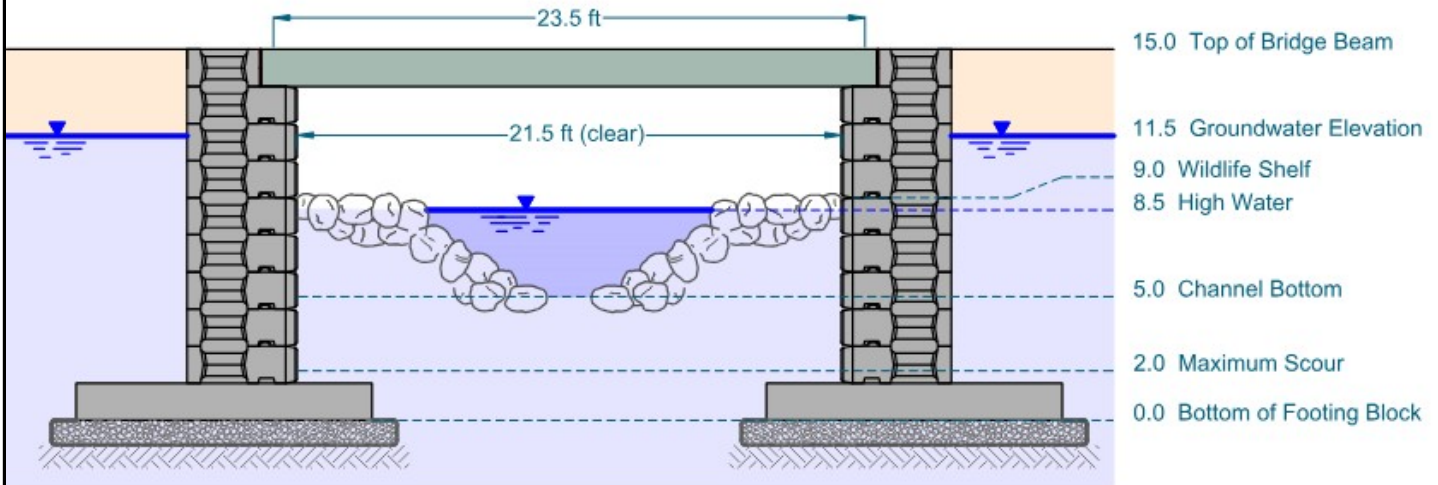
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Description

This example shows the analysis of a 15 foot tall cantilever abutment wall supporting a simple span bridge. The bridge superstructure consists of 1.5 foot thick reinforced concrete T-beams that are 25 foot long with 23.5 feet between centerline of bearing points. The bridge width is 28 feet wide. Assumed conditions for this example are as shown:



Assumed Soil Parameters

Soil Internal Friction Angle	$\phi' := 30^\circ$
Soil Cohesion	$c := 0 \text{ psf}$
Soil Moist Unit Weight	$\gamma := 120 \text{ pcf}$
Soil Buoyant Unit Weight	$\gamma_b := 63 \text{ pcf}$

Block Dimensions

Block Height	$h_{block} := 1.5 \text{ ft}$
Abutment Block Width	$b_{wall} := 4 \text{ ft}$
Block Facing	$b_{facing} := 5.5 \text{ in}$
Footing Block Width	$B := 12 \text{ ft}$
Width of Footing Block Toe	$b_{toe} := 3.5 \text{ ft} - b_{facing} = 3.042 \text{ ft}$
Width of Footing Block Heel	$b_{heel} := B - (b_{wall} + b_{facing} + b_{toe})$
	$b_{heel} = 4.5 \text{ ft}$

Bridge and Abutment Dimensions

Bridge Span	$Span := 25 \text{ ft}$
Abutment Height	$H := 15 \text{ ft}$
Footing Length	$L_{FD} := 36 \text{ ft}$

Water Elevations

Distance from bottom of wall to high water (in stream)	$h_{HW} := 8.5 \text{ ft}$
Distance from high water to groundwater (unbalanced hydrostatic force in rapid drawdown condition)	$h_{DD} := 3 \text{ ft}$
Distance from bottom of wall to groundwater	$h_w := h_{HW} + h_{DD} = 11.5 \text{ ft}$
Distance from groundwater to top of wall	$h_1 := H - h_w = 3.5 \text{ ft}$

Unit Weights

Unit Weight Water	$\gamma_w := 62.4 \frac{\text{lb}}{\text{ft}^3}$
Unit Weight of Concrete (All blocks reinforced)	$\gamma_{conc} := 150 \frac{\text{lb}}{\text{ft}^3}$

Design Loads

Superstructure designed to HL-93



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External Stability of the Cantilever Abutment

External stability of the abutment is evaluated under the Strength 1 load combination limit state. External stability considers the entire abutment, from the bottom of the footing block to the top of the backwall. The analysis evaluates Sliding, Load Eccentricity / Overturning, and Bearing Capacity of the abutment. Because some load factors in the Strength 1 load combination limit state have both maximum and minimum values, three separate sets of calculations are performed, referred to as Strength 1 (a), Strength 1 (b), and Strength 1 (c). In Strength 1 (a), maximum vertical and maximum horizontal loads are used. In Strength 1 (b), maximum vertical and minimum horizontal loads are used. In Strength 1 (c), minimum vertical and maximum horizontal loads are used.

Applicable loads in the Strength 1 load combination limit state for this example include:

$DC + DW + LL + EH + EV + LS + WA + TU + BR$

DC (bridge weight), DW, and LL are provided by the bridge design engineer of record.

DC (abutment weight), EH, EV, LS, WA, TU, and BR are calculated here.

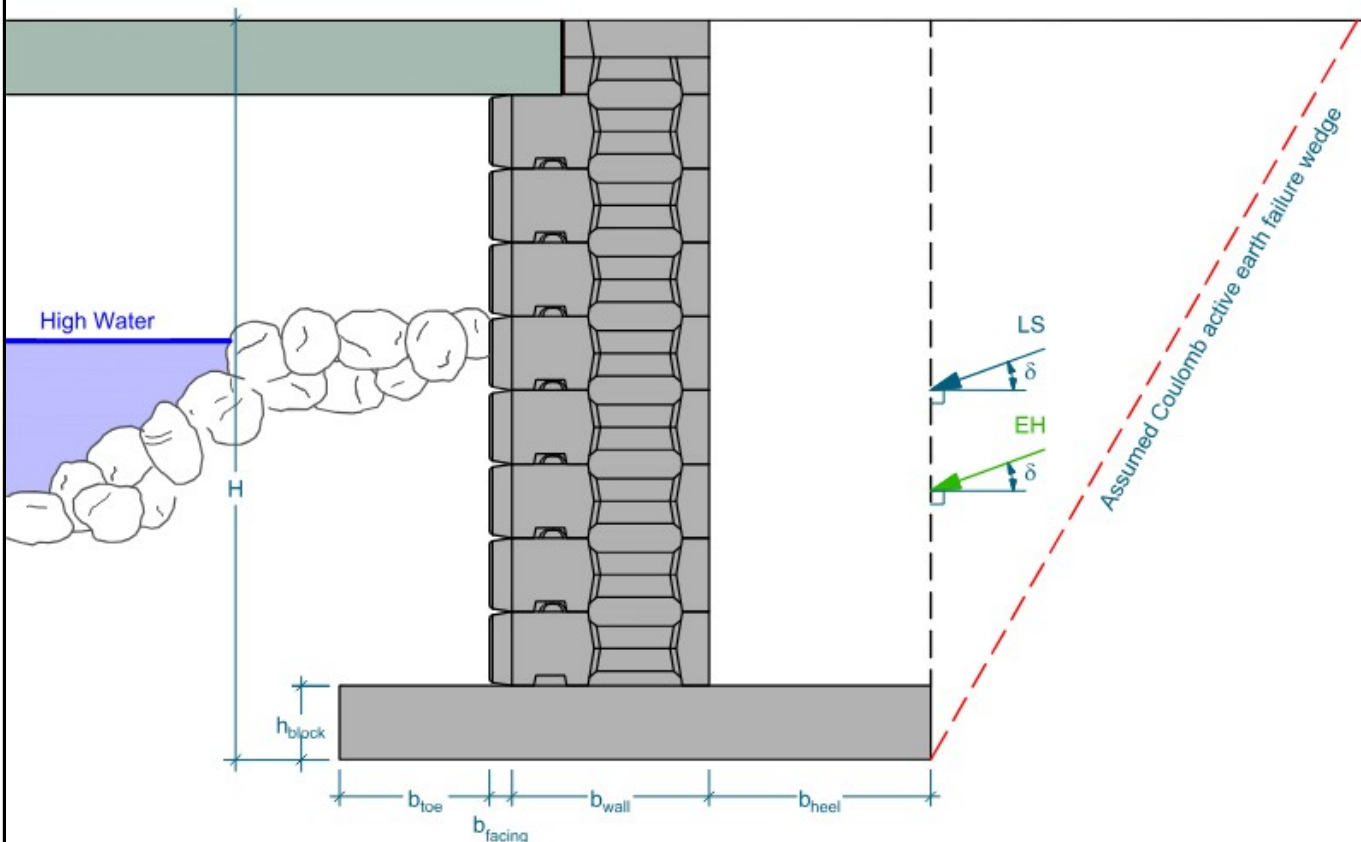
Seismic loading or other extreme events are not considered in this example.

Actual projects may require investigation of additional load combination limit states. The general approach shown here will apply.

Coulomb Active Earth Pressure Coefficient

Coulomb earth pressure calculations are used to determine the active earth pressure and live load surcharge pressure on the back of the abutment wall.

Standard practice in bridge engineering is to use a vertical back of wall when calculating the Coulomb active earth pressure coefficient for a cantilever abutment wall with a short heel. According to AASHTO C3.11.5.3, "...the earth pressure is applied to a plane extending vertically up from the heel of the wall base, and the weight of the soil to the left of the vertical plane is considered as part of the wall weight."



Wall Batter (from Horizontal) $\theta := 90^\circ$

Slope on Top of Wall $\beta := 0^\circ$

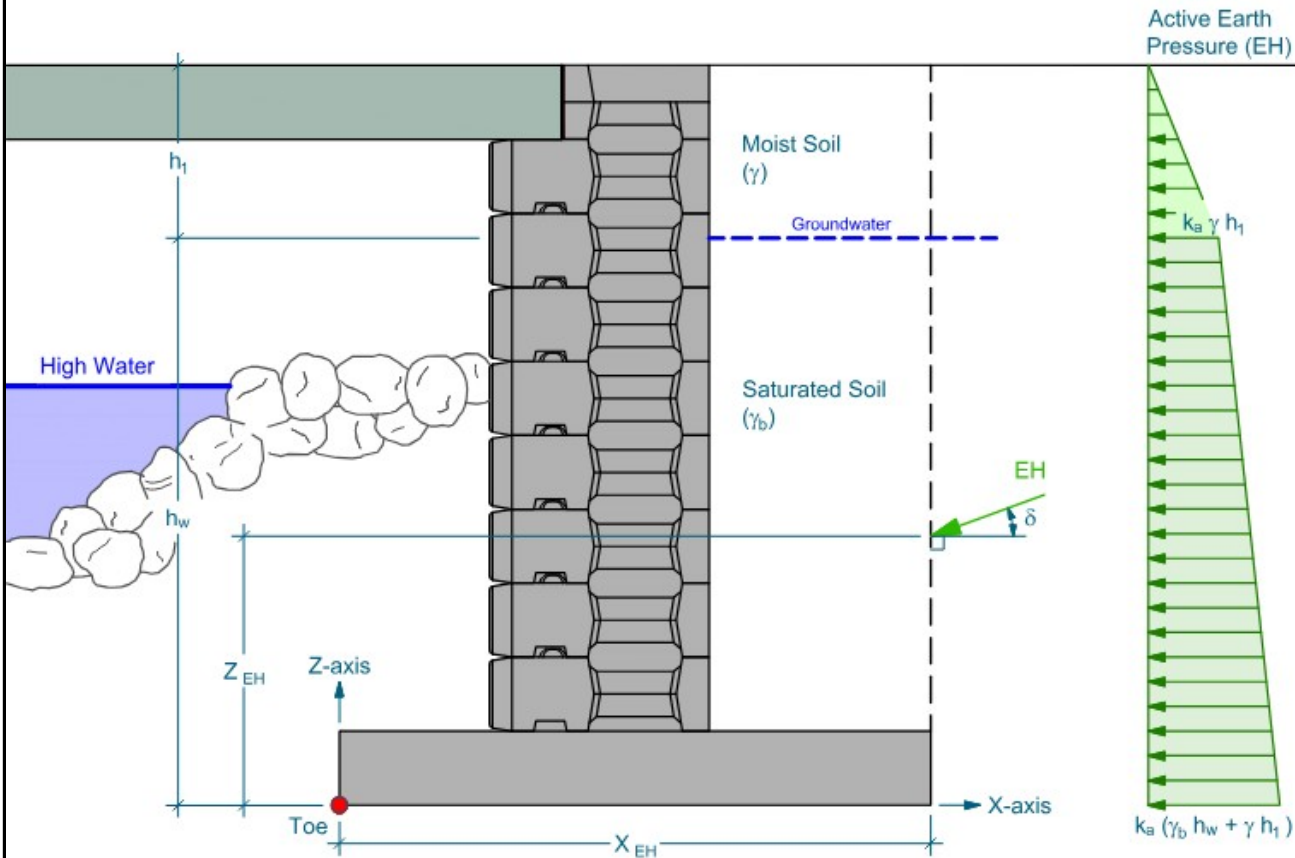
Angle of Friction between Back of Wall and Retained Soil $\delta := \frac{2}{3} \cdot \phi' = 20^\circ$ **AASHTO C3.11.5.3**

$$\Gamma := \left(1 + \sqrt{\frac{\sin(\phi' + \delta) \sin(\phi' - \beta)}{\sin(\theta - \delta) \cdot \sin(\theta + \beta)}} \right)^2 = 2.684 \quad \text{AASHTO Equation 3.11.5.3-2}$$

$$k_a := \frac{\sin(\theta + \phi')^2}{\Gamma \cdot (\sin(\theta)^2 \sin(\theta - \delta))} = 0.297 \quad \text{AASHTO Equation 3.11.5.3-1}$$

Earth Pressure (EH)

This example uses Coulomb earth pressure theory to determine the force from active earth pressure on the back of the abutment wall. The moist soil conditions are considered above the elevation of groundwater and saturated below. The diagram of active earth pressure is divided into triangular-shaped and trapezoidal-shaped areas, representing the pressure from the moist and saturated soils. A resultant force equal to the area of the pressure diagram is assumed to act on a plane extending vertically up from the heel of the wall base at the elevation of the centroid of the pressure diagram.



$$EH := k_a \cdot \left(\frac{1}{2} \cdot \gamma \cdot h_1^2 + \gamma \cdot h_1 \cdot h_w + \frac{1}{2} \cdot \gamma_b \cdot h_w^2 \right) = 2.893 \frac{\text{kip}}{\text{ft}}$$

Horizontal Component $EH_h := EH \cdot \cos(90^\circ - \theta + \delta) = 2.719 \frac{\text{kip}}{\text{ft}}$

Vertical Component $EH_v := EH \cdot \sin(90^\circ - \theta + \delta) = 0.99 \frac{\text{kip}}{\text{ft}}$

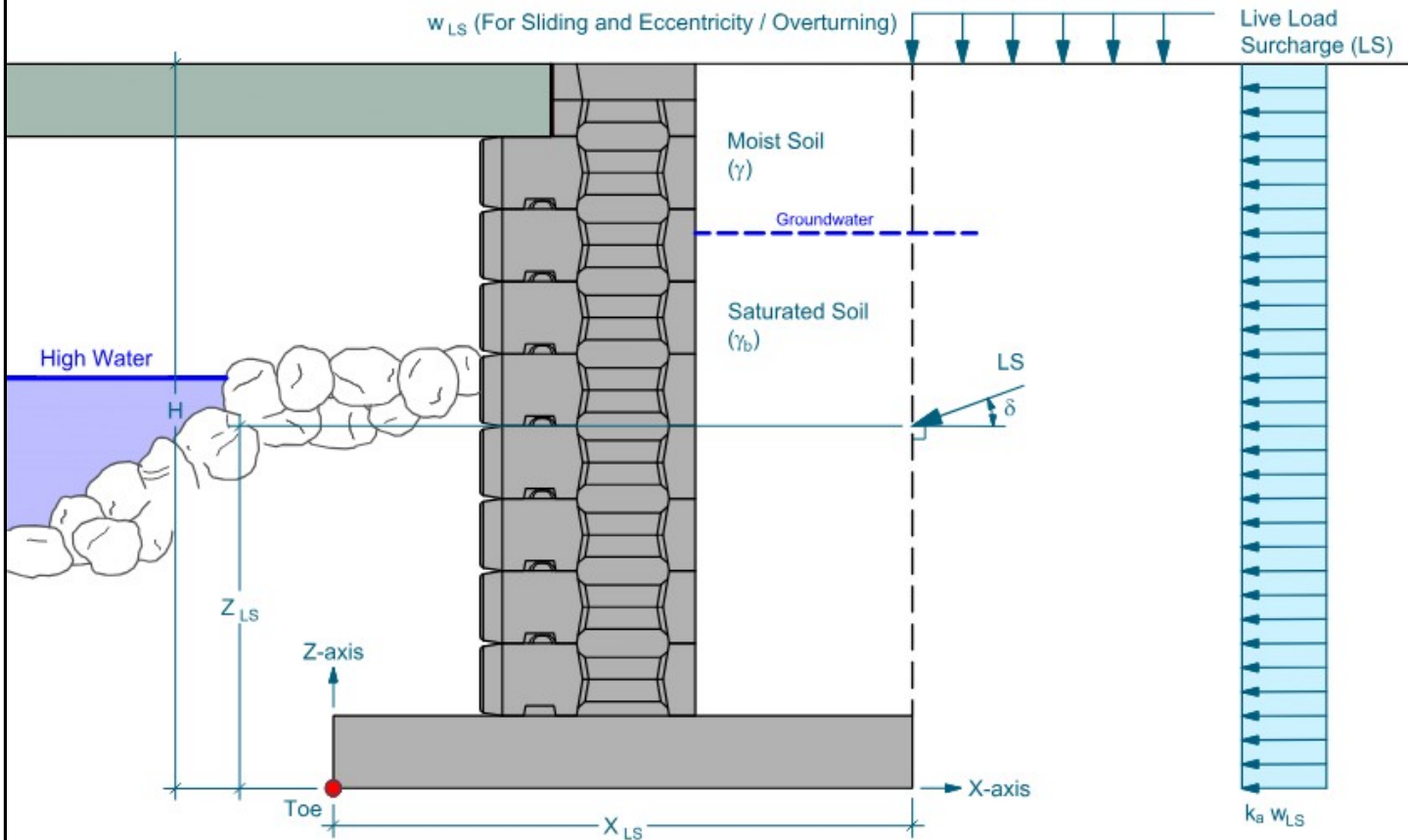
Point of Application (from Toe)

$$Z_{EH} := \frac{\left(\left(\frac{1}{2} \cdot \gamma \cdot h_1^2 \right) \cdot \left(h_w + \frac{h_1}{3} \right) \right) + \left(\left(\gamma \cdot h_1 \cdot h_w \right) \cdot \left(\frac{h_w}{2} \right) \right) + \left(\left(\frac{1}{2} \cdot \gamma_b \cdot h_w^2 \right) \cdot \left(\frac{h_w}{3} \right) \right)}{\left(\frac{1}{2} \cdot \gamma \cdot h_1^2 \right) + \left(\gamma \cdot h_1 \cdot h_w \right) + \left(\frac{1}{2} \cdot \gamma_b \cdot h_w^2 \right)} = 5.452 \text{ ft}$$

$$X_{EH} := B = 12 \text{ ft}$$

Live Load Surcharge (LS)

Live load surcharge applied to the abutment wall. AASHTO Table 3.11.6.4.1-1 provides an equivalent height of soil based on the height of the abutment to be used for the surcharge, yielding a rectangular-shaped pressure diagram. A resultant force equal to the area of the pressure diagram is assumed to act on a plane extending vertically up from the heel of the wall base at the elevation of the centroid of the pressure diagram.



$$h_{equiv} := 2.5 \text{ ft}$$

AASHTO Table 3.11.6.4.1-1

$$w_{LS} := h_{equiv} \cdot \gamma = 300 \text{ psf}$$

$$LS := k_a \cdot w_{LS} \cdot H = 1.338 \frac{\text{kip}}{\text{ft}}$$

$$\text{Horizontal Component} \quad LS_h := LS \cdot \cos(90^\circ - \theta + \delta) = 1.257 \frac{\text{kip}}{\text{ft}}$$

$$\text{Vertical Component} \quad LS_v := LS \cdot \sin(90^\circ - \theta + \delta) = 0.458 \frac{\text{kip}}{\text{ft}}$$

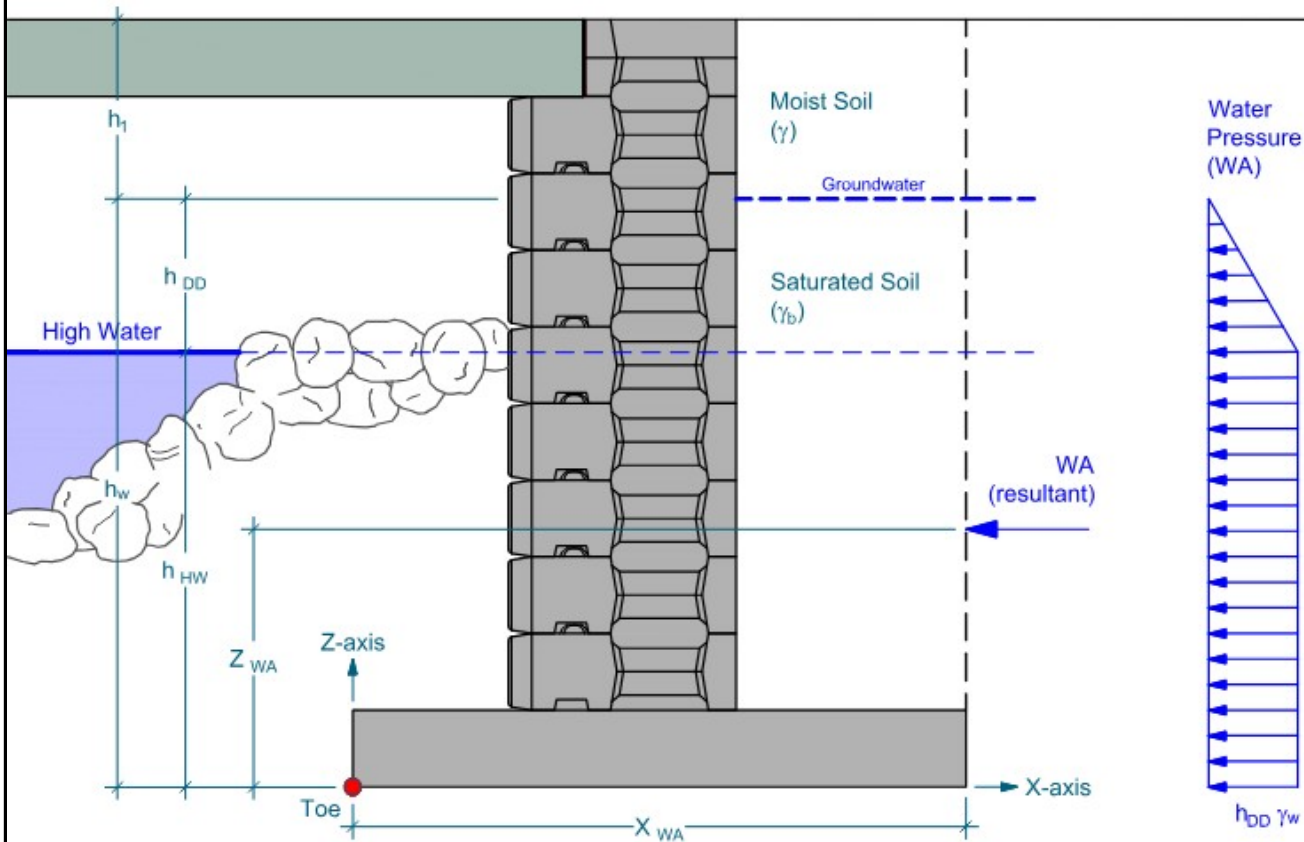
Point of Application (from Toe)

$$Z_{LS} := \frac{H}{2} = 7.5 \text{ ft}$$

$$X_{LS} := B = 12 \text{ ft}$$

Unbalanced Hydrostatic Force (Rapid Drawdown Condition) (WA)

This example assumes a rapid drawdown condition where the groundwater level is higher than the level of water in front of the wall. The result is a trapezoidal-shaped pressure diagram defined by the elevations of the groundwater and surface water in front of the wall. A resultant force equal to the area of the pressure diagram is assumed to act on the back of the abutment wall at the elevation of the centroid of the pressure diagram.



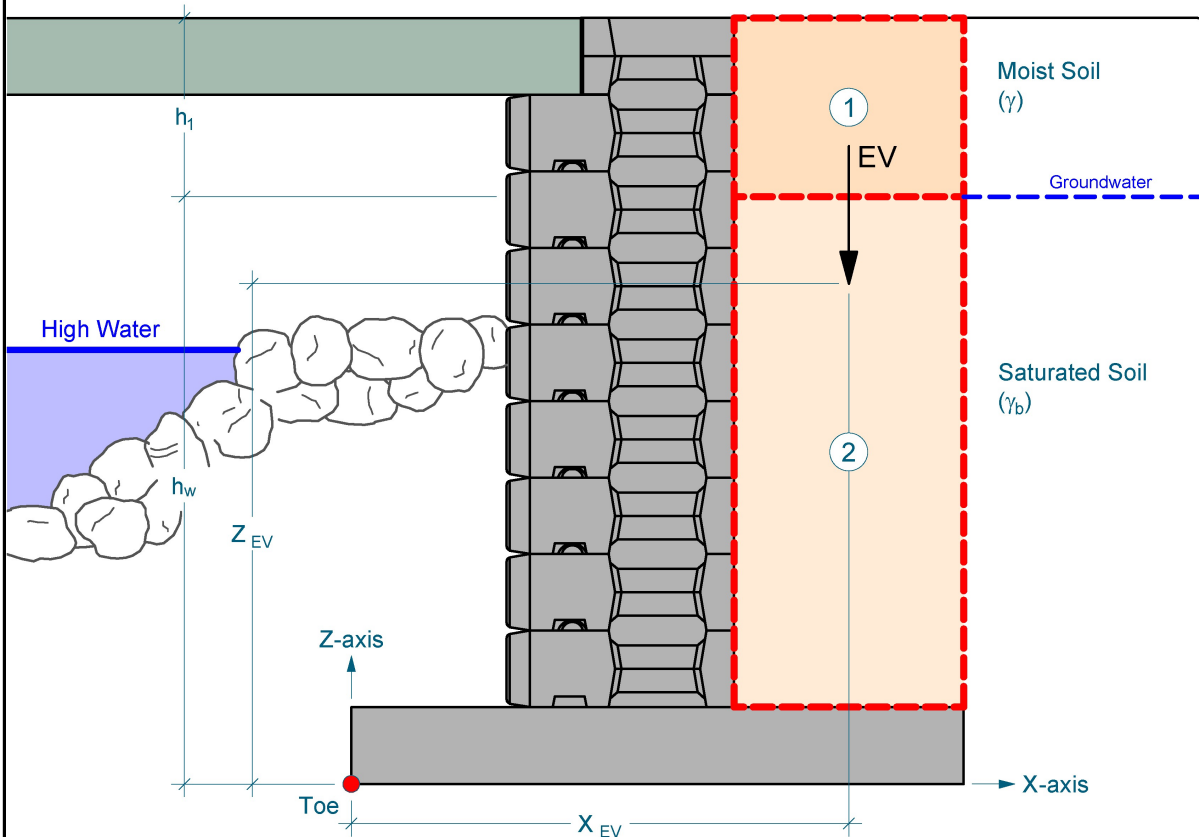
$$WA := \frac{1}{2} \cdot \gamma_w \cdot h_{DD}^2 + \gamma_w \cdot h_{DD} \cdot h_{HW} = 1.872 \frac{\text{kip}}{\text{ft}}$$

Point of Application (from Toe)

$$Z_{WA} := \frac{\frac{1}{2} \cdot \gamma_w \cdot h_{DD}^2 \cdot \left(h_{HW} + \frac{1}{3} \cdot h_{DD} \right) + \gamma_w \cdot h_{DD} \cdot h_{HW} \cdot \left(\frac{h_{HW}}{2} \right)}{WA} = 5.038 \text{ ft}$$

Vertical Earth Pressure (EV)

According to AASHTO C3.11.5.3, vertical earth pressure includes the weight of the soil to the left of the vertical plane extending up from the heel of the wall base. The vertical earth pressure force is assumed to act at the center of gravity of the combined saturated and moist (unsaturated) areas of soil.



Area, weight, and location of center of gravity for moist soil:

$$A_1 := b_{heel} \cdot h_1 = 15.75 \text{ ft}^2 \quad Wt_1 := A_1 \cdot \gamma = 1.89 \frac{\text{kip}}{\text{ft}}$$

$$COG_{x1} := \frac{b_{heel}}{2} + (b_{toe} + b_{facing} + b_{wall}) = 9.75 \text{ ft}$$

Area, weight, and location of center of gravity for saturated soil:

$$A_2 := b_{heel} \cdot (h_{HW} - h_{block}) = 31.5 \text{ ft}^2 \quad Wt_2 := A_2 \cdot \gamma_b = 1.985 \frac{\text{kip}}{\text{ft}}$$

$$COG_{x2} := \frac{b_{heel}}{2} + (b_{toe} + b_{facing} + b_{wall}) = 9.75 \text{ ft}$$

Total weight of soil:

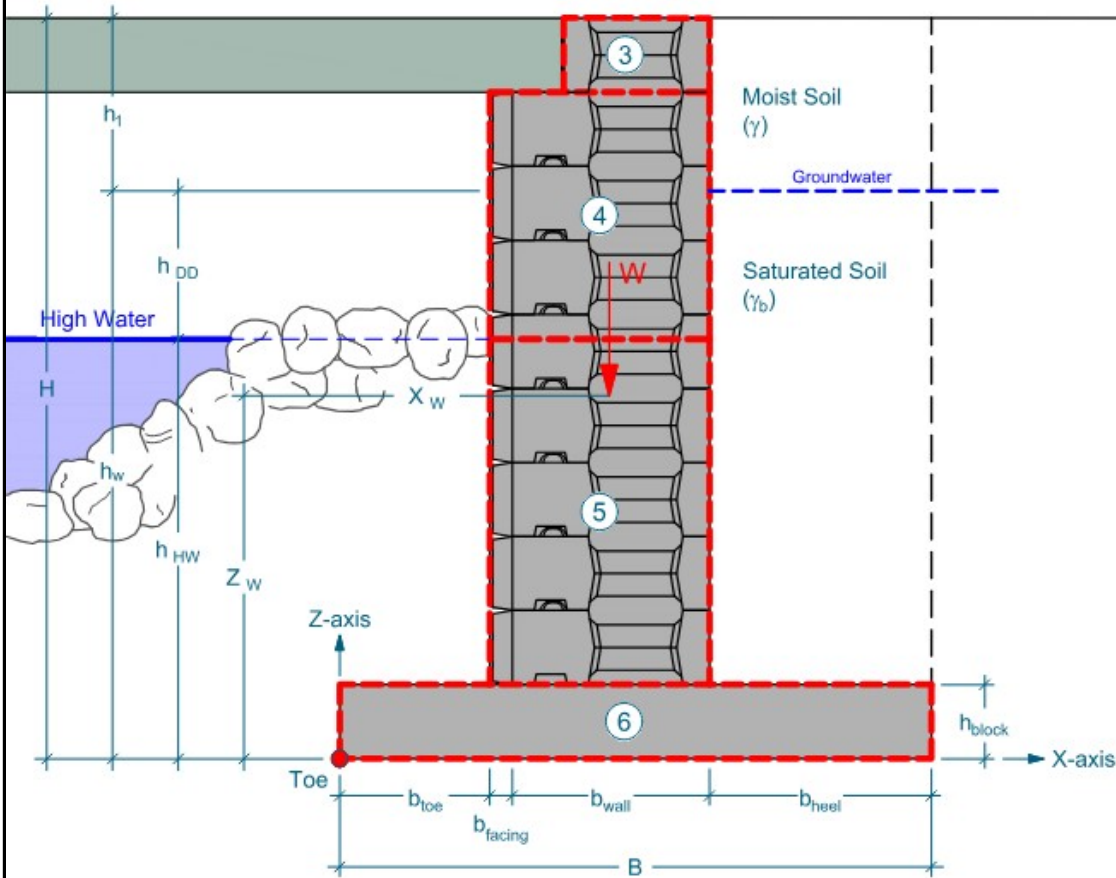
$$EV := Wt_1 + Wt_2 = 3.875 \frac{\text{kip}}{\text{ft}}$$

Center of Gravity / Point of Application (from Toe) of soil:

$$X_{EV} := \frac{Wt_1 \cdot COG_{x1} + Wt_2 \cdot COG_{x2}}{Wt_1 + Wt_2} = 9.75 \text{ ft}$$

Wall Weight (W)

The abutment wall is divided into 4 rectangular regions to determine weight and center of gravity for abutment stability design calculations. These regions are as follows: the backwall behind the bridge beams (region 3), the abutment stem wall above the high water level (region 4), the abutment stem wall below the high water level (region 5), and the abutment footing block (region 6). Since there will be wall drains installed on the back of the abutment blocks, it is assumed that full weight will be used for the portion of the wall above the high water level and buoyant weight will be used for the portion of the wall below this level. Areas, weights, and center of gravity for these regions can be calculated as follows:



Region 3 - Backwall behind the bridge beams:

$$A_3 := (b_{wall} - 1.0 \text{ ft}) \cdot (h_{block}) = 4.5 \text{ ft}^2$$

$$Wt_3 := A_3 \cdot \gamma_{conc} = 0.675 \frac{\text{kip}}{\text{ft}}$$

$$COG_{x3} := (b_{toe} + b_{facing} + 1.0 \text{ ft}) + \frac{(b_{wall} - 1.0 \text{ ft})}{2} = 6 \text{ ft}$$

Region 4 - Abutment stem wall above the high water elevation:

$$A_4 := (b_{wall}) \cdot (H - h_{HW} - h_{block}) = 20 \text{ ft}^2$$

$$Wt_4 := A_4 \cdot \gamma_{conc} = 3 \frac{\text{kip}}{\text{ft}}$$

$$COG_{x4} := b_{toe} + b_{facing} + \frac{b_{wall}}{2} = 5.5 \text{ ft}$$

Region 5 - Abutment stem wall below the high water elevation:

$$A_5 := (b_{wall}) \cdot (h_{HW} - h_{block}) = 28 \text{ ft}^2$$

$$Wt_5 := A_5 \cdot (\gamma_{conc} - \gamma_W) = 2.453 \frac{\text{kip}}{\text{ft}}$$

$$COG_{x5} := b_{toe} + b_{facing} + \frac{b_{wall}}{2} = 5.5 \text{ ft}$$

Region 6 - Abutment footing block:

$$A_6 := B \cdot h_{block} = 18 \text{ ft}^2$$

$$Wt_6 := A_6 \cdot (\gamma_{conc} - \gamma_W) = 1.577 \frac{\text{kip}}{\text{ft}}$$

$$COG_{x6} := \frac{B}{2} = 6 \text{ ft}$$

Total weight of the abutment wall:

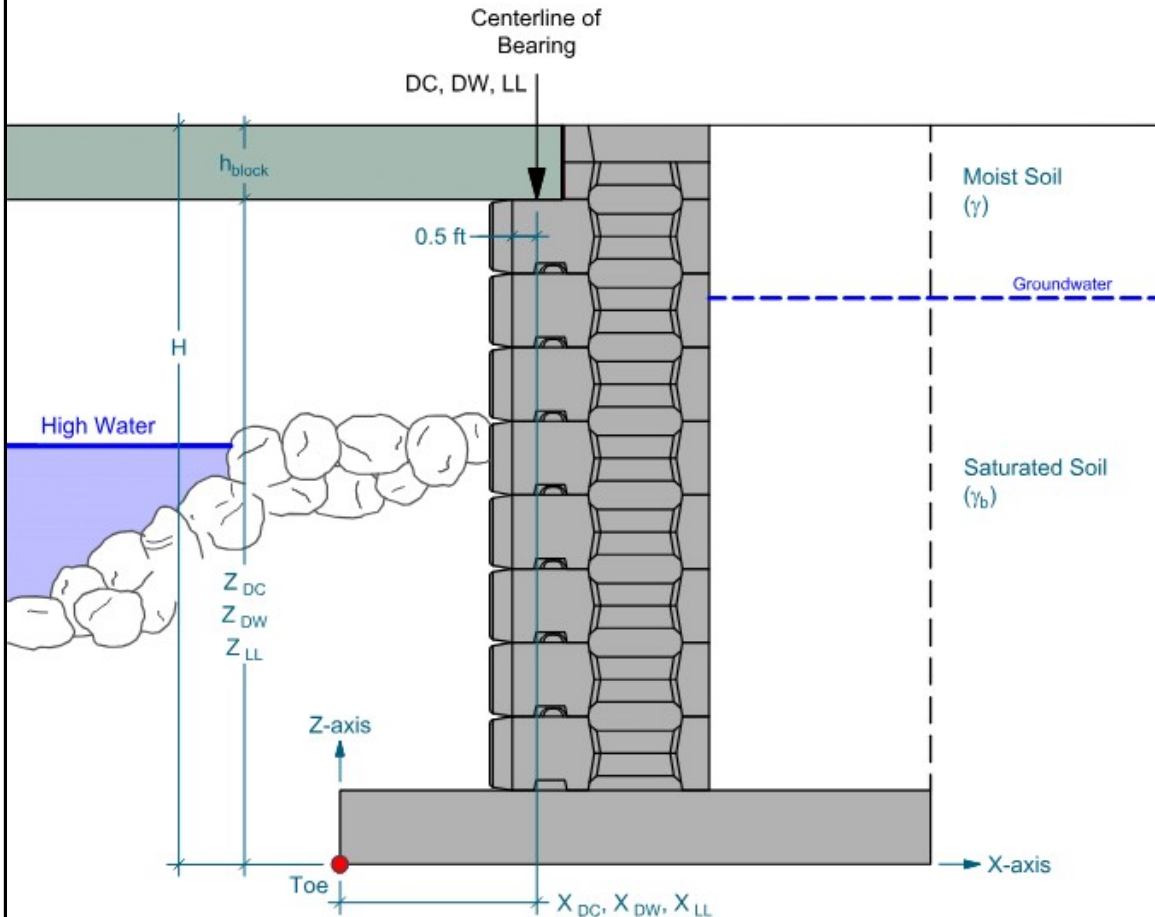
$$W := Wt_3 + Wt_4 + Wt_5 + Wt_6 = 7.705 \frac{\text{kip}}{\text{ft}}$$

Center of Gravity / Point of Application (from Toe) of the abutment wall:

$$X_W := \frac{Wt_3 \cdot COG_{x3} + Wt_4 \cdot COG_{x4} + Wt_5 \cdot COG_{x5} + Wt_6 \cdot COG_{x6}}{W} = 5.646 \text{ ft}$$

Bridge Loads (Live, Dead, Wearing Course)

Bridge loads are project specific and are provided by the Professional Engineer responsible for design of the bridge superstructure. They are assumed to act in the center of the bearing area below the bridge beams.



Assumed loads for this example:

Bridge Dead Load (DC)

$$DC := 2.8125 \frac{\text{kip}}{\text{ft}}$$

Point of Application (from Toe) $X_{DC} := b_{toe} + b_{facing} + 0.5 \text{ ft} = 4 \text{ ft}$

Bridge Wearing Course (DW)

$$DW := 0.4375 \frac{\text{kip}}{\text{ft}}$$

Point of Application (from Toe) $X_{DW} := b_{toe} + b_{facing} + 0.5 \text{ ft} = 4 \text{ ft}$

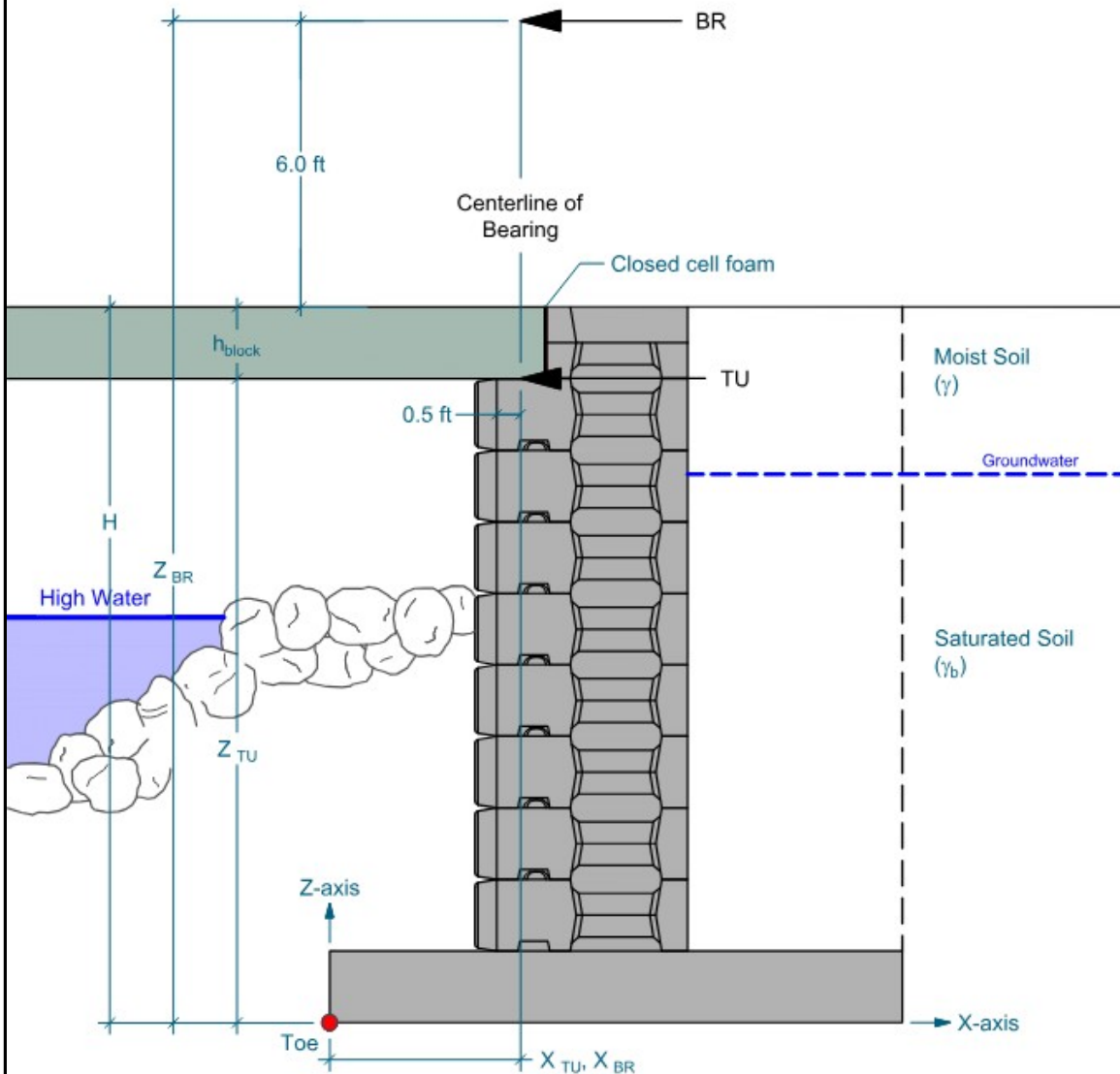
Bridge Live Load (LL)

$$LL := 5.400 \frac{\text{kip}}{\text{ft}}$$

Point of Application (from Toe) $X_{LL} := b_{toe} + b_{facing} + 0.5 \text{ ft} = 4 \text{ ft}$

Additional Horizontal Loads

Additional horizontal loads are applied to the abutment. Specific projects may have additional loads that may apply. For this example, temperature and breaking loads are considered.



Temperature Load (TU)

Thermal Expansion Coefficient of Concrete
Temperature Range
Bridge Expansion / Contraction
Shear Modulus of Bearing Pad

$$\alpha := 5.5 \cdot 10^{-6} / ^\circ\text{F}$$

$$T := 80 \quad ^\circ\text{F}$$

$$\Delta T := \alpha \cdot T \cdot \text{Span} = 0.132 \text{ in}$$

$$G_{\text{bearing}} := 0.2 \text{ ksi}$$

AASHTO Table 14.7.6.2-1

Assume a 1" thick x 5" wide bearing pad

$$A_{\text{bearing}} := 60 \frac{\text{in}^2}{\text{ft}} \quad t_{\text{bearing}} := 1.00 \text{ in}$$

$$TU := \frac{G_{\text{bearing}} \cdot A_{\text{bearing}} \cdot \Delta T}{t_{\text{bearing}} \cdot 2} = 0.792 \frac{\text{kip}}{\text{ft}}$$

(Force divided between both to both Abutments)

Point of Application (from Toe)

$$Z_{TU} := (H - h_{\text{block}}) = 13.5 \text{ ft}$$



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Breaking Load (BR)

BR = 25% of the Axle Weights. (The two rear axels of the design truck controls over the tandem)

Assume a truck in both lanes and that the load is spread over both abutments.

$m := 1.0$ (Multiple Presence Factor)

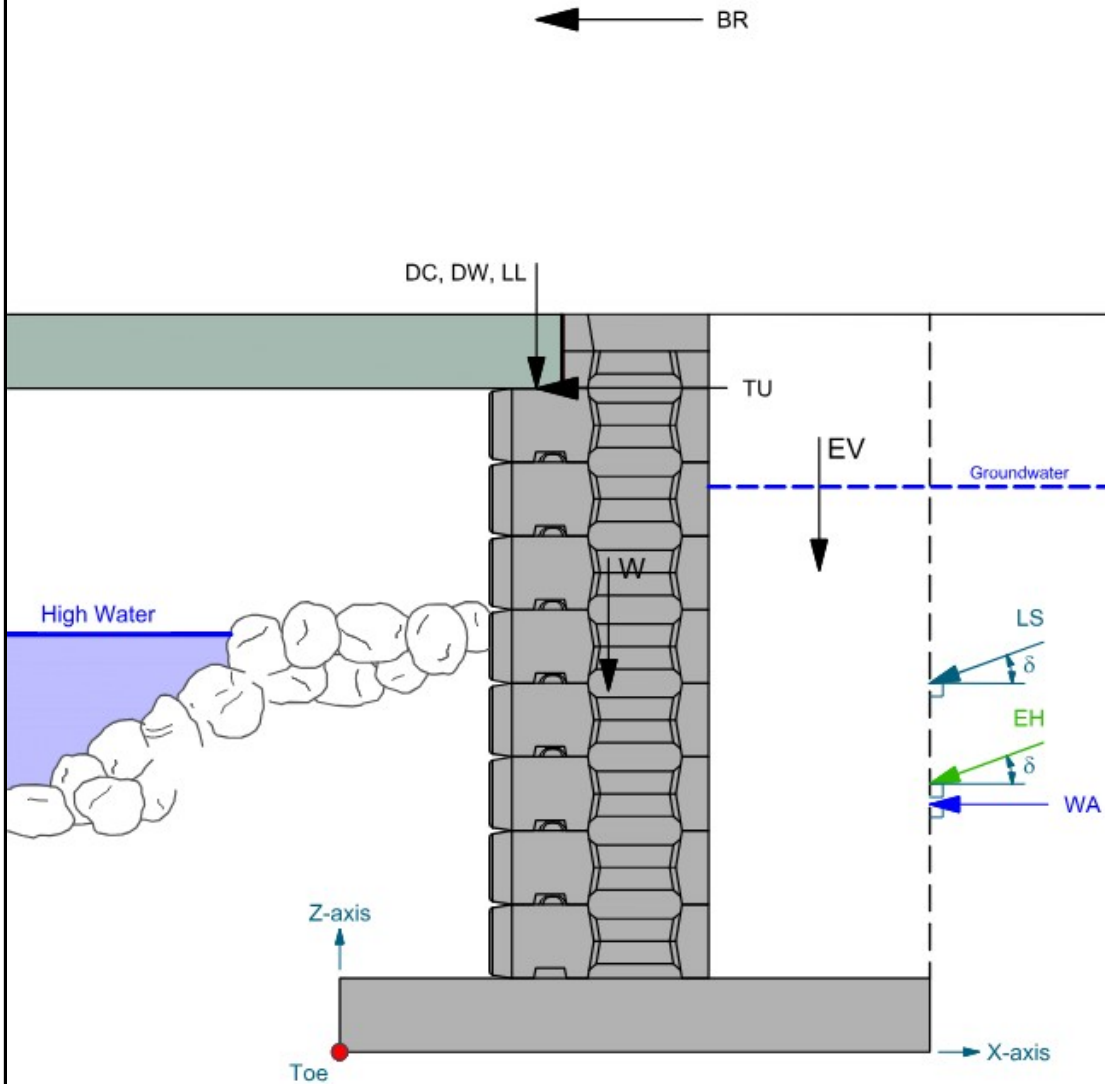
AASHTO Table 3.6.1.1.2-1

$$BR := m \cdot \frac{0.25 \cdot 64 \text{ kip}}{L_{FD}} = 0.444 \frac{\text{kip}}{\text{ft}}$$

Point of Application (from Toe)

$$Z_{BR} := (H + 6 \text{ ft}) = 21 \text{ ft}$$

Summary of loads acting on the abutment



Load Factors

Loads:	Maximum	Minimum
DC	$\gamma_p = 1.25$	$\gamma_p = 0.90$
DW	$\gamma_p = 1.50$	$\gamma_p = 0.65$
EH	$\gamma_p = 1.50$	$\gamma_p = 0.90$
EV	$\gamma_p = 1.35$	$\gamma_p = 1.00$
LL	$\gamma_{LL} = 1.75$	
BR	$\gamma_{BR} = 1.75$	
LS	$\gamma_{LS} = 1.75$	
WA	$\gamma_{WA} = 1.00$	
TU	$\gamma_{TU} = 1.20$	

Load Modifier η and components η_D , η_R , $\eta_I = 1.0$ for example analysis

Load Combination = Strength 1 (a)

Maximum Vertical and Maximum Horizontal Loads

DC	$Y_{p_DC} := 1.25$ (Maximum)	EH	$Y_{p_EH} := 1.5$ (Maximum)
LL	$Y_{LL} := 1.75$	LS	$Y_{LS} := 1.75$
DW	$Y_{p_DW} := 1.5$ (Maximum)	BR	$Y_{BR} := 1.75$
EV	$Y_{p_EV} := 1.35$ (Maximum)	WA	$Y_{WA} := 1.0$
		TU	$Y_{TU} := 1.2$

Sliding Calculations

Driving Force

$$F_{H_STR1a} := (Y_{p_EH} \cdot EH_h) + (Y_{LS} \cdot LS_h) + (Y_{BR} \cdot BR) + (Y_{WA} \cdot WA) + (Y_{TU} \cdot TU) = 9.878 \frac{\text{kip}}{\text{ft}}$$

Sum of Vertical Forces

$$V_{STR1a} := (Y_{p_DC} \cdot W) + (Y_{p_EH} \cdot EH_v) + (Y_{LS} \cdot LS_v) + (Y_{p_EV} \cdot EV) + (Y_{p_DC} \cdot DC) + (Y_{LL} \cdot LL) + (Y_{p_DW} \cdot DW) = 30.768 \frac{\text{kip}}{\text{ft}}$$

Resisting Force

$$\phi_{SL} := 0.9 \quad \text{Resistance Factor for Sliding}$$

$$C := 0.8 \quad \text{AASHTO Equation 10.6.3.4-2 (Precast Concrete Footing)}$$

$$\phi_f := 40^\circ \quad \text{(Internal Friction Angle of Stone under Foundation Mat)}$$

$$\phi R_{T_STR1a} := \phi_{SL} \cdot C \cdot V_{STR1a} \cdot \tan(\phi_f) = 18.589 \frac{\text{kip}}{\text{ft}}$$

AASHTO Equations 10.6.3.4-1 and 10.6.3.4-2

$$CDR_{SL_STR1a} := \frac{\phi R_{T_STR1a}}{F_{H_STR1a}} = 1.882$$

$$Check_{SL_STR1a} := \text{if}(CDR_{SL_STR1a} > 1, \text{"OK for Sliding"}, \text{"Not OK for Sliding"})$$

$$Check_{SL_STR1a} = \text{"OK for Sliding"}$$

Load Eccentricity (Overturning) Calculations

Overturning Moment

$$M_{O_STR1a} := (Y_{p_EH} \cdot EH_h \cdot Z_{EH}) + (Y_{LS} \cdot LS_h \cdot Z_{LS}) + (Y_{BR} \cdot BR \cdot Z_{BR}) + (Y_{WA} \cdot WA \cdot Z_{WA}) + (Y_{TU} \cdot TU \cdot Z_{TU}) = 77.328 \frac{\text{kip} \cdot \text{ft}}{\text{ft}}$$

Resisting Moment

$$M_{R_STR1a} := (Y_{p_DC} \cdot W \cdot X_W) + (Y_{p_EH} \cdot EH_v \cdot X_{EH}) + (Y_{LS} \cdot LS_v \cdot X_{LS}) + (Y_{p_EV} \cdot EV \cdot X_{EV}) + (Y_{p_DC} \cdot DC \cdot X_{DC}) + (Y_{LL} \cdot LL \cdot X_{LL}) + (Y_{p_DW} \cdot DW \cdot X_{DW})$$

$$M_{R_STR1a} = 187.283 \frac{\text{kip} \cdot \text{ft}}{\text{ft}}$$

Load Eccentricity

$$e_{max} := \frac{B}{3} = 4 \text{ ft}$$

AASHTO 11.6.3-3

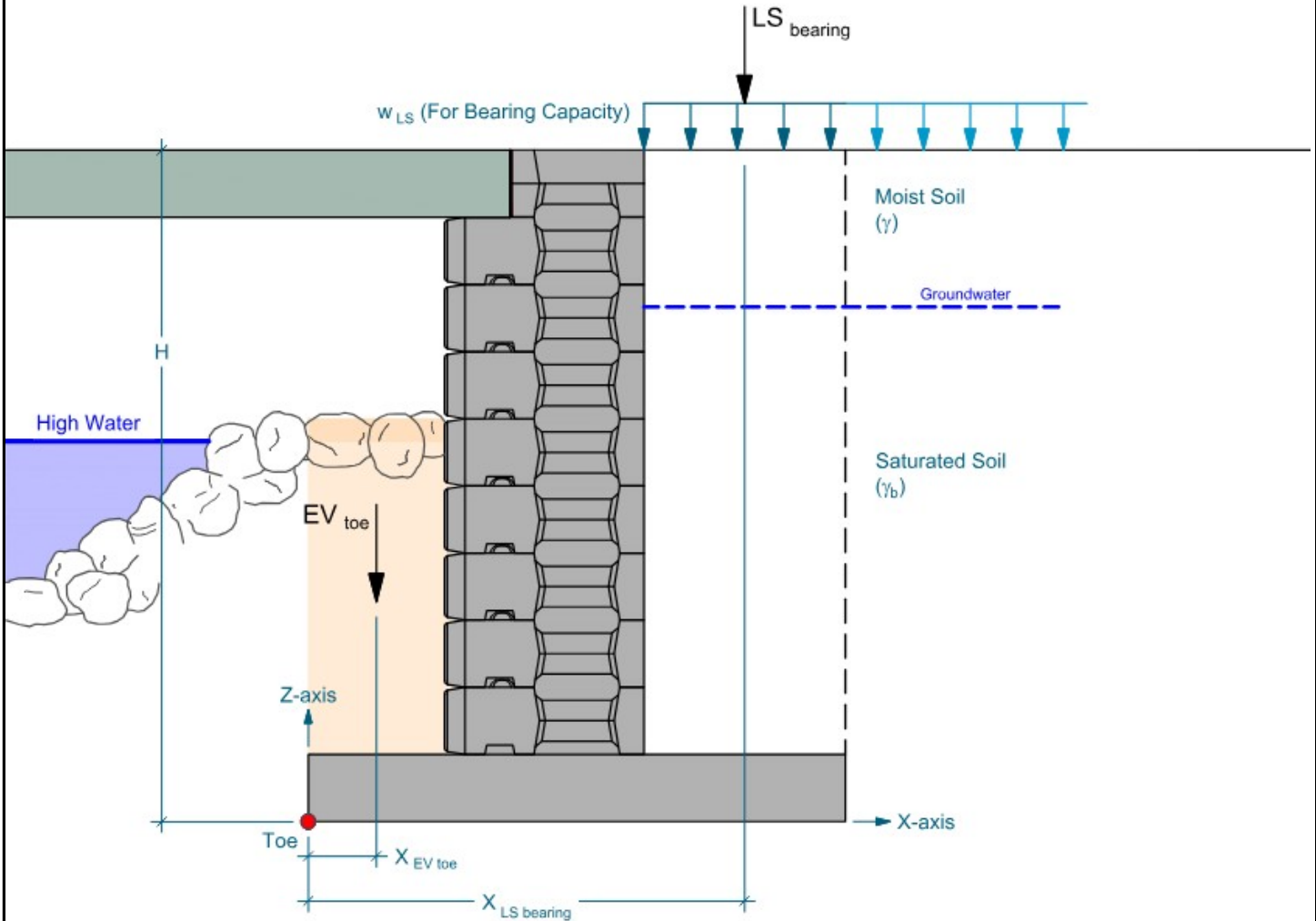
$$e_{STR1a} := \frac{B}{2} - \frac{(M_{R_STR1a} - M_{O_STR1a})}{V_{STR1a}} = 2.426 \text{ ft}$$

$$Check_{e_STR1a} := \text{if}(e_{STR1a} < e_{max}, \text{"OK for Load Eccentricity"}, \text{"Not OK for Load Eccentricity"})$$

$$Check_{e_STR1a} = \text{"OK for Load Eccentricity"}$$

Bearing Capacity Calculations

There are extra vertical loads that are included in bearing capacity, but not considered in sliding and overturning/eccentricity. These loads are the weight of the live load surcharge above the heel of the wall per AASHTO Figure C11.5.6-3 and the weight of the soil above the toe of the wall.



$$EV_{toe} := b_{toe} \cdot (h_{HW} - h_{block}) \cdot \gamma_b + 0.5 \text{ ft} \cdot b_{toe} \cdot \gamma = 1.524 \frac{\text{kip}}{\text{ft}} \quad (\text{Streambank material above the base block toe})$$

$$\text{Point of Application (from Toe)} \quad X_{EV_{toe}} := \frac{b_{toe}}{2} = 1.521 \text{ ft}$$

$$LS_{Bearing} := w_{LS} \cdot (b_{heel}) = 1.35 \frac{\text{kip}}{\text{ft}} \quad (\text{Vertical live load force which that is included in bearing capacity calculations per AASHTO Figure C11.5.6-3})$$

$$\text{Point of Application (from Toe)} \quad X_{LS_Bearing} := \frac{(b_{heel})}{2} + (b_{wall} + b_{facing} + b_{toe}) = 9.75 \text{ ft}$$

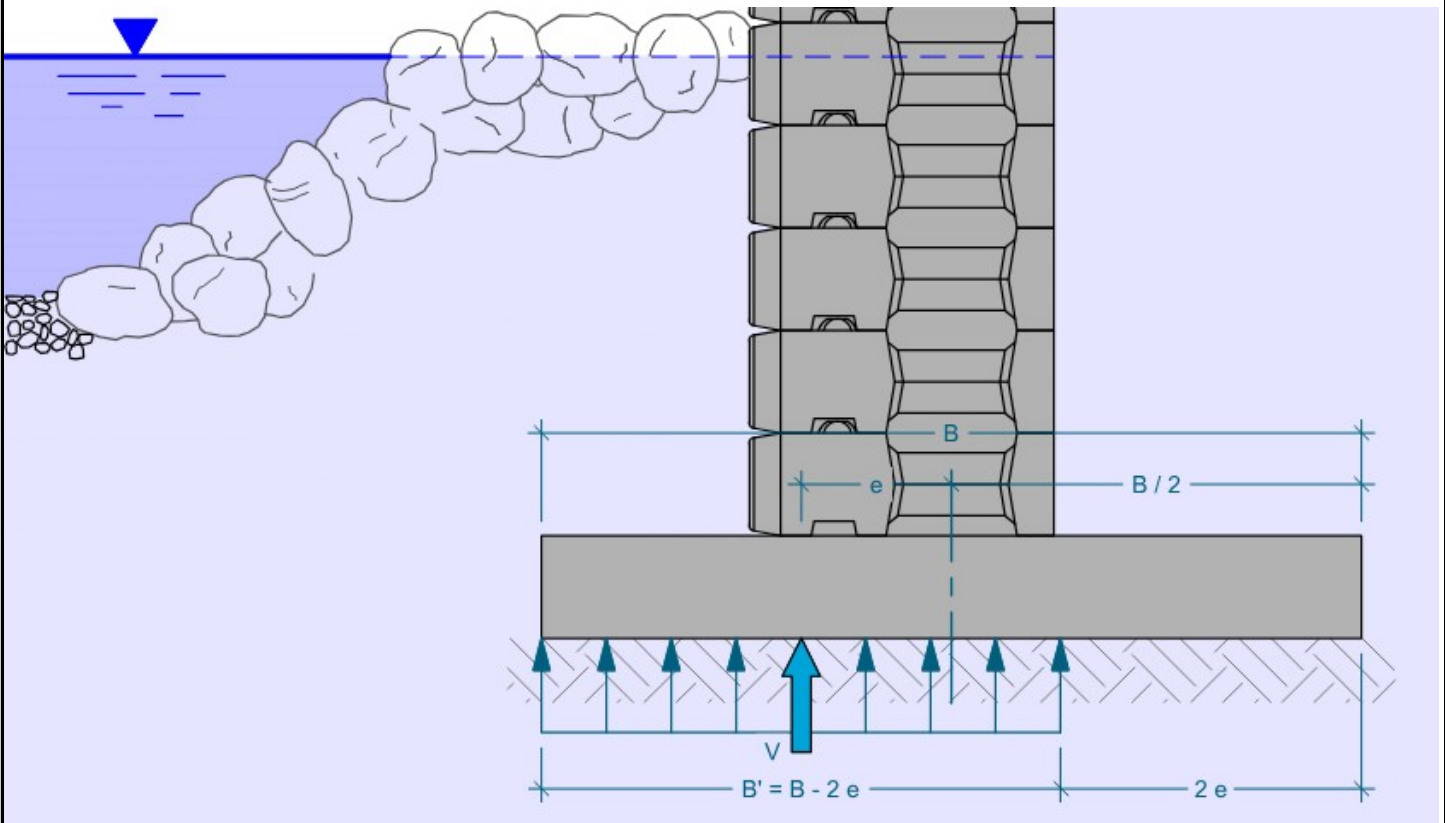
Vertical loads, resisting moment, and load eccentricity values are updated using the additional loads:

$$M_{R_STR1a_Bearing} := M_{R_STR1a} + (Y_{p_EV} \cdot EV_{toe} \cdot X_{EVtoe}) + (Y_{LS} \cdot LS_{Bearing} \cdot X_{LS_Bearing}) = 213.446 \frac{kip \cdot ft}{ft}$$

$$V_{STR1a_Bearing} := V_{STR1a} + (Y_{LS} \cdot LS_{Bearing}) + (Y_{p_EV} \cdot EV_{toe}) = 35.188 \frac{kip}{ft}$$

$$e_{STR1a_Bearing} := \frac{B}{2} - \frac{(M_{R_STR1a_Bearing} - M_{O_STR1a})}{(V_{STR1a_Bearing})} = 2.132 \text{ ft}$$

Bearing pressure is assumed to apply to a reduced footing area per AASHTO 10.6.1.3 (Meyerhof method).



$$B'_{STR1a} := B - 2 \cdot e_{STR1a_Bearing} = 7.737 \text{ ft}$$

AASHTO Equation 10.6.1.3-1

Applied Bearing Pressure (Factored)

$$q_{a_STR1a} := \frac{V_{STR1a_Bearing}}{B'_{STR1a}} = 4.548 \frac{kip}{ft^2}$$

Bearing Resistance

Bearing resistance will have a depth (embedment) term and a unit weight (footing width) term. Cohesion is neglected.

$$N_q := 18.4 \quad N_\gamma := 22.4 \quad \text{AASHTO Table 10.6.3.1.2a-1}$$

$$C_{wq} := 0.5 \quad C_{w\gamma} := 0.5 \quad \text{AASHTO Table 10.6.3.1.2a-2 (Water table above the bottom of footing)}$$

Footing Embedment Depth $D_f := 6.75 \text{ ft}$ This example uses a reduced footing embedment depth that is equal to the distance from the bottom of the footing to half of the channel height.

$$q_{n_STR1a} := \gamma \cdot D_f \cdot N_q \cdot C_{wq} + 0.5 \cdot \gamma \cdot B'_{STR1a} \cdot N_\gamma \cdot C_{w\gamma} = 12.651 \frac{\text{kip}}{\text{ft}^2} \quad \text{AASHTO Equation 10.6.3.1.2a-1}$$

$$\phi_b := 0.45 \quad \text{AASHTO Table 10.5.5.2.2-1}$$

$$q_{R_STR1a} := \phi_b \cdot q_{n_STR1a} = 5.693 \frac{\text{kip}}{\text{ft}^2} \quad \text{AASHTO Equation 10.6.3.1.1-1}$$

$$CDR_{BC_STR1a} := \frac{q_{R_STR1a}}{q_{a_STR1a}} = 1.252$$

$Check_{BC_STR1a} := \text{if}(CDR_{BC_STR1a} > 1, \text{"OK for Bearing Capacity"}, \text{"Not OK for Bearing Capacity"})$

$Check_{BC_STR1a} = \text{"OK for Bearing Capacity"}$

Load Combination = Strength 1 (b)

Maximum Vertical and Minimum Horizontal Loads

DC	$Y_{p_DC} := 1.25$	(Maximum)	EH	$Y_{p_EH} := 0.9$	(Minimum)
LL	$Y_{LL} := 1.75$		LS	$Y_{LS} := 1.75$	
DW	$Y_{p_DW} := 1.5$	(Maximum)	BR	$Y_{BR} := 1.75$	
EV	$Y_{p_EV} := 1.35$	(Maximum)	WA	$Y_{WA} := 1.0$	
			TU	$Y_{TU} := 1.2$	

Sliding Calculations

Driving Force

$$F_{H_STR1b} := (Y_{p_EH} \cdot EH_h) + (Y_{LS} \cdot LS_h) + (Y_{BR} \cdot BR) + (Y_{WA} \cdot WA) + (Y_{TU} \cdot TU) = 8.247 \frac{\text{kip}}{\text{ft}}$$

Sum of Vertical Forces

$$V_{STR1b} := (Y_{p_DC} \cdot W) + (Y_{p_EH} \cdot EH_v) + (Y_{LS} \cdot LS_v) + (Y_{p_EV} \cdot EV) + (Y_{p_DC} \cdot DC) + (Y_{LL} \cdot LL) + (Y_{p_DW} \cdot DW)$$

$$V_{STR1b} = 30.175 \frac{\text{kip}}{\text{ft}}$$

Resisting Force

$$\phi R_{T_STR1b} := \phi_{SL} \cdot C \cdot V_{STR1b} \cdot \tan(\phi_f) = 18.23 \frac{\text{kip}}{\text{ft}}$$

$$CDR_{SL_STR1b} := \frac{\phi R_{T_STR1b}}{F_{H_STR1b}} = 2.21$$

$$Check_{SL_STR1b} := \text{if}(CDR_{SL_STR1b} > 1, \text{"OK for Sliding"}, \text{"Not OK for Sliding"})$$

$$Check_{SL_STR1b} = \text{"OK for Sliding"}$$

Load Eccentricity (Overturning) Calculations

Overturning Moment

$$M_{O_STR1b} := (Y_{p_EH} \cdot EH_h \cdot Z_{EH}) + (Y_{LS} \cdot LS_h \cdot Z_{LS}) + (Y_{BR} \cdot BR \cdot Z_{BR}) + (Y_{WA} \cdot WA \cdot Z_{WA}) + (Y_{TU} \cdot TU \cdot Z_{TU})$$

$$M_{O_STR1b} = 68.435 \frac{\text{kip} \cdot \text{ft}}{\text{ft}}$$

Resisting Moment

$$M_{R_STR1b} := (Y_{p_DC} \cdot W \cdot X_W) + (Y_{p_EH} \cdot EH_v \cdot X_{EH}) + (Y_{LS} \cdot LS_v \cdot X_{LS}) + (Y_{p_EV} \cdot EV \cdot X_{EV}) + (Y_{p_DC} \cdot DC \cdot X_{DC}) + (Y_{LL} \cdot LL \cdot X_{LL}) + (Y_{p_DW} \cdot DW \cdot X_{DW})$$

$$M_{R_STR1b} = 180.158 \frac{\text{kip} \cdot \text{ft}}{\text{ft}}$$

Load Eccentricity

$$e_{max} = 4 \text{ ft}$$

$$e_{STR1b} := \frac{B}{2} - \frac{(M_{R_STR1b} - M_{O_STR1b})}{V_{STR1b}} = 2.297 \text{ ft}$$

$$Check_{e_STR1b} := \text{if}(e_{STR1b} < e_{max}, \text{"OK for Load Eccentricity"}, \text{"Not OK for Load Eccentricity"})$$

$$Check_{e_STR1b} = \text{"OK for Load Eccentricity"}$$

Bearing Capacity Calculations

$$M_{R_STR1b_Bearing} := M_{R_STR1b} + (Y_{p_EV} \cdot EV_{toe} \cdot X_{EVtoe}) + (Y_{LS} \cdot LS_{Bearing} \cdot X_{LS_Bearing}) = 206.321 \frac{kip \cdot ft}{ft}$$

$$V_{STR1b_Bearing} := V_{STR1b} + (Y_{LS} \cdot LS_{Bearing}) + (Y_{p_EV} \cdot EV_{toe}) = 34.594 \frac{kip}{ft}$$

$$e_{STR1b_Bearing} := \frac{B}{2} - \frac{(M_{R_STR1b_Bearing} - M_{O_STR1b})}{(V_{STR1b_Bearing})} = 2.014 \text{ ft}$$

$$B'_{STR1b} := B - 2 \cdot e_{STR1b_Bearing} = 7.972 \text{ ft}$$

Applied Bearing Pressure (Factored)

$$q_{a_STR1b} := \frac{V_{STR1b_Bearing}}{B'_{STR1b}} = 4.34 \frac{kip}{ft^2}$$

Bearing Resistance

$$q_{n_STR1b} := \gamma \cdot D_f \cdot N_q \cdot C_{wq} + 0.5 \cdot \gamma \cdot B'_{STR1b} \cdot N_\gamma \cdot C_{w\gamma} = 12.809 \frac{kip}{ft^2}$$

$$q_{R_STR1b} := \phi_b \cdot q_{n_STR1b} = 5.764 \frac{kip}{ft^2}$$

$$CDR_{BC_STR1b} := \frac{q_{R_STR1b}}{q_{a_STR1b}} = 1.328$$

$Check_{BC_STR1b} := \text{if } (CDR_{BC_STR1b} > 1, \text{"OK for Bearing Capacity"}, \text{"Not OK for Bearing Capacity"})$

$Check_{BC_STR1b} = \text{"OK for Bearing Capacity"}$

Load Combination = Strength 1 (c)

Minimum Vertical and Maximum Horizontal Loads (No LL or BR)

DC	$Y_{p_DC} := 0.90$	(Minimum)	EH	$Y_{p_EH} := 1.5$	(Maximum)
LL	$Y_{LL} := 0$		LS	$Y_{LS} := 1.75$	
DW	$Y_{p_DW} := 0.65$	(Minimum)	BR	$Y_{BR} := 0$	
EV	$Y_{p_EV} := 1.0$	(Minimum)	WA	$Y_{WA} := 1.0$	
			TU	$Y_{TU} := 1.2$	

Sliding Calculations

Driving Force

$$F_{H_STR1c} := (Y_{p_EH} \cdot EH_h) + (Y_{LS} \cdot LS_h) + (Y_{BR} \cdot BR) + (Y_{WA} \cdot WA) + (Y_{TU} \cdot TU) = 9.101 \frac{\text{kip}}{\text{ft}}$$

Sum of Vertical Forces

$$V_{STR1c} := (Y_{p_DC} \cdot W) + (Y_{p_EH} \cdot EH_v) + (Y_{LS} \cdot LS_v) + (Y_{p_EV} \cdot EV) + (Y_{p_DC} \cdot DC) + (Y_{LL} \cdot LL) + (Y_{p_DW} \cdot DW)$$

$$V_{STR1c} = 15.909 \frac{\text{kip}}{\text{ft}}$$

Resisting Force

$$\phi R_{T_STR1c} := \phi_{SL} \cdot C \cdot V_{STR1c} \cdot \tan(\phi_f) = 9.612 \frac{\text{kip}}{\text{ft}}$$

$$CDR_{SL_STR1c} := \frac{\phi R_{T_STR1c}}{F_{H_STR1c}} = 1.056$$

$$Check_{SL_STR1c} := \text{if}(CDR_{SL_STR1c} > 1, \text{"OK for Sliding"}, \text{"Not OK for Sliding"})$$

$$Check_{SL_STR1c} = \text{"OK for Sliding"}$$

Load Eccentricity (Overturning) Calculations

Overturning Moment

$$M_{O_STR1c} := (Y_{p_EH} \cdot EH_h \cdot Z_{EH}) + (Y_{LS} \cdot LS_h \cdot Z_{LS}) + (Y_{BR} \cdot BR \cdot Z_{BR}) + (Y_{WA} \cdot WA \cdot Z_{WA}) + (Y_{TU} \cdot TU \cdot Z_{TU})$$

$$M_{O_STR1c} = 60.994 \frac{\text{kip} \cdot \text{ft}}{\text{ft}}$$

Resisting Moment

$$M_{R_STR1c} := (Y_{p_DC} \cdot W \cdot X_W) + (Y_{p_EH} \cdot EH_v \cdot X_{EH}) + (Y_{LS} \cdot LS_v \cdot X_{LS}) + (Y_{p_EV} \cdot EV \cdot X_{EV}) + (Y_{p_DC} \cdot DC \cdot X_{DC}) + (Y_{LL} \cdot LL \cdot X_{LL}) + (Y_{p_DW} \cdot DW \cdot X_{DW})$$

$$M_{R_STR1c} = 115.611 \frac{\text{kip} \cdot \text{ft}}{\text{ft}}$$

Load Eccentricity

$$e_{max} = 4 \text{ ft} \quad e_{STR1c} := \frac{B}{2} - \frac{(M_{R_STR1c} - M_{O_STR1c})}{V_{STR1c}} = 2.567 \text{ ft}$$

$$Check_{e_STR1c} := \text{if}(e_{STR1c} < e_{max}, \text{"OK for Load Eccentricity"}, \text{"Not OK for Load Eccentricity"})$$

$$Check_{e_STR1c} = \text{"OK for Load Eccentricity"}$$

Bearing Capacity Calculations

$$M_{R_STR1c_Bearing} := M_{R_STR1c} + (Y_{p_EV} \cdot EV_{toe} \cdot X_{EVtoe}) + (Y_{LS} \cdot LS_{Bearing} \cdot X_{LS_Bearing}) = 140.962 \frac{kip \cdot ft}{ft}$$

$$V_{STR1c_Bearing} := V_{STR1c} + (Y_{LS} \cdot LS_{Bearing}) + (Y_{p_EV} \cdot EV_{toe}) = 19.796 \frac{kip}{ft}$$

$$e_{STR1c_Bearing} := \frac{B}{2} - \frac{(M_{R_STR1c_Bearing} - M_{O_STR1c})}{(V_{STR1c_Bearing})} = 1.96 \text{ ft}$$

$$B'_{STR1c} := B - 2 \cdot e_{STR1c_Bearing} = 8.079 \text{ ft}$$

Applied Bearing Pressure (Factored)

$$q_{a_STR1c} := \frac{V_{STR1c_Bearing}}{B'_{STR1c}} = 2.45 \frac{kip}{ft^2}$$

Bearing Resistance

$$q_{n_STR1c} := \gamma \cdot D_f \cdot N_q \cdot C_{wq} + 0.5 \cdot \gamma \cdot B'_{STR1c} \cdot N_\gamma \cdot C_{w\gamma} = 12.881 \frac{kip}{ft^2}$$

$$q_{R_STR1c} := \phi_b \cdot q_{n_STR1c} = 5.797 \frac{kip}{ft^2}$$

$$CDR_{BC_STR1c} := \frac{q_{R_STR1c}}{q_{a_STR1c}} = 2.366$$

$Check_{BC_STR1c} := \text{if } (CDR_{BC_STR1c} > 1, \text{"OK for Bearing Capacity"}, \text{"Not OK for Bearing Capacity"})$

$Check_{BC_STR1c} = \text{"OK for Bearing Capacity"}$

Summary of External Stability Analysis

	Strength 1(a)	Strength 1(b)	Strength 1(c)
	Maximum Vertical	Maximum Vertical	Minimum Vertical
	Maximum Horizontal	Minimum Horizontal	Maximum Horizontal
Sliding			
Driving Force	$F_{H_STR1a} = 9.878 \frac{\text{kip}}{\text{ft}}$	$F_{H_STR1b} = 8.247 \frac{\text{kip}}{\text{ft}}$	$F_{H_STR1c} = 9.101 \frac{\text{kip}}{\text{ft}}$
Resisting Force	$\phi R_{T_STR1a} = 18.589 \frac{\text{kip}}{\text{ft}}$	$\phi R_{T_STR1b} = 18.23 \frac{\text{kip}}{\text{ft}}$	$\phi R_{T_STR1c} = 9.612 \frac{\text{kip}}{\text{ft}}$
CDR_{sliding}	$CDR_{SL_STR1a} = 1.882$	$CDR_{SL_STR1b} = 2.21$	$CDR_{SL_STR1c} = 1.056$
Eccentricity			
	$e_{STR1a} = 2.426 \text{ ft}$	$e_{STR1b} = 2.297 \text{ ft}$	$e_{STR1c} = 2.567 \text{ ft}$
Bearing Capacity			
Applied Bearing Pressure	$q_{a_STR1a} = 4.548 \frac{\text{kip}}{\text{ft}^2}$	$q_{a_STR1b} = 4.34 \frac{\text{kip}}{\text{ft}^2}$	$q_{a_STR1c} = 2.45 \frac{\text{kip}}{\text{ft}^2}$
Bearing Resistance	$q_{R_STR1a} = 5.693 \frac{\text{kip}}{\text{ft}^2}$	$q_{R_STR1b} = 5.764 \frac{\text{kip}}{\text{ft}^2}$	$q_{R_STR1c} = 5.797 \frac{\text{kip}}{\text{ft}^2}$
CDR_{bearing}	$CDR_{BC_STR1a} = 1.252$	$CDR_{BC_STR1b} = 1.328$	$CDR_{BC_STR1c} = 2.366$

Abutment wall meets minimum requirements for **external stability** under the **Strength 1** load combination limit state. Controlling conditions are **highlighted**.