Project	Project #	Date
Gravity Wall Design - LRFD	20004.00	12/5/23

GRAVITY WALL DESIGN - LRFD

STONE STRONG PRECAST MODULAR BLOCK

This engineering section presents information for design of Stone Strong retaining walls in a gravity configuration using Load and Resistance Factor Design (LRFD) procedures.

The design methodologies presented conform substantially to AASHTO specifications (LRFD Bridge Specifications, 8th Edition, 2017). This section includes the following documents:

LRFD Gravity Wall Design Methodology (17 pages)
Example LRFD Gravity Wall Calculations (22 pages)
Example LRFD Spreadsheet Output (12 pages)

The example calculations and example spreadsheet output match identical design conditions and are intended as verification of the spreadsheet method. Note that the Gravity Analysis Spreadsheet is available on the Stone Strong website.

GRAVITY WALL LRFD DESIGN METHODOLOGY

STONE STRONG PRECAST MODULAR BLOCK

Evaluate gravity retaining wall using strength design approach (Load and Resistance Factor Design) following AASHTO analytical techniques – refer to:

AASHTO LRFD Bridge Design Specifications, 9th Edition 2020

Additional analytical methods and theories are taken from previous AASHTO specifications and other FHWA guidelines – refer to:

Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, NHI-10-024

AASHTO Standard Specifications for Highway Bridges 2002, 17th Addition

Properties of Soil/Aggregate

Soil and material properties should be determined for the specific materials to be used:

unit fill - γ_u = 110 pcf (17.3 kN/m^3) max (see AASHTO 2002 5.9.2) & ϕ_u

leveling base –γ_b & ϕ_b for typical aggregate base (or concrete base may be substituted)

retained soil - γ & ϕ by site conditions (where select backfill is used, select material must encompass entire retained soil influence zone)

foundation soil - γ ϕ & c by site conditions

interface angle (see AASHTO LRFD Table C3.11.5.9-1)

For stepped modules, when the block width varies within a vertical section, $\delta = ¾\ \phi$

For cases where all blocks are substantially uniform width, $\delta = ½\ \phi$

Note: infill weight is reduced to account for infill not engaged by modular units in overturning. Only 80% of the weight of aggregate is included in the overturning calculations, W' (see AASHTO LRFD 11.11.4.4)

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Precast Modular Unit Geometric Properties

Block Library – Imperial Units (not all units available from all dealers, verify availability)

Block Type	Description	Conc. Wt. (lbs)	Void Vol. (ft³)	Length (ft)	Height (ft)	Unit Width (in)	Conc. Cen. of Gravity x_b (in)	Void Cen. of Gravity x_a (in)
6-28	6SF-28 unit (6 square feet)	950	6.65	4	1.50	28	12.8	14.0
6-44	6SF-44 unit (6 square feet)	1,500	10.95	4	1.50	44	21.0	23.5
24-44	24SF-44 unit (24 square feet)	6,000	43.21	8	3.00	44	21.2	24.8
24-ME	24SF Mass Extender unit	10,000	44.94	8	3.00	56	32.7	25.8
24-62	24SF-62 unit	6,800	76.05	8	3.00	62	29.1	33.0
24-86	24SF-86 unit	7,600	117.90	8	3.00	86	40.0	45.1
D150	D150 Assembly (24SF-150)	12,650	210.32	8	3.00	150	74.5	75.5

dimensions are for battered units - for vertical face 24SF units, the width and center of gravity dimensions are all reduced by 1 inch

Block Library – Metric Units (not all units available from all dealers, verify availability)

Block Type	Description	Conc. Wt. (kN)	Void Vol. (m³)	Length (m)	Height (m)	Unit Width (mm)	Conc. Cen. of Gravity x_b (mm)	Void Cen. of Gravity x_a (mm)
6-28	6SF-28 unit (6 square feet)	4.23	0.19	1.22	0.46	711	324	356
6-44	6SF-44 unit (6 square feet)	6.67	0.31	1.22	0.46	1,118	533	597
24-44	24SF-44 unit (24 square feet)	26.69	1.22	2.44	0.91	1,118	538	630
24-ME	24SF Mass Extender unit	44.48	1.28	2.44	0.91	1,422	831	655
24-62	24SF-62 unit	30.25	2.16	2.44	0.91	1,575	739	838
24-86	24SF-86 unit	33.80	3.35	2.44	0.91	2,184	1,016	1,146
D150	D150 Assembly (24SF-150)	56.27	5.96	2.44	0.91	3,810	1,892	1,918

dimensions are for battered units - for vertical face 24SF units, the width and center of gravity dimensions are all reduced by 25 mm

Wall stability calculations are performed per unit length of wall, so all weights and forces are expressed per foot or m of wall length.

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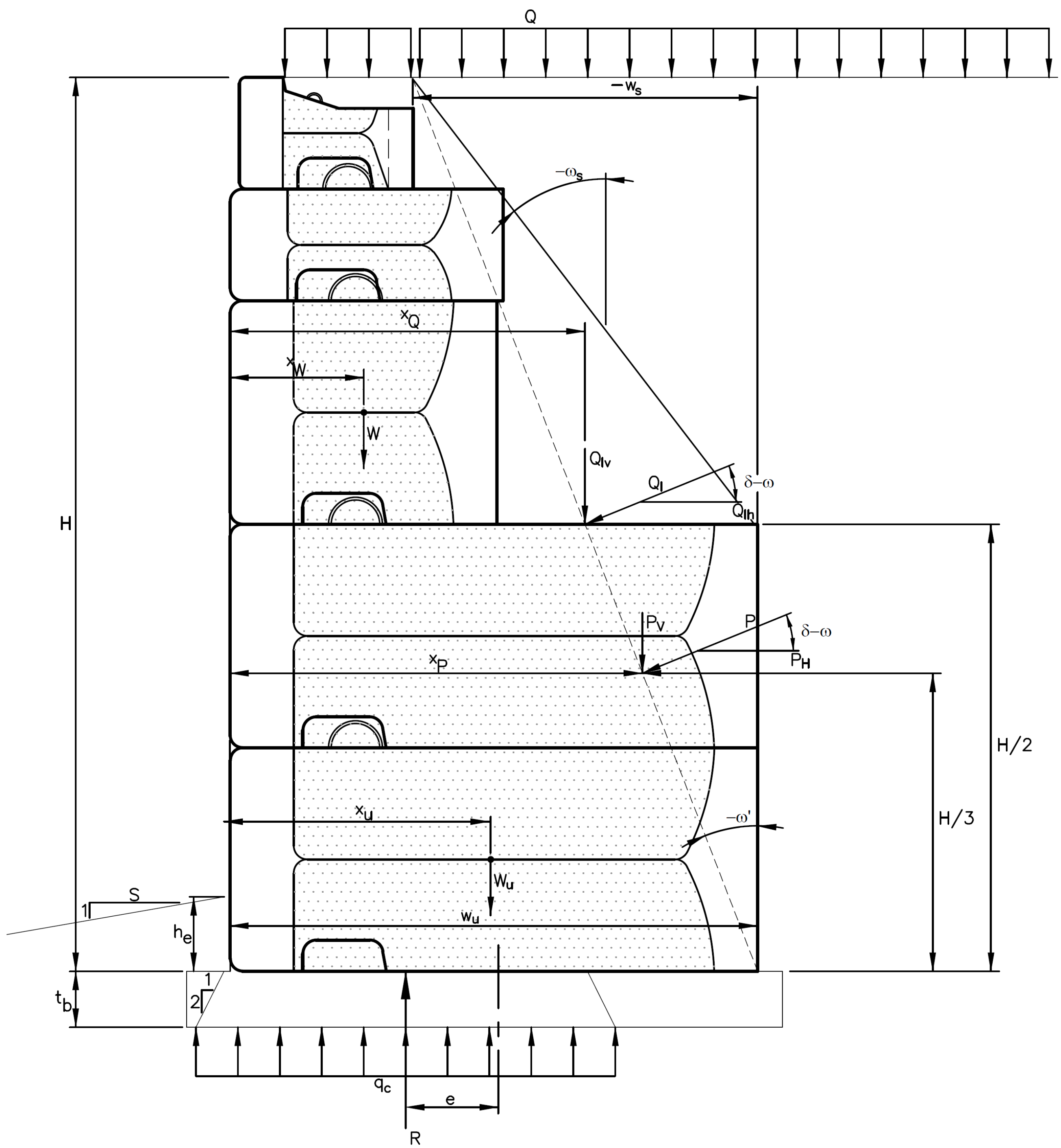
Typical gravity wall configuration with precast stepped modules, variables, and nomenclature:



Note that surcharge loads over the top of the wall are treated separately from surcharge behind the wall.

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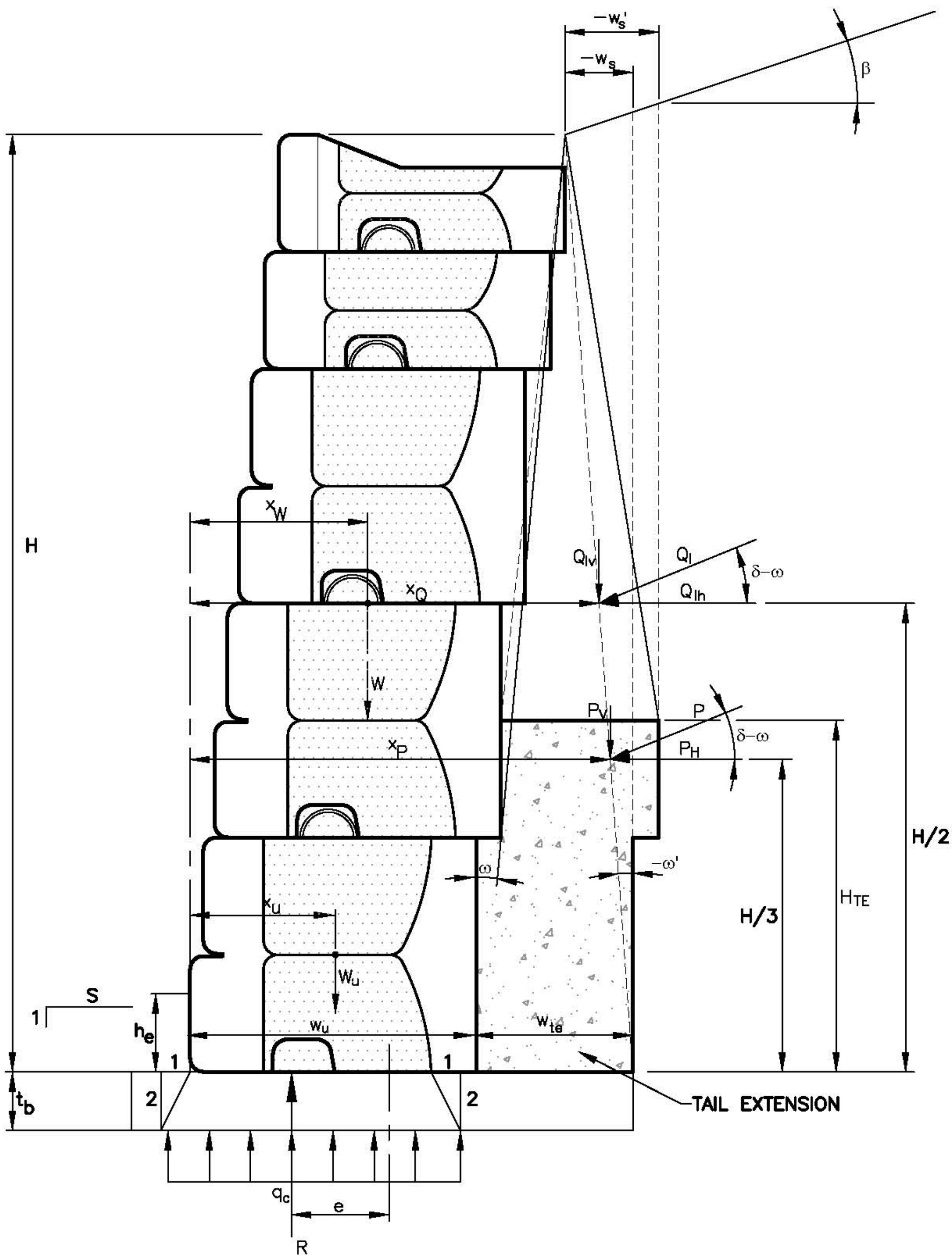
Typical gravity wall with cast in place tail extension, variables, and nomenclature:



Wall units that vary in width are referred to as “stepped” modules. Wider wall units are typically placed at the bottom of the wall. In addition to using wider precast units, the stability of a gravity wall can be improved by using cast-in-place tail extensions to increase the width of the units. The width of the CIP extension is not limited, but it is recommend that the height be at least 2 times the width to provide shear through the tail openings (unless connecting with reinforcing steel).

Wall batter

The block units may be installed with either a vertical face or a battered face. In vertical applications, the units are be installed with no batter or setback between units, $\omega = 0°$

In a battered configuration, the 24-44, 24-62, 24-86, and 24-ME units are 36 inches (914 mm) high and the next block atop a 24 SF block will batter back 4 inches (102 mm). The 6-44 and 6-28 units are 18 inches (457 mm) tall, and the next block atop a 6 SF block will batter 2 inches (51 mm). These blocks may be interchanged within a wall stack, but the batter is determined by the height of the unit below.

4 in. setback per 24 SF block (36 in. tall) 102 mm setback per 24 SF block (914 mm tall)

2 in. setback per 6 SF block (18 in. tall) 51 mm setback per 6 SF block (457 mm tall)

The face batter is calculated as:

$\omega = \arctan(4/36) = 6.34°$ $\omega = \arctan(102/914) = 6.34°$

or $\omega = \arctan(2/18) = 6.34°$ $\omega = \arctan(51/457) = 6.34°$

For uniform modules, the batter of the back face matches the batter of the front face. For stepped modules, the batter is recalculated along the back of the wall from the rear of the bottom unit to the rear of the top of the wall (see AASHTO LRFD 3.11.5.9). Use ω' in Coulomb equation and earth pressure component calculations. To calculate ω' it is necessary to know the effective setback width, w_s, which is the horizontal distance between the back edge of the top block and the back edge of the lower unit including any tail extension. w_s is negative when the mass extender projects further than the back of the top block. Knowing this distance and the height of wall:

$$\omega' = \arctan(w_s / H_w)$$

Base Thickness/Embedment

The type and thickness of wall base or leveling pad and depth of embedment can vary by site requirements. A granular base with a thickness of 9 inches is commonly used, but the thickness can be adjusted to reduce the contact pressure. A concrete leveling pad or footing can also be used. The required embedment to the top of the base is related to the exposed height of the wall and by the slope at the toe, as well as other factors. The required embedment can be calculated for slopes steeper than 6H:1V using the following equation (see AASHTO LRFD Table C11.10.2.2-1):

$$h_e = H'/(20*S/6)$$

where S is the run of the toe slope per unit fall and H’ is the exposed height

A minimum embedment of 12 inches (300 mm) for level toe and 24 inches (600 mm) for toe slopes of 4H:1V or steeper is recommended for highway applications (AASHTO LRFD 11.10.2.2)

Weight of Wall

The weight of the wall includes the contributions of the blocks, the aggregate unit fill, the tail extension, and the soil wedge atop extended modules or tail extension

The weight of the tail extension is calculated:

$W_{te} = (w_{te} * H_{te}) * 145$ pcf (22.8 kN/m^3) (typical unit weight for concrete)

where w_{te} is the width of the tail extension and H_{te} is the height of the extension (both in ft.)

The angle of the batter (from vertical) of the soil wedge above the tail extension, ω_s, is calculated:

$\omega_s = \arctan(-w_s'/H_{wedge})$

The weight of soil in the wedge above the tail extension is calculated for the trapezoidal area of the wedge that lies behind each block

h_s = height of the soil trapezoid behind the block (may differ from height of the block)

w_u = width of the block

h_1 = dist. from the top of wall to top of the soil trapezoid behind the block

h_2 = dist. from the top of wall to bottom of the soil trapezoid behind the block

s = dist. from the face of wall to face of the block

s_u = dist. from the face of wall to back of the block = $s + w_u$

s_T = dist. from the face of wall to the back of top-most block of wall

b_1 = length of top side of trapezoid of soil behind block = $h_1 * \tan(\omega_s)+(s_T - s_u)$

b_2 = length of bottom side of trapezoid of soil behind block = $h_2 * \tan(\omega_s)+(s_T - s_u)$

The weight of the soil wedge above the tail extension behind each block, W_s, is calculated as the trapezoidal area multiplied by the lesser of the unit weight of the retained soil or the unit fill:

$W_s = [h_s * (b_1+b_2)/2] * (\text{min of } \gamma_{ret} \text{ or } \gamma_u)$

The center of gravity of the trapezoidal wedge behind each block, measured from the face of the wall at the bottom course, is calculated:

$x_s = [(b_1*b_2+(b_2^2-2*b_1*b_2+b_1^2)/3)/(b_1+b_2)]+ s + w_u$

$y_s = [h_s/3*(2b_1+b_2)/(b_1+b_2)]+ H - h_2$

W_s is treated as aggregate infill subject to 80% limitations for overturning calculations (conservative)

Static Forces

Coulomb active earth pressure coefficient (see AASHTO LRFD 3.11.5.3)

$$K_a = \frac{\cos^2(\phi + \omega')}{\cos^2(\omega')\cos(\omega' - \delta)\left[1 + \sqrt{\frac{\sin(\phi + \delta)\sin(\phi - \beta)}{\cos(\omega' - \delta)\cos(\omega' + \beta)}}\right]^2}$$

As an alternate, a trial wedge technique may be used to determine the earth pressure forces acting on the modular wall.

Earth Load Components (see AASHTO LRFD 11.10.5.2)

Vertical forces:

$P_v = 0.5\ K_a\ \gamma\ H^2 * \sin(\delta - \omega')$

$Q_{lv} = K_a\ Q\ H * \sin(\delta - \omega')$ where Q is the effective surcharge in psf (kPa)

Horizontal forces:

$P_h = 0.5\ K_a\ \gamma\ H^2 * \cos(\delta - \omega')$

$Q_{lh} = K_a\ Q\ H * \cos(\delta - \omega')$ where Q is the effective surcharge in psf (kPa)

Resultants of earth load components:

$y_P = H/3$

$x_P = (H/3) * \tan(\omega') + w_u$

$y_{Ql} = H/2$

$x_{Ql} = (H/2) * \tan(\omega') + w_u$

where w_u is the width of the bottom unit, including any tail extension (w_{te})

Weight Components

Vertical forces:

W_b – Weight of wall units

W_{te} – Weight of concrete tail extension, if used

W_a – Weight of infill aggregate (use 80% aggregate weight for overturning)

W_s – Weight of soil atop tail extension (use 80% aggregate weight for overturning)

$W_b = \sum(W_{b1} + W_{b2} + \cdots + W_{bn})$

$W_{te} = \sum(W_{te1} + W_{te2} + \cdots + W_{te})$

$W_a = \sum(W_{a1} + W_{a2} + \cdots + W_{an})$

$W_s = \sum(W_{s1} + W_{s2} + \cdots + W_{sn})$

Resultants of weight components:

The center of mass of the stack of blocks is calculated as:

$x_b = \sum(W_{b1}*x_{b1} + W_{b2}*x_{b2} + \cdots + W_{bn}*x_{bn}) / \sum(W_{b1} + W_{b2} + \cdots + W_{bn})$

$y_b = \sum(W_{b1}*y_{b1} + W_{b2}*y_{b2} + \cdots + W_{bn}*y_{bn}) / \sum(W_{b1} + W_{b2} + \cdots + W_{bn})$

The center of mass of the aggregate fill is:

$x_a = \sum(W_{a1}*x_{a1} + W_{a2}*x_{a2} + \cdots + W_{an}*x_{an}) / \sum(W_{a1} + W_{a2} + \cdots + W_{an})$

$y_a = \sum(W_{a1}*y_{a1} + W_{a2}*y_{a2} + \cdots + W_{an}*y_{an}) / \sum(W_{a1} + W_{a2} + \cdots + W_{an})$

The center of mass of the soil wedge over the tail is:

$x_s = \sum(W_{s1}*x_{s1} + W_{s2}*x_{s2} + \cdots + W_{sn}*x_{sn}) / \sum(W_{s1} + W_{s2} + \cdots + W_{sn})$

$y_s = \sum(W_{s1}*y_{s1} + W_{s2}*y_{s2} + \cdots + W_{sn}*y_{sn}) / \sum(W_{s1} + W_{s2} + \cdots + W_{sn})$

The center of mass of the tail extension can be calculated with the following equation:

$x_{te} = \sum(W_{te1}*x_{te1} + W_{te2}*x_{te2} + \cdots + W_{ten}*x_{ten}) / \sum(W_{te1} + W_{te2} + \cdots + W_{te})$

$y_{te} = \sum(W_{te1}*y_{te1} + W_{te2}*y_{te2} + \cdots + W_{ten}*y_{ten}) / \sum(W_{te1} + W_{te2} + \cdots + W_{te})$

The overall adjusted center of mass of the blocks and tail extension:

$x_{b+te} = (W_b*x_b + W_{te}*x_{te}) / (W_b + W_{te})$

$y_{b+te} = (W_b*y_b + W_{te}*y_{te}) / (W_b + W_{te})$

The overall adjusted center of mass of the aggregate and the soil above the tail is:

$x_{a+s} = (W_a*x_a + W_s*x_s) / (W_a + W_s)$

$y_{a+s} = (W_a*y_a + W_s*y_s) / (W_a + W_s)$

Seismic Loads

Seismic components of force are calculated according to the procedures in FHWA 4.2h.

The maximum acceleration A_m = (1.45 - A)*A where A is the peak horizontal ground acceleration.

The seismic earth pressure coefficient is calculated with the following equation:

$$K_{ae} = \frac{\cos^2(\phi + \omega' - \xi)}{\cos(\xi)\cos^2(-\omega')\cos(\delta - \omega' + \xi)\left[1 + \sqrt{\frac{\sin(\phi+\delta)\sin(\phi-\xi-\beta)}{\cos(\delta-\omega'+\xi)\cos(\omega'+\beta)}}\right]^2}$$

where $\xi = \arctan[k_h/(1 - k_v)]$

The trial wedge technique is recommended in high seismicity regions to determine the dynamic thrust forces acting on the modular wall.

<u>Seismic Earth load components</u>

k_v is generally taken as 0. k_h is the maximum horizontal acceleration of the wall, and is a function of the maximum allowable displacement of the wall during a seismic event. It is calculated with the following equation:

$k_h = 0.74 * A_s * [A_s/(d)]^{0.25}$ (where d is in inches)

$k_h = 1.66 * A_s * [A_s/(d)]^{0.25}$ (where d is in mm)

d is the maximum horizontal displacement and is typically set at 2 inches (50 mm) as conservative.

$A_s = PGA * F_{pga}$

k_h is generally taken as no greater than ½ of A_s

The horizontal inertial force P_{ir} is calculated as follows:

$P_{ir} = (W_b+W_{te}+W_a+W_s)*k_h$

The seismic thrust is calculated as follows:

$\Delta P_{ae} = 0.5 * \gamma * H^2 * (K_{ae} - K_a)$

$\Delta P_{aeh} = 0.5 * \gamma * H^2 * (K_{ae} - K_a) * \cos(\delta - \omega')$

$\Delta P_{aev} = 0.5 * \gamma * H^2 * (K_{ae} - K_a) * \sin(\delta - \omega')$

<u>Resultants of Seismic Earth load components</u>

In overturning analysis, the inertial force is applied at the vertical center of gravity of the wall, while the seismic thrust is applied at 1/3 of the wall height.

x_{Pae} = H/3*tan(ω') + w_u

y_{Pae} = H/3

$y_{Pir} = (W_b*y_b + W_{te}*y_{te} + W_a*y_a + W_s*y_s) / (W_b + W_{te} + W_a + W_s)$

The combined earth pressure P_{ae} is the sum of the static earth pressure P_a and the seismic thrust ΔP_{ae}. By AASHTO LRFD requirements, two seismic load conditions must be evaluated (AASHTO LRFD 11.6.5.1):

$P_{ae}/2 + P_{ir} = P_a/2 + \Delta P_{ae}/2 + P_{ir}$ (but not less than $P_a + P_{ir}$)

$P_{ae} + P_{ir}/2 = P_a + \Delta P_{ae} + P_{ir}/2$

Load cases a & b are separately evaluated to include the alternate combinations above.

Base Friction

Friction across the base of the wall is used to resist sliding failure. Frictional resistance must be determined both between the wall assembly and the base and between the base and the foundation soil (or through the foundation soil).

The unfactored sliding resistance is calculated as the smaller result of the following equations:

For base to foundation soil failure, use:

$R_{s(foundation\ soil)} = (W_b + W_{te} + W_a + W_s + P_v + t_b*w_b*\gamma_b) \tan \phi + B_w*c$

$= (F_v+W_{base})* \tan \phi + B_w*c$

where ϕ represents foundation soils, B_w is base width (block width plus ½H:1V distribution through base), and c represents foundation soil cohesion.

For block to base material sliding, use:

$R_{s(footing)} = \mu_b (W_b + W_{te} + W_a + W_s + P_v) = \mu_b (F_v)$

where μ_b represents a composite coefficient of friction for the base

The composite friction coefficient is calculated using contributory areas. The base of a Stone Strong unit consists of a percentage of open void space to be filled with aggregate and a percentage of concrete. These percentages are calculated as follows:

$\%_{void} = V_{void}/(V_{void}+V_{concrete})$

$\%_{concrete} = V_{concrete}/(V_{void}+V_{concrete})$

If a cast-in-place tail extension is used, the area of the tail extension must also be calculated and the total area is also increased accordingly. Thus, the equation for composite friction coefficient across the base becomes:

$\mu_b = (\%_{void}*w_{u(bottom)}*\mu_{p\ -\ unit\ fill/base} + \%_{concrete}*\ w_{u(bottom)}*\mu_{p\ -\ block/base} + w_{te}*\mu_{p\ -\ extension/base})/(\ w_{u(bottom)} + w_{te})$

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Partial friction coefficients can be interpreted from the following table:
(see AASHTO LRFD 10.6.3.4)

	Coefficient of Friction
Block to Aggregate Base formed precast surface on compacted aggregate surface (includes Mass Extender)	0.8*tan ϕ_b
Unit Fill to Aggregate Base screened aggregate (loose to moderate relative density - dumped) on compacted aggregate surface	lower tan ϕ_b or tan ϕ_u
Block to Concrete Base formed precast surface on floated concrete surface (includes Mass Extender)	0.60
Unit Fill Aggregate to Concrete Base screened aggregate (loose to moderate relative density - dumped) on floated concrete surface	0.8*tan ϕ_u
Concrete Tail Extension to Aggregate Base cast in place concrete on aggregate surface	tan ϕ_b
Concrete Tail Extension to Concrete Base cast in place concrete on floated concrete surface	0.75
Concrete Tail Extension Directly on Foundation Soil (Sand) cast in place concrete on granular soil	tan ϕ_f

Note: These typical values may be used for evaluation of base sliding at the discretion of the user. The licensed engineer of record is responsible for all design input and for evaluating the reasonableness of calculation output based upon his/her knowledge of local materials and practices and on the specific design details.

Since the unit fill aggregate is typically placed to a moderately loose state, the friction angle for the screened unit fill aggregate typically controls for the interface between the unit fill and the base aggregate.

If actual test data for the project specific materials is not available, or for preliminary design, the following conservative friction angles are suggested for base and infill aggregates:
(see AASHTO LRFD Fig. 10.4.6.2.4-1)

	Friction Angle (degrees)		
	Well Graded, Aggregate, Densely Compacted	Screened Aggregate, Compacted	Screened Aggregate, Loose to Moderate Relative Density
Crushed Hard Aggregate >75% w/ 2 fractured faces, hard natural rock	42	40	36
Crushed Aggregate >75% w/ 2 fractured faces, medium natural rock or recycled concrete	40	38	35
Cracked Gravel >90% w/ 1 fractured face	36	35	32

Note: Physical testing of specific aggregates is recommended. When test data is not available, these typical values may be used at the discretion of the user. The licensed engineer of record is responsible for all design input and for evaluating the reasonableness of calculation output based upon his/her knowledge of local materials and practices and on the specific design details.

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Table of Unfactored Forces & Moments

	Force (lb) or (kN)	Arm (ft) or (m)	Moment about toe (lb*ft) or (kN *m)
Vertical Forces			
weight of blocks	$W_b + W_{te}$	x_{b+te}	$(W_b + W_{te})^* x_{b+te}$
weight of agg. & soil over tail	$W_a + W_s$	x_{a+s}	$(W_a + W_s) * x_{a+s}$
modified weight of a & s (80%)	$0.8*(W_a + W_s)$	x_{a+s}	$0.8*(W_a + W_s) * x_{a+s}$
earth pressure	P_v	x_{Pv}	P_v*x_{Pv}
LL surcharge	Q_{lv}	x_{Qlv}	$Q_{lv}*x_{Qlv}$
Horizontal Forces			
static earth pressure*	P_h	x_{Ph}	P_h*y_{Ph}
seismic thrust*	ΔP_{aeh}	x_{Paeh}	$\Delta P_{aeh}* y_{Paeh}$
inertial force*	P_{ir}	x_{Pir}	$P_{ir}* y_{Pir}$
LL surcharge	Q_{lh}	x_{Qlh}	$Q_{lh}*y_{Qlh}$

* For seismic load case, separate analysis should be run using **a)** reduced combined earth pressure (50% of $P_h + \Delta P_{aeh}$, but not less than P_h) with the full inertial force (P_{ir}) and **b)** full earth pressure ($P_h + \Delta P_{aeh}$) with reduced inertial force (50% of P_{ir}).

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Table of Load and Resistance Factors for the relevant load cases
(based on AASHTO LRFD Tables 3.4.1-1, 3.4.1-2, and 10.5.5.2.2-1)

	Strength I-a	Strength I-b	Strength IV	Extreme I-a (EQ)	Extreme I-b (EQ)	Extreme II (CT)	Service I
Load Factors							
LL	1.75	1.75	0.00	0.00	0.00	0.5	1.00
EH	1.50	1.50	1.50	1.00	1.00	1.00	1.00
EQ	0.00	0.00	0.00	1.00	1.00	0.00	0.00
CT	0.00	0.00	0.00	0.00	0.00	1.00	0.00
LL Surcharge Over Wall	0.00	1.75	0.00	0.00	0.00	0.00	1.00
Resistance Factors							
DC	0.90	1.25	1.50	1.00	1.00	1.00	1.00
EV	1.00	1.35	1.35	1.00	1.00	1.00	1.00
BC	0.45	0.45	0.45	1.00	1.00	1.00	1.00
ϕ_τ precast to agg	0.90	0.90	0.90	1.00	1.00	1.00	1.00
ϕ_τ CIP to agg/soil	0.80	0.80	0.80	1.00	1.00	1.00	1.00
ϕ_τ soil to soil	0.90	0.90	0.90	1.00	1.00	1.00	1.00
ϕ_τ precast to precast	0.90	0.90	0.90	1.00	1.00	1.00	1.00

For each of the load cases, the unfactored vertical and horizontal forces are multiplied by the corresponding load and resistance factors for each.

Table of Calculated Factored Forces and Moments

	Force (lb) or (kN)	**Moment** (lb*ft) or (kN*m)
Vertical Forces		
block weight	$(W_b + W_{te})$*DC	$(W_b + W_{te})$*x_{b+te} *DC
aggregate & soil weight	$(W_a + W_s)$*EV	$(W_a + W_s)$*x_{a+s} *EV
modified agg & soil weight	0.8*$(W_a + W_s)$*EV	0.8*$(W_a + W_s)$*x_{a+s} *EV
earth pressure	P_v*EH	P_v*x_{Pv}*EH
LL surcharge	Q_{lv}*LL	Q_{lv}*x_{Qlv}*LL
seismic thrust*	ΔP_{aev}*EQ	ΔP_{aev}* $x_{P_{aeh}}$*EQ
Horizontal Forces		
static earth pressure*	P_h*EH	P_h*y_{P_h}*EH
LL surcharge	Q_{lh}*LL	Q_{lh}*y_{Qlh}*LL
seismic thrust*	ΔP_{aeh}*EQ	ΔP_{aeh}* $y_{P_{aeh}}$*EQ
inertial force*	P_{ir}*EQ	P_{ir}* $y_{P_{ir}}$ *EQ

* For seismic load case, separate analysis should be run using **a)** reduced combined earth pressure (50% of $P_h + \Delta P_{aeh}$, but not less than P_h) with the full inertial force (P_{ir}) and **b)** full earth pressure ($P_h + \Delta P_{aeh}$) with reduced inertial force (50% of P_{ir}).

Overturning/Eccentricity

For overturning, the modified weights using 80% of the aggregate weight (including the soil over the tail extension) are used for all overturning calculations.

Although not an explicit requirement of the AASHTO specification, the driving and resisting overturning moments should be compared:

M'_V	Σ factored moments from vertical forces (using 80% W_s & W_a)
M_H	Σ factored moments from horizontal forces

For each load case, the factored overturning resistance should be greater than the factored overturning load

Check that $M'_V > M_H$

This behavior rarely controls. The AASHTO specification uses eccentricity as a proxy for overturning (but still using 80% of the infill weight).

Eccentricity should be calculated to check overturning. For an aggregate base, the resultant of the vertical forces must fall within the center 2/3 of the base, so eccentricity must be less than 1/3 times the base width (see AASHTO LRFD 11.6.3.3)

$B/3 = (w_{u(bottom\ unit)} + w_{te})/3$

For a concrete base, or a base bearing on rock, the resultant of the vertical forces must fall within the center 90% of the base, so eccentricity must be less than 45% of the base width (see AASHTO LRFD 11.6.3.3).

$B*0.45 = (w_{u(bottom\ unit)} + w_{te})*0.45$

For the Extreme load cases, the resultant of the vertical forces must fall within the center 80% of the base, so eccentricity must be less than 40% times the base width (see AASHTO LRFD 11.6.5.1)

$B*0.4 = (w_{u(bottom\ unit)} + w_{te})*0.4$

(note that for EQ between 0.0 and 1.0, interpolate between 1/3 and 0.4)

Eccentricity or the location of the vertical resultant is calculated as:

F'_V	Σ factored vertical forces (using 80% W_s & W_a)
M'_v	Σ factored moments from vertical forces (using 80% W_s & W_a)
M_H	Σ factored moments from horizontal forces
e	$e = (w_{u(bottom)} + w_{te})/2 + (M_H - M'_V)/F'_V$

For each load case, verify that the eccentricity is less than 1/3 of the base width (or 45% for concrete base, or 40% for Extreme load cases)

Check that $e < B/3$, or $B*0.45$, or $B*0.40$

Sliding

For each load case, the minimum value for sliding resistance is calculated. A resistance factor of 0.8 is used for a cast in place interface (concrete base or a cast in place tail extension), and a factor of 0.9 is used in all other cases.

F_H	Σ factored horizontal forces
F_V	Σ factored vertical forces (using 100% W_s & W_a)
$R_{s\ (footing)}$	$\mu_b F_V*\phi_\tau$
$R_{s\ (foundation\ soil)}$	$[(F_V + W_{base})*\tan(\phi) + B_w*c]*\phi_\tau$
ϕ_τ	0.8 for cast in place base or extension, 0.9 for other cases
min R_s	smaller of $R_{s\ (footing)}$ or $R_{s\ (foundation\ soil)}$

For each load case, the factored sliding resistance should be greater than the sum of factored horizontal forces

check that min $R_s > F_H$

Bearing

Load Case Strength I-b generally controls bearing.

B_f' is the equivalent bearing area. This is the base block width adjusted for eccentricity, and including a ½H:1V distribution through granular base or 1H:1V distribution through concrete base.

$B_f' = w_u + w_{te} + t_b - 2*e$ or

$B_f' = w_u + w_{te} + 2*t_b - 2*e$ (for concrete base)

F_V	Σ factored vertical forces (using 100% W_s & W_a)
surcharge over wall	$q_{LL}*w_{u(top)}*LL$
weight of base	$t_b * \gamma_b*EH$
M_v	Σ factored moments from vertical forces (using 100% W_s & W_a)
M_H	Σ factored moments from horizontal forces
e	$(w_u + w_{te})/2 - (M_V - M_H)/F_V$
B_f' (granular base)	$w_u + w_{te} + t_b - 2*e$
B_f' (concrete base)	$w_u + w_{te} + 2*t_b - 2*e$
contact pressure q_c	$(F_V + q_{LL}*w_{u(top)}*LL)/B_f' + t_b*\gamma_b*EH$
bearing resistance q_b	$[c*N_c*d_c*g_c + (h_e + t_b)*\gamma_{found}*N_q*d_q*g_q +0.5*\gamma_{found}*B_f'*N_\gamma*d_\gamma*g_\gamma]*BC$

Note that inclined loading factors are customarily ignored for retaining systems (see AASHTO LRFD C10.6.3.1.2a).

For each load case, the factored bearing resistance should be greater than the factored contact pressure Check that qb > qc

Internal Analysis

Internal stability analysis is conducted for each section above the wall base. Since bearing conditions are addressed in the external stability analysis, only toppling and shear failures are evaluated.

Toppling is evaluated similarly to external overturning analysis, except that the overturning point is set in 1 inch (25 mm) to account for face rounding. Eccentricity for block to block contact should be within the middle 90% of the base as required for a rock foundation.

For each load case:

check that $e < B*0.45$

Shear, or sliding, resistance is calculated based on the interface shear test (see interaction test reports for complete test data)

$R_s = [S_i + (W + P_v + Q_{dv})* \tan(35.2°)]*\varphi_T$

where $\varphi_T = 0.90$ (precast to precast and aggregate to aggregate)

$S_i = 362$ lb/ft or 5.28 kN/m

For each load case, the factored sliding resistance must be greater than the factored horizontal force:

check that $R_s > F_H$

At a minimum, internal stability should be evaluated at each change in block width (including any tail extension), at the base of any dual-face units, and for the top course(s) if a surcharge or lateral load is applied.

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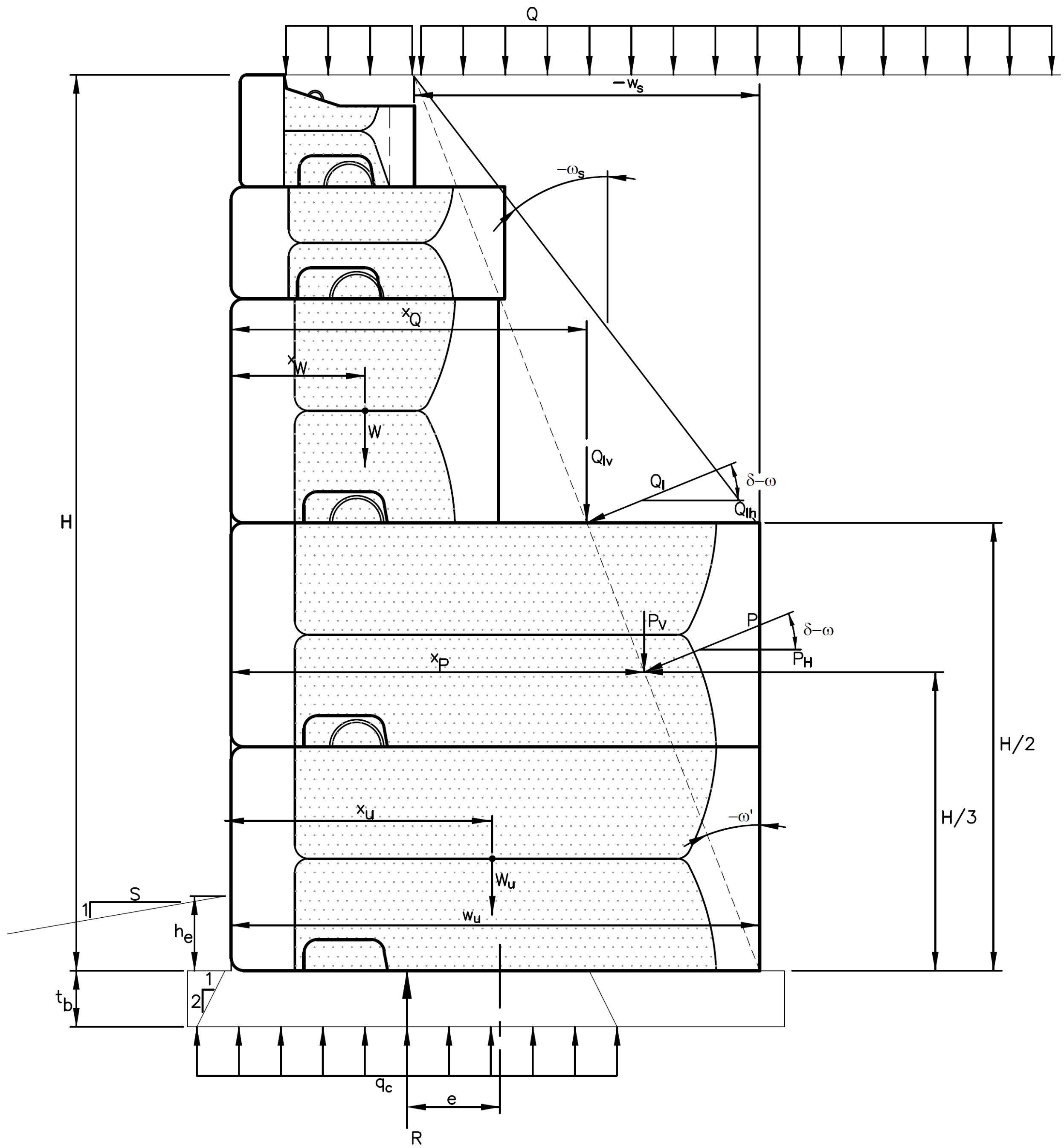
EXAMPLE GRAVITY WALL CALCULATIONS
LRFD METHOD USING AASHTO LOAD/RESISTANCE FACTORS

Example 1: 12 feet tall wall, vertical face, level back slope, 250 psf traffic surcharge

Retained Soil:	sand with γ = 120 pcf and ϕ = 30 degrees
Foundation Soil:	clay with γ = 125 pcf, ϕ = 26 degrees, and c' = 150 psf
Infill Aggregate:	screened crushed aggregate with γ = 110 pcf and ϕ = 35 degrees
Base Aggregate:	well graded crushed aggregate with γ = 125 pcf and ϕ = 40 degrees



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Wall Configuration (all weights per foot along length of wall)

Modular Units			Setback (in)		Concrete (/ft.)		Unit Fill (/ft.)		Soil Wedge (/ft.)	
unit	w (in)	h (ft)	face	tail	W_b (lb)	x_b (in)	W_a (lb)	x_a (in)	W_s (lb)	x_s (in)
V6-28	28.0	1.50	0.0	-57.0	238	12.8	183	14.0	110	33.3
V6-44	44.0	1.50	0.0	-41.0	375	21.0	301	23.5	94	48.6
V24-44	43.0	3.00	0.0	-42.0	750	20.2	594	23.8	779	58.3
V24-86	85.0	3.00	0.0	0.0	950	39.0	1,621	44.1	0	0.0
V24-86	85.0	3.00	0.0	0.0	950	39.0	1,621	44.1	0	0.0

External Stability Analysis

Weight and Center of Gravity of Wall Components

W_b = 950+950+750+375+238 = 3,263 lb/ft

W_a = 1,621+1,621+594+301+183= 4,320 lb/ft

W_s = 779+94+110 = 983 lb/ft

Total Wall Weight = 3,263+4,320+983 = 8,490 lb/ft

x_b = (950*39.0+950*39.0+750*20.2+375*21.0+238*12.8) / 3,263 =30.7 in

y_b = (950*18+950*54+750*90+375*117+238*135) / 3,263 = 64.9 in

x_a = (1,621*44.1+1,621*44.1+594*23.8+301*23.5+183*14.0) / 4,320 = 38.6 in

y_a = (1,621*18+1,621*54+594*90+301*117+183*135) / 4,320 = 53.3 in

x_s = (779*58.3+94*48.6+110*33.3) / 983 = 54.5 in

y_s = (779*89.9+94*117.0+110*132.0) / 983 = 97.1 in

x_{a+s} = (4,320*38.6+983*54.5) / (4,320+983) = 41.5 in

y_{a+s} = (4,320*53.3+983*97.1) / (4,320+983) = 61.4 in

Earth Pressure Components

ω' = arctan(-57/12/12.0) = -21.6°

δ = 0.75*30 = 22.5°

$$K_a = \frac{\cos^2(30+-21.6)}{\cos^2(-21.6)\cos(-21.6-22.5)\left[1+\sqrt{\frac{\sin(30+22.5)\sin(30-0)}{\cos(-21.6-22.5)\cos(-21.6+0)}}\right]^2}$$

K_a = 0.503

P_h = 0.5*(0.503)*120*(12)^2*cos(22.5+21.6) = 3,119 lb/ft

P_v = 0.5*(0.503)*120*(12)^2*sin(22.5+21.6) = 3,022 lb/ft

Q_{lh} = 0.503*250*12*cos(22.5+21.6) = 1,083 lb/ft

Q_{lv} = 0.503*250*12*sin(22.5+21.6) = 1,049 lb/ft

x_P = (12/3)*tan(-21.6)+85/12 = 5.50 ft

y_P = 12/3 = 4.00 ft

x_{Ql} = (12/2)*tan(-21.6)+85/12 = 4.71 ft

y_{Ql} = 12/2 = 6.00 ft

Table of Unfactored Forces & Moments (per foot of wall)

	Unfactored Force (lb)	arm (ft)	Unfactored Moment about toe (lb*ft)
Vertical Forces			
W_b	3,263	2.56	8,346
$W_a + W_s$	5,304	3.46	18,366
$0.80*(W_a + W_s)$	4,243	3.46	14,693
P_v	3,022	5.50	16,622
Q_{lv}	1,049	4.71	4,941
$Q_{l\ over\ wall}$	583	1.17	681
Horizontal Forces			
P_h	3,119	4.00	12,477
Q_{lh}	1,083	6.00	6,498

Table of Load & Resistance Factors

	Strength I-a	Strength I-b	Strength IV	Service I
Load Factors				
LL	1.75	1.75	0.00	1.00
EH	1.50	1.50	1.50	1.00
EQ	0.00	0.00	0.00	0.00
CT	0.00	0.00	0.00	0.00
LL over wall	0.00	1.75	0.00	1.00
Resistance Factors				
DC	0.90	1.25	1.50	1.00
EV	1.00	1.35	1.35	1.00
BC	0.45	0.45	0.45	1.00
ϕ_τ precast to agg	0.90	0.90	0.90	1.00
ϕ_τ CIP to agg/soil	0.80	0.80	0.80	1.00
ϕ_τ soil to soil	0.90	0.90	0.90	1.00
ϕ_τ precast to precast	0.90	0.90	0.90	1.00

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Table of Calculated Factored Forces (lbs per foot of wall)

	Unfactored Force	Load Factor	Strength I-a	Strength I-b	Strength IV	Service I
Vertical Forces						
W_b	3,263	DC	2,936	4,078	4,894	3,263
$W_a + W_s$	5,304	EV	5,304	7,160	7,160	5,304
$0.80*(W_a + W_s)$	4,243	EV	4,243	5,728	5,728	4,243
P_v	3,022	EH	4,533	4,533	4,533	3,022
Q_{lv}	1,049	LL	1,836	1,836	0	1,049
$Q_{l\ over\ wall}$	583	LL over	0	1,021	0	583
Horizontal Forces						
P_h	3,119	EH	4,679	4,679	4,679	3,119
Q_{lh}	1,083	LL	1,895	1,895	0	1,083

Table of Calculated Factored Moments (lb*ft per foot of wall)

	Unfactored Moment	Load Factor	Strength I-a	Strength I-b	Strength IV	Service I
Vertical Forces						
W_b	8,346	DC	7,511	10,433	12,519	8,346
$W_a + W_s$	18,366	EV	18,366	24,794	24,794	18,366
$0.80*(W_a + W_s)$	14,693	EV	14,693	19,835	19,835	14,693
P_v	16,622	EH	24,933	24,933	24,933	16,622
Q_{lv}	4,941	LL	8,646	8,646	0	4,941
$Q_{l\ over\ wall}$	681	LL over	0	1,191	0	681
Horizontal Forces						
P_h	12,477	EH	18,715	18,715	18,715	12,477
Q_{lh}	6,498	LL	11,372	11,372	0	6,498

Overturning/Eccentricity

Check that $M'_V > M_H$

Check that e>B/3 (40% of B for extreme load cases)

Strength Case I-a:

M'_V = 7,511+14,693+24,933+8,646 = 55,784 lb*ft/ft

M_H = 18,715+11,372 = 30,087 lb*ft/ft

$M'_V > M_H$ **OK!!**

e = (85/12)/2+(30,087-55,784)/(2,936+4,243+4,533+1,836) = 1.65 ft

B/3 = (85/12)/3 = 2.36 ft

e < B/3 **OK!!**

Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
F'_v	13,549	17,196	15,155	12,160
M'_v	55,784	65,038	57,287	45,282
M_h	30,087	30,087	18,715	18,975
e	1.65	1.51	1.00	1.38

All load cases **OK!!**

Sliding

Check that $R'_s > F_h$

Strength Case I-a:

Use the smaller sliding resistance, R'_s, across footing or through foundation soil:

$R'_{s\ (soil)}$ = [(2,936+5,304+4,533+1,836+ (85/12)*(9/12)*125*1.0)*tan(26)+((85+9)/12*150)]*0.9
= 7,762 lb/ft

$\%_{void}$ = (1,621/110) / (950/145+1,621/110) = 0.6922

$\%_{concrete}$ = (950/145) / (950/145+1,621/110) = 0.3078

μ_b = 0.6922*tan(35)+0.3078*0.8*tan(40) = 0.69

$R'_{s\ (footing)}$ = [0.69*(2,936+5,304+4,533+1,836)]*0.9
= 9,090 lb/ft

F_h = 4,679+1,895 = 6,574 lb/ft

$R'_s > F_h$ **OK!!**

Project	Project #	Date
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Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
F_h	6,574	6,574	4,679	4,202
F_v	14,610	18,628	16,587	13,221
F_v w/ base weight	15,274	19,525	17,483	13,885
ϕ_τ	0.90	0.90	0.90	1.00
$R'_{s\ (foundation\ soil)}$	7,762	9,628	8,732	7,947
$R'_{s\ (footing)}$	9,090	11,590	10,320	9,140

All Load Cases **OK!!**

Bearing

Check that $q_b > q_c$

Strength Case I-a:

e = (85/12)/2-((7,511+18,366+24,933+8,646)-(18,715+11,372)) / (2,936+5,304+4,533+1,836) = 1.53

B_f'= (85+9)/12-2*1.53 ft = 4.77 ft

Bearing Factors (Vesic):

N_q = 11.85	N_c = 22.25	$N\gamma$ = 12.54
d_c = 1.13	d_q = 1.10	d_γ = 1.00
g_c = 1.00	g_q = 1.00	g_γ = 1.00

q_b = [150*22.25*1.13*1.00+(12+9)/12*125*11.85*1.10*1.00+ 0.5*125*4.76*12.54]*0.45*1.00*1.00 = 4,669 psf

weight of base = t_b *γ_{base}*EH = 9/12*125*1.5 = 141 psf

q_c = (14,610)/4.77+141 = 3,203 psf

$q_b > q_c$ **OK!!**

Project	Project #	Date
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Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
F_v	14,610	18,628	16,587	13,221
M_v	59,457	69,997	62,246	48,955
M_h	30,087	30,087	18,715	18,975
e	1.53	1.40	0.92	1.27
B_f	4.77	5.03	6.00	5.29
q_c	3,203	3,841	2,906	2,595
q_b	4,669	4,762	5,102	10,780

All Load Cases **OK!!**

Project	Project #	Date
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Internal Stability

Internal stability should be checked at each change in block width, at all dual-face unit, and at the top unit at a minimum. The following is taken at the first change from 24-86 to 24-44. Internal stability of the block stack above this interface is calculated as follows:

Wall Configuration (all weights per foot along length of wall)

Modular Units			Setback (in)		Concrete (/ft.)		Unit Fill (/ft.)		Soil Wedge (/ft.)	
unit	w (in)	h (ft)	face	tail	W_b (lb)	x_b (in)	W_a (lb)	x_a (in)	W_s (lb)	x_s (in)
V6-28	28.0	1.50	0.0	-15.0	238	11.8	183	13.0	110	32.3
V6-44	44.0	1.50	0.0	1.0	375	20.0	301	22.5	0	0.0
V24-44	43.0	3.00	0.0	0.0	750	19.2	594	22.8	0	0.0

Weight and Center of Gravity of Wall Components

W_b = 750+375+238 = 1,363 lb/ft

W_a = 594+301+183 = 1,078 lb/ft

W_s = 110 lb/ft

x_b= (750*19.2+375*20.0+238*11.8) / 1,363 = 18.1 in

y_b = (750*18+375*45+238*63) / 1,363 = 33.3 in

x_a = (594*22.8+301*22.5+183*13.0) / 1,078 = 21.1 in

y_a = (594*18+301*45+183*63) / 1,078 = 33.2 in

x_s = 32.3 in

y_s = 110*60/110 = 60 in

x_{a+s} = (1,078*21.1+110*32.3) / (1,078+110) = 22.1 in

y_{a+s} = (1,078*33.3+110*60) / (1,078+110) = 35.7 in

Earth Pressure Components

ω' = arctan(-15/12/6.0) = -11.77°

δ = 0.75*30 = 22.5°

$$K_a = \frac{\cos^2(30+-11.77)}{\cos^2(-11.77)\cos(22.5--11.77)\left[1+\sqrt{\frac{\sin(30+22.5)\sin(30-0)}{\cos(22.5--11.77)\cos(-11.77+0)}}\right]^2}$$

K_a = 0.394

P_h = 0.5*(0.394)*120*(6)^2*cos(22.5+11.77) = 703 lb/ft

P_v = 0.5*(0.394)*120*(6)^2*sin(22.5+11.77) = 479 lb/ft

Q_{lh} = 0.394*250*6*cos(22.5+11.77) = 488 lb/ft

Q_{lv} = 0.394*250*6*sin(22.5+11.77) = 333 lb/ft

x_P = (6/3)*tan(-11.77)+43/12 = 3.17 ft

y_P = 6/3 = 2.0 ft

x_{Ql} = (6/2)*tan(-11.77)+43/12 = 2.96 ft

y_{Ql} = 6/2 = 3.00 ft

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Table of Unfactored Forces & Moments (per foot of wall)

	Unfactored Force (lb)	arm (ft)	Unfactored Moment about toe (lb*ft)
Vertical Forces			
Wb	1,363	1.51	2,058
Wa + Ws	1,188	1.84	2,188
0.80*(Wa + Ws)	951	1.84	1,750
Pv	479	3.08	1,478
Qlv	333	2.88	957
$Ql_{\text{over wall}}$	583	1.08	632
Horizontal Forces			
Ph	703	2.00	1,407
Qlh	488	3.00	1,465

Table of Load & Resistance Factors

	Strength I-a	Strength I-b	Strength IV	Service I
Load Factors				
LL	1.75	1.75	0.00	1.00
EH	1.50	1.50	1.50	1.00
EQ	0.00	0.00	0.00	0.00
CT	0.00	0.00	0.00	0.00
LL over wall	0.00	1.75	0.00	1.00
Resistance Factors				
DC	0.90	1.25	1.50	1.00
EV	1.00	1.35	1.35	1.00
$\phi\tau_{\text{precast to precast}}$	0.90	0.90	0.90	1.00

Table of Calculated Factored Forces (lbs per foot of wall)

	Unfactored Force	Load Factor	Strength I-a	Strength I-b	Strength IV	Service I
Vertical Forces						
W_b	1,363	DC	1,226	1,703	2,044	1,363
$W_a + W_s$	1,188	EV	1,188	1,604	1,604	1,188
$0.80*(W_a + W_s)$	951	EV	951	1,283	1,283	951
P_v	479	EH	719	719	719	479
Q_{lv}	333	LL	582	582	0	333
$Q_{l\ over\ wall}$	583	LL over	0	1,021	0	583
Horizontal Forces						
P_h	703	EH	1,055	1,055	1,055	703
Q_{lh}	488	LL	855	855	0	488

Table of Calculated Factored Moments (lb*ft per foot of wall)

	Unfactored Moment	Load Factor	Strength I-a	Strength I-b	Strength IV	Service I
Vertical Forces						
W_b	2,058	DC	1,852	2,572	3,086	2,058
$W_a + W_s$	2,188	EV	2,188	2,954	2,954	2,188
$0.80*(W_a + W_s)$	1,750	EV	1,750	2,363	2,363	1,750
P_v	1,478	EH	2,216	2,216	2,216	1,478
Q_{lv}	957	LL	1,674	1,674	0	957
$Q_{l\ over\ wall}$	632	LL over	0	1,106	0	632
Horizontal Forces						
P_h	1,407	EH	2,110	2,110	2,110	1,407
Q_{lh}	1,465	LL	2,564	2,564	0	1,465

Overturning/Topple

Check that $M'_V > M_H$

Check that $e < B*0.45$ (40% of B for extreme load cases)

Strength Case I-a:

M'_V = 1,852+1,750+2,216+1,674 = 7,493 lb*ft/ft

M_H = 2,110+2,564 = 4,674 lb*ft/ft

$M'_V > M_H$ **OK!!**

e = (42/12)/2+(4,674-7,493)/(1,226+951+719+582) = 0.94 ft

B*0.45 = (42/12)*0.45 = 1.58 ft

e < B*0.45 **OK!!**

Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
F'_v	3,478	5,308	4,046	3,708
M'_v	7,493	9,932	7,666	6,874
M_h	4,674	4,674	2,110	2,872
e	0.94	0.76	0.38	0.67

All Load Cases **OK!!**

Interface Shear

Check that $R'_s > F_h$

Strength Case I-a:

R'_s = [362+ (1,226+1,188+719+582)*tan(35.2)]* 0.9 = 2,685

F_h = 1,055+855 = 1,910 lb/ft

$R'_s > F_h$ **OK!!**

Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
Fh	1,910	1,910	1,055	1,192
Fv	3,716	5,629	4,367	3,946
$\phi\tau$	0.90	0.90	0.90	1.00
R's	2,685	3,900	3,098	3,146

All Load cases **OK!!**

External & Internal Stability **OK!!**

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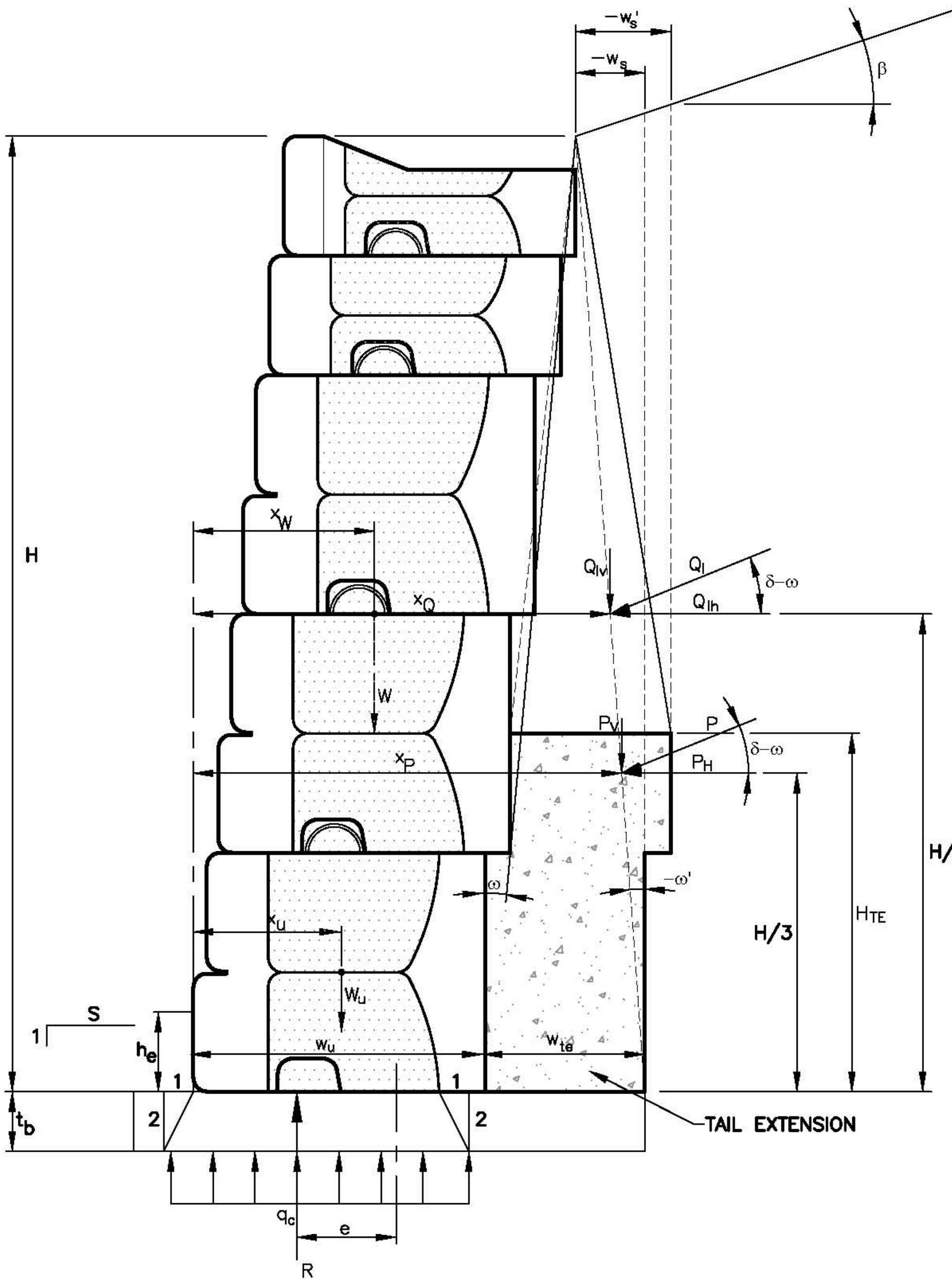
<u>Example 2:</u> 12 feet tall wall, battered face, 3H:1V back slope, CIP tail extension

Retained Soil:	sand with γ = 120 pcf and ϕ = 30 degrees
Foundation Soil:	clay with γ = 125 pcf, ϕ = 26 degrees, and c' = 150 psf
Infill Aggregate:	screened crushed aggregate with γ = 110 pcf and ϕ = 35 degrees
Base Aggregate:	well graded crushed aggregate with γ = 125 pcf and ϕ = 40 degrees
Tail Extension:	24 inches wide by 54 inches tall, placed on aggregate base



Project	Project #	Date
LRFD Example Calculations	20004.00	12/5/23

Wall Configuration including CIP tail extension (all weights per foot along length of wall)

Modular Units			**Setback (in)**		**Concrete (/ft.)**		**Unit Fill (/ft.)**		**Soil Wedge (/ft.)**	
unit	**w (in)**	**h (ft)**	**face**	**tail**	**W_b (lb)**	**x_b (in)**	**W_a (lb)**	**x_a (in)**	**W_s (lb)**	**x_s (in)**
6-44	44.0	1.50	14.0	-10.0	375	35.0	301	37.5	19	58.9
6-44	44.0	1.50	12.0	-12.0	375	33.0	301	35.5	85	59.2
24-44	44.0	3.00	8.0	-16.0	750	29.2	594	32.8	396	59.3
24-44	68.0	3.00	4.0	4.0	1,185	38.0	594	28.8	311	71.1
24-44	68.0	3.00	0.0	0.0	1,620	39.9	594	24.8	0	0.0

External Stability Analysis

Weight and Center of Gravity of Wall Components

$W_b + W_{te}$ = (750+145*2.0*3.0)+ (750+145*2.0*1.5)+750+375+375 = 4,305 lb/ft

W_a = 594+594+594+301+301 = 2,385 lb/ft

W_s = 311+396+85+19 = 811 lb/ft

x_{b+te} = (1,620*39.9+1,185*38.0+750*29.2+375*33.0+375*35.0) / 4,305 = 36.5 in

y_{b+te} = (1,620*18+1,185*54+750*90+375*117+375*135) / 4,305 = 59.3 in

x_a = (594*24.8+594*28.8+594*32.8+301*35.5+301*37.5) / 2,385 = 30.7 in

y_a = (594*18+594*54+594*90+301*117+301*135) / 2,385 = 72.2 in

x_s = (311*71.1+396*59.3+85*59.2+19*58.9) / 811 = 63.8 in

y_s = (311*60.0+396*88.8+85*116.3+19*132) / 811 = 81.7 in

x_{a+s} = (2,385*30.7+811*63.8) / (2,385+811) = 39.1 in

y_{a+s} = (2,385*72.2+811*81.7) / (2,385+811) = 74.6in

Earth Pressure Components

ω' = arctan(-10/12/12.0) = -3.97° δ = 0.75*30 = 22.5°

$$K_a = \frac{\cos^2(30+-3.97)}{\cos^2(-3.97)\cos(-3.97-22.5)\left[1+\sqrt{\frac{\sin(30+22.5)\sin(30-18.4)}{\cos(-3.97-22.5)\cos(-3.97+18.4)}}\right]^2}$$

K_a = 0.444

$P_h = 0.5*(0.444)*120*(12)^2*\cos(22.5+3.79)$ = 3,436 lb

$P_v = 0.5*(0.444)*120*(12)^2*\sin(22.5+3.79)$ = 1,711 lb

x_p = (12/3)*tan(-3.97)+(68/12) = 5.39 ft

y_p = (12/3) = 4.00

Project	Project #	Date
LRFD Example Calculations	20004.00	12/5/23

Table of Unfactored Forces & Moments (per foot of wall)

	Unfactored Force (lb)	arm (ft)	Unfactored Moment about toe (lb*ft)
Vertical Forces			
W_b	4,305	3.04	13,085
$W_a + W_s$	3,196	3.26	10,421
$0.80*(W_a + W_s)$	2,557	3.26	8,337
P_v	1,711	5.39	9,221
Q_{lv}	0	5.25	0
$Q_{l\ over\ wall}$	0	2.92	0
Horizontal Forces			
P_h	3,436	4.00	13,744
Q_{lh}	0	6.00	0

Table of Load & Resistance Factors

	Strength I-a	Strength I-b	Strength IV	Service I
Load Factors				
LL	1.75	1.75	0.00	1.00
EH	1.50	1.50	1.50	1.00
EQ	0.00	0.00	0.00	0.00
CT	0.00	0.00	0.00	0.00
LL over wall	0.00	1.75	0.00	1.00
Resistance Factors				
DC	0.90	1.25	1.50	1.00
EV	1.00	1.35	1.35	1.00
BC	0.45	0.45	0.45	1.00
ϕ_τ precast to agg	0.90	0.90	0.90	1.00
ϕ_τ CIP to agg/soil	0.80	0.80	0.80	1.00
ϕ_τ soil to soil	0.90	0.90	0.90	1.00
ϕ_τ precast to precast	0.90	0.90	0.90	1.00

Project	Project #	Date
LRFD Example Calculations	20004.00	12/5/23

Table of Calculated Factored Forces (lbs per foot of wall)

	Unfactored Force	Load Factor	Strength I-a	Strength I-b	Strength IV	Service I
Vertical Forces						
W_b	4,305	DC	3,875	5,381	6,458	4,305
$W_a + W_s$	3,196	EV	3,196	4,314	4,314	3,196
$0.80*(W_a + W_s)$	2,557	EV	2,557	3,452	3,452	2,557
P_v	1,711	EH	2,567	2,567	2,567	1,711
Q_{lv}	0	LL	0	0	0	0
$Q_{l\ over\ wall}$	0	LL over	0	0	0	0
Horizontal Forces						
P_h	3,436	EH	5,154	5,154	5,154	3,436
Q_{lh}	0	LL	0	0	0	0

Table of Calculated Factored Moments (lb*ft per foot of wall)

	Unfactored Moment	Load Factor	Strength I-a	Strength I-b	Strength IV	Service I
Vertical Forces						
W_b	13,085	DC	11,777	16,356	19,628	13,085
$W_a + W_s$	10,421	EV	10,421	14,069	14,069	10,421
$0.80*(W_a + W_s)$	8,337	EV	8,337	11,255	11,255	8,337
P_v	9,221	EH	13,831	13,831	13,831	9,221
Q_{lv}	0	LL	0	0	0	0
$Q_{l\ over\ wall}$	0	LL over	0	0	0	0
Horizontal Forces						
P_h	13,744	EH	20,615	20,615	20,615	13,744
Q_{lh}	0	LL	0	0	0	0

Overturning/Eccentricity

Check that $M'_V > M_H$

Check that e>B/3 (40% of B for extreme load cases)

Strength Case I-a:

M'_V = 11,777+8,337+13,831 = 33,944 lb*ft/ft

M_H = 20,615 lb*ft/ft

$M'_V > M_H$ **OK!!**

e = (68/12)/2+(20,615-33,944) / (3,875+2,557+2,567) = 1.35 ft

B/3 = (68/12)/3 = 1.89 ft

e < B/3 **OK!!**

Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
F'_v	8,998	11,399	12,476	8,573
M'_v	33,944	41,442	44,713	30,643
M_h	20,615	20,615	20,615	13,744
e	1.35	1.01	0.90	0.86

All load cases **OK!!!**

Sliding

Check that $R'_s > F_h$

Strength Case I-a:

Use the smaller sliding resistance, R'_s, across footing or through foundation soil:

$R'_{s\,(soil)}$ = [(3,875+3,196+2,567+(68/12)*(9/12)*110*1.0)*tan(26)*((68+9)/12)*150]*0.9
= 5,330 lb/ft

Tail extension is assumed to be on aggregate base

$\%_{void}$ = (594/110) / (594/110+750/145+24/12*3) = 0.2281

$\%_{precast}$ = (750/145) / (594/110+750/145+24/12*3) = 0.2095

$\%_{CIP}$ = (24/12*3) / (594/110+750/145+24/12*3) = 0.3038

μ_b = (0.2281*tan(35)+0.2095*0.8*tan(40)+0.3038*tan(40)) = 0.74

$R'_{s\,(footing)}$ = 0.9*0.74*(3,875+3,196+2,567)
= 6,419 lb/ft

F_h = 5,154 lb/ft

$R'_s > F_h$ **OK!!**

Project	Project #	Date
LRFD Example Calculations	20004.00	12/5/23

Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
F_h	5,154	5,154	5,154	3,436
F_v	9,637	12,262	13,339	9,212
F_v w/ base weight	10,168	12,979	14,056	9,743
ϕ_τ	0.90	0.90	0.90	1.00
$R'_{s\ (foundation\ soil)}$	5,330	6,564	7,036	5,715
$R'_{s\ (footing)}$	6,419	8,167	8,884	6,817

All Load Cases **OK!!**

Bearing

Check that $q_b > q_c$

Strength Case I-a:

e = ((68/12)/2+(20,615-11,777+10,421+13,831) / (3,875+3,196+2,567) = 1.23

B_f'= (68+9)/12-2*1.23 ft = 3.95 ft

Bearing Factors (Vesic):

N_q = 11.85 N_c = 22.25 N_γ = 12.54

d_c = 1.14 d_q = 1.11 d_γ = 1.00

g_c = 1.00 g_q = 1.00 g_γ = 1.00

q_b = [150*22.25*1.14*1.00+(12+9)/12*125*11.85*1.11*1.00+
0.5*125*3.96*12.54]*0.45*1.10*1.00 = 4,406 psf

weight of base = t_b *γ_{base}*EH = 9/12*125*1.5 = 141 psf

q_c = (9,637)/3.95+141 = 2,581 psf

$q_b > q_c$ **OK!!**

Project	Project #	Date
LRFD Example Calculations	20004.00	12/5/23

Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
Fv	9,637	12,262	13,339	9,212
Mv	36,029	44,256	47,527	32,727
Mh	20,615	20,615	20,615	13,744
e	1.23	0.91	0.82	0.77
Bf	3.95	4.61	4.79	4.87
qc	2,581	2,803	2,928	1,985
qb	4,406	4,638	4,701	10,515

All Load Cases **OK!!**!

Project	Project #	Date
LRFD Example Calculations	20004.00	12/5/23

Internal Stability

Internal stability should be checked at each change in block width, at all dual-face units, and at the top unit at a minimum. The following is taken at the first change from 24-44 with tail extension to a standard 24-44 unit. Internal stability of the block stack above this interface is calculated as follows:

Wall Configuration (all weights per foot along length of wall)

Modular Units			Setback (in)		Concrete (/ft.)		Unit Fill (/ft.)	
unit	**w (in)**	**h (ft)**	**face**	**tail**	**W_b (lb)**	**x_b (in)**	**W_a (lb)**	**x_a (in)**
6-44	44.0	1.50	6.0	6.0	375	26.0	301	28.5
6-44	44.0	1.50	4.0	4.0	375	24.0	301	26.5
24-44	44.0	3.00	0.0	0.0	750	20.2	594	23.8

Weight and Center of Gravity of Wall Components

W_b = 750+375+375 = 1,500 lb/ft

W_a = 594+301+301 = 1,196 lb/ft

x_b= (750*20.2+375*24.0+375*26.0) / 1,500 = 22.6 in

y_b = (750*18+375*45+375*63) / 1,500 = 36.0 in

x_a = (594*23.8+301*26.5+301*28.5) / 1,196 = 25.7 in

y_a = (594*18+301*45+301*63) / 1,196 = 36.1 in

Earth Pressure Components

ω' = 6.34°

δ = 0.5*30 = 15.0°

$$K_a = \frac{\cos^2(30+6.34)}{\cos^2(6.34)\cos(6.34-15.0)\left[1+\sqrt{\frac{\sin(30+15.0)\sin(30-18.4)}{\cos(6.34-15.0)\cos(6.34+18.4)}}\right]^2}$$

K_a = 0.340

P_h = 0.5*(0.340)*120*(6)^2*cos(15-6.34) = 727 lb

P_v = 0.5*(0.340)*120*(6)^2*sin(15-6.34) =111 lb

x_P = (6/3)*tan(6.34)+(43/12) = 3.81 ft

y_P = 6/3 = 2.00 ft

Project	Project #	Date
LRFD Example Calculations	20004.00	12/5/23

Table of Unfactored Forces & Moments (per foot of wall)

	Unfactored Force (lb)	**arm (ft)**	**Unfactored Moment about toe (lb*ft)**
Vertical Forces			
W_b	1,500	1.88	2,825
$W_a + W_s$	1,196	2.14	2,559
$0.80*(W_a + W_s)$	957	2.14	2,047
P_v	111	3.81	421
Q_{lv}	0	3.92	0
$Q_{l\ over\ wall}$	0	2.92	0
Horizontal Forces			
P_h	727	2.00	1,453
Q_{lh}	0	3.00	0

Table of Load & Resistance Factors

	Strength I-a	**Strength I-b**	**Strength IV**	**Service I**
Load Factors				
LL	1.75	1.75	0.00	1.00
EH	1.50	1.50	1.50	1.00
EQ	0.00	0.00	0.00	0.00
CT	0.00	0.00	0.00	0.00
LL over wall	0.00	1.75	0.00	1.00
Resistance Factors				
DC	0.90	1.25	1.50	1.00
EV	1.00	1.35	1.35	1.00
ϕ_τ precast to precast	0.90	0.90	0.90	1.00

Project	Project #	Date
LRFD Example Calculations	20004.00	12/5/23

Table of Calculated Factored Forces (lbs per foot of wall)

	Unfactored Force	Load Factor	Strength I-a	Strength I-b	Strength IV	Service I
Vertical Forces						
W_b	1,500	DC	1,350	1,875	2,250	1,500
$W_a + W_s$	1,196	EV	1,196	1,615	1,615	1,196
$0.80*(W_a + W_s)$	957	EV	957	1,292	1,292	957
P_v	111	EH	166	166	166	111
Q_{lv}	0	LL	0	0	0	0
$Q_{l\ over\ wall}$	0	LL over	0	0	0	0
Horizontal Forces						
P_h	727	EH	1,090	1,090	1,090	727
Q_{lh}	0	LL	0	0	0	0

Table of Calculated Factored Moments (lb*ft per foot of wall)

	Unfactored Moment	Load Factor	Strength I-a	Strength I-b	Strength IV	Service I
Vertical Forces						
W_b	2,825	DC	2,543	3,531	4,238	2,825
$W_a + W_s$	2,559	EV	2,559	3,454	3,454	2,559
$0.80*(W_a + W_s)$	2,047	EV	2,047	2,763	2,763	2,047
P_v	421	EH	632	632	632	421
Q_{lv}	0	LL	0	0	0	0
$Q_{l\ over\ wall}$	0	LL over	0	0	0	0
Horizontal Forces						
P_h	1,453	EH	2,180	2,180	2,180	1,453
Q_{lh}	0	LL	0	0	0	0

Overturning/Topple

Check that $M'_V > M_H$

Check that $e<B*0.45$ (40% of B for extreme load cases)

Project	Project #	Date
LRFD Example Calculations	20004.00	12/5/23

Strength Case I-a:

M'_V = 2,543+2,047+642 = 5,221 lb*ft/ft

M_H = 2,180 lb*ft/ft

$M'_V > M_H$ **OK!!**

e = (43)/12/2+(2,180-5,221) / (1,350+957+166) = 0.56 ft

B*0.45 = (43/12)*0.45 = 1.61 ft

e < B*0.45 **OK!!**

Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
F'_v	2,473	3,333	3,708	2,568
M'_v	5,221	6,926	7,632	5,293
M_h	2,180	2,180	2,180	1,453
e	0.56	0.37	0.32	0.30

All Load Cases **OK!!**

Interface Shear

Check that $R'_s > F_h$

Strength Case I-a:

R'_s = [362+ (1,350+1,196+166)*tan(35.2)]*0.9 = 2,048

F_h = 1,090 lb/ft

$R'_s > F_h$ **OK!!**

Table for all load cases

	Strength I-a	Strength I-b	Strength IV	Service I
F_h	1,090	1,090	1,090	727
F_v	2,712	3,656	4,031	2,807
ϕ_τ	0.90	0.90	0.90	1.00
R'_s	2,048	2,647	2,885	2,342

All Load cases **OK!!**

External & Internal Stability **OK!!**

STONE STRONG SYSTEMS

STONE STRONG GRAVITY CALCULATIONS - ver 6.6

Project Name: LRFD Methodology
Location: Example Calculations
Job#: 20004.00
Section: Example #1, level grade w/ surcharge
Calc by: D Thiele

(AASHTO 9th Edition, 2020)

12/5/23 15:37

Notes 12.0 tall wall, 12 inches of embedment, 9 inch thick base, no tail extension, level back slope, highway surcharge 250 psf, vertical face, 30 degree sand retained

External stability

Wall Configuration

			setback (in)		modular units		unit fill		soil wedge		CIP Extension			
unit	w (in)	h (ft)	face	tail	Wb (lb)	xb (in)	Wa (lb)	xa (in)	Ws (lb)	xs (in)	we (in)	h_t	Internal	Max Utiliization
V6-28	28.0	1.50	0.0	-57.0	238	12.8	183	14.0	110	33.3			Internal Stability OK!	40%
V6-44	44.0	1.50	0.0	-41.0	375	21.0	301	23.5	94	48.6			Internal Stability OK!	50%
V24-44	43.0	3.00	0.0	-42.0	750	20.2	594	23.8	779	58.3			Internal Stability OK!	71%
V24-86	85.0	3.00	0.0	0.0	950	39.0	1,621	44.1	0	0.0			Internal Stability OK!	59%
V24-86	85.0	3.00	0.0	0.0	950	39.0	1,621	44.1	0	0.0				
													External Stability OK!	**85%**
	85.0	12.00	0.0	-57.0	3,263	30.7	4,320	38.6	983	54.5				

backfill height 12.00 feet — ω= 0.00 deg — interface friction angle

exposed height 11.00 feet — ω'= -21.60 deg — δ 22.5 deg

Retained Soil
- γ 120 pcf
- φ 30 deg

Foundation Soil
- γ 125 pcf
- φ 26 deg
- c' 150 psf

base embedment 12 in
base thickness 9 in
base material agg
toe slope H:1V slope

factored bearing resistance (if specified) n/a psf (net)

Aggregate Unit Fill γ 110 pcf

composite friction coefficient μ_b 0.69

STONE STRONG SYSTEMS

STONE STRONG GRAVITY CALCULATIONS - ver 6.6

Project Name:	LRFD Methodology
Location:	Example Calculations
Job#:	20004.00
Section:	Example #1, level grade w/ surcharge
Calc by:	D Thiele

12/5/23 15:37

Seismic Load PGA G site class (A to E or 1) D Fpga 1.60 Fa 1.60 k_h 0.00

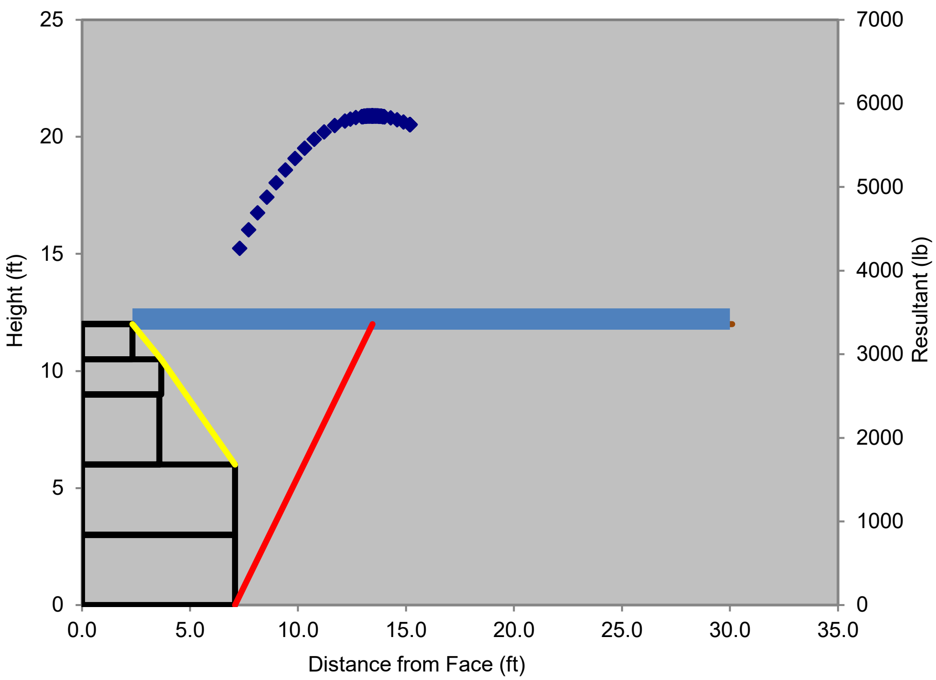
Backfill Slope & Surcharge

			rise in grade		LL surcharge		tier height	
length 1	30	feet (horizontal)		ft	250	psf		ft
length 2		feet (horizontal)		ft		psf		ft
length 3		feet (horizontal)		ft		psf		ft
length 4		feet (horizontal)		ft		psf		

effective slope H:1V slope β 0.0 deg avg q 250 psf

failure plane α 62.06 deg zone of influence 13.45 ft

Ground Surface & Trial Wedge Plot



Unfactored Loads

K_a =	0.503	K_{AE} =	0.503
P_h =	3,119 lb	ΔK_{AE} =	0.000
P_v =	3,022 lb	P_{IR} =	0 lb
Q_{lh} =	1,083 lb	ΔP_{AEh} =	0 lb
Q_{lv} =	1,049 lb	ΔP_{AEv} =	0 lb

STONE STRONG GRAVITY CALCULATIONS - ver 6.6

Project Name: LRFD Methodology
Location: Example Calculations
Job#: 20004.00
Section: Example #1, level grade w/ surcharge
Calc by: D Thiele

Load Cases:		Strngth I-a	Strngth I-b	Strngth IV	Extrme I-a (EQ)	Extrme I-b (EQ)	Extrme II (CT)	Service I	
Factored Loading	*Overturning (lb-ft):*	30,087	30,087	18,715	12,477	12,477	15,726	18,975	**OK!**
	Sliding (lb):	6,574	6,574	4,679	3,119	3,119	3,661	4,202	**OK!**
	Bearing (psf):	3,203	3,841	2,906	2,001	2,001	2,213	2,595	**OK!**
	e (ft):	1.65	1.51	1.00	0.96	0.96	1.15	1.38	**OK!**
	Bf' (ft):	4.77	5.03	6.00	6.08	6.08	5.72	5.29	
Factored Resistance	*Overturning (lb-ft):*	55,784	65,038	57,287	39,661	39,661	42,131	45,282	
	Sliding (lb):	7,762	9,628	8,732	7,151	7,151	7,407	7,947	
	Bearing (psf):	4,669	4,762	5,102	11,399	11,399	11,117	10,780	
	(@ top of base) Max e (ft):	2.36	2.36	2.36	2.83	2.83	2.83	2.36	
Load & Resistance Factors	LL	1.75	1.75	0.00	0.00	0.00	0.50	1.00	
	EH	1.50	1.50	1.50	1.00	1.00	1.00	1.00	
	EQ	0.00	0.00	0.00	1.00	1.00	0.00	0.00	
	CT	0.00	0.00	0.00	0.00	0.00	1.00	0.00	
	LL Surcharge over Wall	0.00	1.75	0.00	0.00	0.00	0.00	1.00	
	DC	0.90	1.25	1.50	1.00	1.00	1.00	1.00	
	EV	1.00	1.35	1.35	1.00	1.00	1.00	1.00	
	BC	0.45	0.45	0.45	1.00	1.00	1.00	1.00	
	ϕt precast to agg	0.90	0.90	0.90	1.00	1.00	1.00	1.00	
	ϕt CIP to agg/soil	0.80	0.80	0.80	1.00	1.00	1.00	1.00	
	ϕt soil to soil	0.90	0.90	0.90	1.00	1.00	1.00	1.00	
	ϕt precast to precast	0.90	0.90	0.90	1.00	1.00	1.00	1.00	
	concrete interface - eccentricity limit	0.45	0.45	0.45	0.40	0.40	0.45	0.45	
	bearing on soil - eccentricity limit	0.33	0.33	0.33	0.40	0.40	0.40	0.33	

Max Utiliization
85%

Min Capacity/Demand Ratio
1.18

STONE STRONG GRAVITY CALCULATIONS - ver 6.6

Project Name: LRFD Methodology
Location: Example Calculations
Job#: 20004.00
Section: Example #1, level grade w/ surcharge
Calc by: D Thiele

(AASHTO 9th Edition, 2020)

12/5/23 15:37

Notes 12.0 tall wall, 12 inches of embedment, 9 inch thick base, no tail extension, level back slope, highway surcharge 250 psf, vertical face, 30 degree sand retained

Internal stability (top 6 feet)

Wall Configuration

unit	w (in)	h (ft)	setback (in) face	setback (in) tail	modular units Wb (lb)	modular units xb (in)	unit fill Wa (lb)	unit fill xa (in)	soil wedge Ws (lb)	soil wedge xs (in)	CIP Extension we (in)	CIP Extension h_t	Internal	Max Utiliization
V6-28	28.0	1.50	0.0	-15.0	238	11.8	183	13.0	110	32.3			Internal Stability OK!	40%
V6-44	44.0	1.50	0.0	1.0	375	20.0	301	22.5	0	0.0			Internal Stability OK!	50%
V24-44	43.0	3.00	0.0	0.0	750	19.2	594	22.8	0	0.0				
													Internal Stability OK!	**71%**
	43.0	6.00	0.0	-15.0	1,363	18.1	1,078	21.1	110	32.3				

backfill height 6.00 feet

ω= 0.00 deg

ω'= -11.77 deg

interface friction angle

δ 22.5 deg

Retained Soil

γ 120 pcf

ϕ 30 deg

Internal ONLY

Aggregate Unit Fill

γ 110 pcf

STONE STRONG GRAVITY CALCULATIONS - ver 6.6

Project Name:	LRFD Methodology
Location:	Example Calculations
Job#:	20004.00
Section:	Example #1, level grade w/ surcharge
Calc by:	D Thiele

Seismic Load PGA [ ] G site class (A to E or 1) D Fpga 1.60 Fa 1.60 k_h 0.00

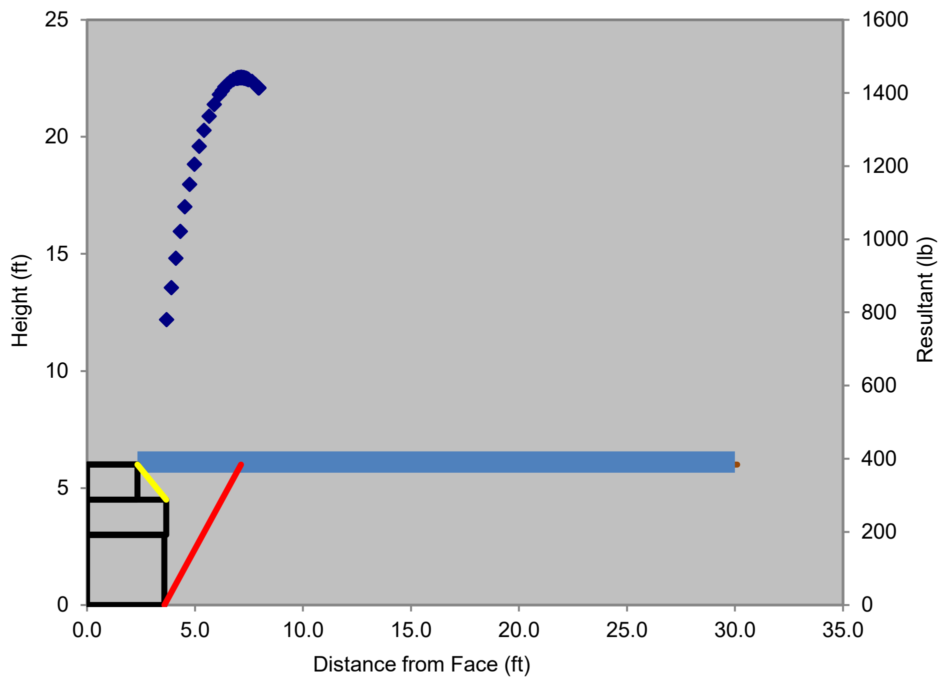
Backfill Slope & Surcharge

			rise in grade		LL surcharge		tier height	
length 1	30	feet (horizontal)		ft	250	psf		ft
length 2		feet (horizontal)		ft		psf		ft
length 3		feet (horizontal)		ft		psf		ft
length 4		feet (horizontal)		ft		psf		

effective slope H:1V slope β 0.0 deg avg q 250 psf

failure plane α 59.43 deg zone of influence 7.13 ft

Ground Surface & Trial Wedge Plot



Unfactored Loads

K_a =	0.394	K_{AE} =	0.394
P_h =	703 lb	ΔK_{AE} =	0.000
P_v =	479 lb	P_{IR} =	0 lb
Q_{lh} =	488 lb	ΔP_{AEh} =	0 lb
Q_{lv} =	333 lb	ΔP_{AEv} =	0 lb

STONE STRONG GRAVITY CALCULATIONS - ver 6.6

Project Name:	LRFD Methodology
Location:	Example Calculations
Job#:	20004.00
Section:	Example #1, level grade w/ surcharge
Calc by:	D Thiele

Load Cases:		Strngth I-a	Strngth I-b	Strngth IV	Extrme I-a (EQ)	Extrme I-b (EQ)	Extrme II (CT)	Service I		
Factored Loading	*Overturning (lb-ft):*	4,674	4,674	2,110	1,407	1,407	2,139	2,872	**OK!**	**Max Utiliization**
	Sliding (lb):	1,910	1,910	1,055	703	703	948	1,192	**OK!**	71%
	Bearing (psf):								**OK!**	
	e (ft):	0.94	0.76	0.38	0.36	0.36	0.52	0.67	**OK!**	
	Bf' (ft):									
Factored Resistance	*Overturning (lb-ft):*	7,493	9,932	7,666	5,285	5,285	5,764	6,874		**Min Capacity/Demand Ratio**
	Sliding (lb):	2,685	3,900	3,098	2,499	2,499	2,617	3,146		1.41
	Bearing (psf):									
	(@ interface) Max e (ft):	1.58	1.58	1.58	1.40	1.40	1.58	1.58		
Load & Resistance Factors	LL	1.75	1.75	0.00	0.00	0.00	0.50	1.00		
	EH	1.50	1.50	1.50	1.00	1.00	1.00	1.00		
	EQ	0.00	0.00	0.00	1.00	1.00	0.00	0.00		
	CT	0.00	0.00	0.00	0.00	0.00	1.00	0.00		
	LL Surcharge over Wall	0.00	1.75	0.00	0.00	0.00	0.00	1.00		
	DC	0.90	1.25	1.50	1.00	1.00	1.00	1.00		
	EV	1.00	1.35	1.35	1.00	1.00	1.00	1.00		
	BC	0.45	0.45	0.45	1.00	1.00	1.00	1.00		
	ϕt precast to agg	0.90	0.90	0.90	1.00	1.00	1.00	1.00		
	ϕt CIP to agg/soil	0.80	0.80	0.80	1.00	1.00	1.00	1.00		
	ϕt soil to soil	0.90	0.90	0.90	1.00	1.00	1.00	1.00		
	ϕt precast to precast	0.90	0.90	0.90	1.00	1.00	1.00	1.00		
	concrete interface - eccentricity limit	0.45	0.45	0.45	0.40	0.40	0.45	0.45		
	bearing on soil - eccentricity limit	0.33	0.33	0.33	0.40	0.40	0.40	0.33		

STONE STRONG GRAVITY CALCULATIONS - ver 6.6

Project Name: LRFD Methodology
Location: Example Calculations
Job#: 20004.00
Section: Example #2, 3H:1V backslope
Calc by: D Thiele

(AASHTO 9th Edition, 2020)

12/5/23 15:37

Notes 12.0 tall wall, 12 inches of embedment, 9 inch thick base, 3H:1V backslope, battered face, 30 degree sand retained, CIP tail extension on lower 4.5 feet

External stability

Wall Configuration

unit	w (in)	h (ft)	setback (in) face	setback (in) tail	modular units Wb (lb)	modular units xb (in)	unit fill Wa (lb)	unit fill xa (in)	soil wedge Ws (lb)	soil wedge xs (in)	CIP Extension we (in)	CIP Extension h_t	Internal	Max Utiliization
6-44	44.0	1.50	14.0	-10.0	375	35.0	301	37.5	19	58.9			Internal Stability OK!	11%
6-44	44.0	1.50	12.0	-12.0	375	33.0	301	35.5	85	59.2			Internal Stability OK!	23%
24-44	44.0	3.00	8.0	-16.0	750	29.2	594	32.8	396	59.3			Internal Stability OK!	53%
24-44	68.0	3.00	4.0	4.0	1,185	38.0	594	28.8	311	71.1	24	1/2 h	Internal Stability OK!	66%
24-44	68.0	3.00	0.0	0.0	1,620	39.9	594	24.8	0	0.0	24			
													External Stability OK!	**97%**
	68.0	12.00	14.0	-10.0	4,305	36.5	2,385	30.7	811	63.8				

backfill height 12.00 feet ω= 6.34 deg interface friction angle

exposed height 11.00 feet ω'= -3.97 deg δ 22.5 deg

Retained Soil
γ 120 pcf
ϕ 30 deg

Foundation Soil
γ 125 pcf
ϕ 26 deg
c' 150 psf

base embedment 12 in
base thickness 9 in
base material agg
toe slope H:1V slope

factored bearing resistance n/a psf
(if specified) (net)

Aggregate Unit Fill
γ 110 pcf

composite friction coefficient μ_b 0.74

Project Name:	LRFD Methodology
Location:	Example Calculations
Job#:	20004.00
Section:	Example #2, 3H:1V backslope
Calc by:	D Thiele

Seismic Load PGA [ ] G site class (A to E or 1) D Fpga 1.60 Fa 1.60 k_h 0.00

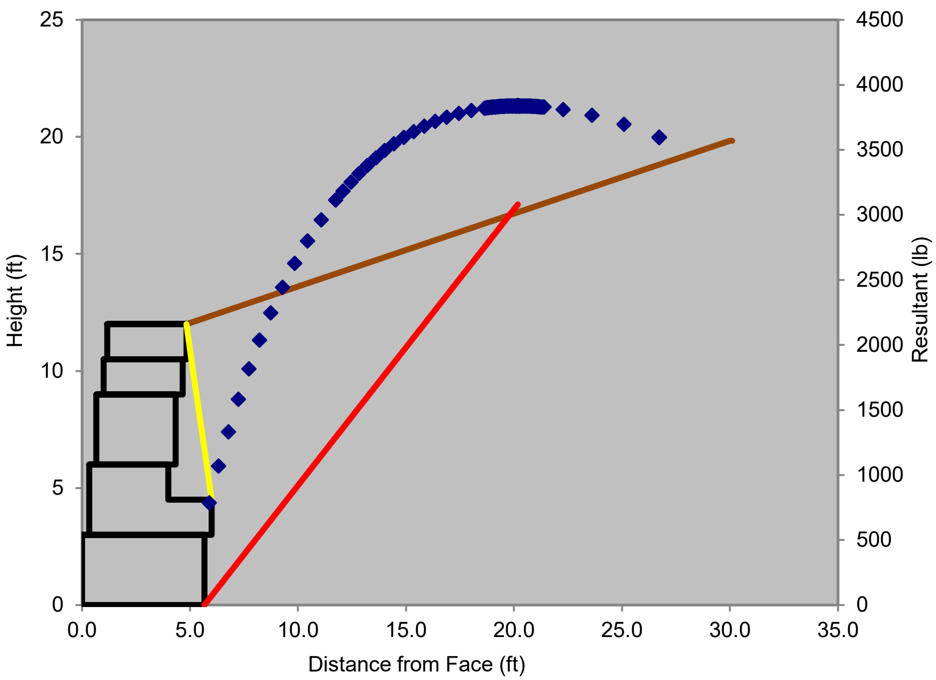
Backfill Slope & Surcharge

			backslope		LL surcharge		tier height	
length 1	30	feet (horizontal)	3	H:1V slope		psf		ft
length 2		feet (horizontal)		H:1V slope		psf		ft
length 3		feet (horizontal)		H:1V slope		psf		ft
length 4		feet (horizontal)		H:1V slope		psf		

effective slope 3.00 H:1V slope β 18.4 deg avg q 0 psf

failure plane α 49.71 deg zone of influence 20.18 ft

Ground Surface & Trial Wedge Plot



Unfactored Loads

K_a =	0.444	K_{AE} =	0.444
P_h =	3,436 lb	ΔK_{AE} =	0.000
P_v =	1,711 lb	P_{IR} =	0 lb
Q_{lh} =	0 lb	ΔP_{AEh} =	0 lb
Q_{lv} =	0 lb	ΔP_{AEv} =	0 lb

Project Name:	**LRFD Methodology**
Location:	**Example Calculations**
Job#:	**20004.00**
Section:	**Example #2, 3H:1V backslope**
Calc by:	**D Thiele**

Load Cases:		Strngth I-a	Strngth I-b	Strngth IV	Extrme I-a (EQ)	Extrme I-b (EQ)	Extrme II (CT)	Service I		
Factored Loading	*Overturning (lb-ft):*	20,615	20,615	20,615	13,744	13,744	13,744	13,744	**OK!**	**Max Utiliization**
	Sliding (lb):	5,154	5,154	5,154	3,436	3,436	3,436	3,436	**OK!**	97%
	Bearing (psf):	2,581	2,803	2,928	1,985	1,985	1,985	1,985	**OK!**	
	e (ft):	1.35	1.01	0.90	0.86	0.86	0.86	0.86	**OK!**	
	Bf' (ft):	3.95	4.61	4.79	4.87	4.87	4.87	4.87		
Factored Resistance	*Overturning (lb-ft):*	33,944	41,442	44,713	30,643	30,643	30,643	30,643		**Min Capacity/Demand Ratio**
	Sliding (lb):	5,330	6,564	7,036	5,715	5,715	5,715	5,715		1.03
	Bearing (psf):	4,406	4,638	4,701	10,515	10,515	10,515	10,515		
	(@ top of base) Max e (ft):	1.89	1.89	1.89	2.27	2.27	2.27	1.89		
Load & Resistance Factors	LL	1.75	1.75	0.00	0.00	0.00	0.50	1.00		
	EH	1.50	1.50	1.50	1.00	1.00	1.00	1.00		
	EQ	0.00	0.00	0.00	1.00	1.00	0.00	0.00		
	CT	0.00	0.00	0.00	0.00	0.00	1.00	0.00		
	LL Surcharge over Wall	0.00	1.75	0.00	0.00	0.00	0.00	1.00		
	DC	0.90	1.25	1.50	1.00	1.00	1.00	1.00		
	EV	1.00	1.35	1.35	1.00	1.00	1.00	1.00		
	BC	0.45	0.45	0.45	1.00	1.00	1.00	1.00		
	ϕt precast to agg	0.90	0.90	0.90	1.00	1.00	1.00	1.00		
	ϕt CIP to agg/soil	0.80	0.80	0.80	1.00	1.00	1.00	1.00		
	ϕt soil to soil	0.90	0.90	0.90	1.00	1.00	1.00	1.00		
	ϕt precast to precast	0.90	0.90	0.90	1.00	1.00	1.00	1.00		
	concrete interface - eccentricity limit	0.45	0.45	0.45	0.40	0.40	0.45	0.45		
	bearing on soil - eccentricity limit	0.33	0.33	0.33	0.40	0.40	0.40	0.33		

STONE STRONG SYSTEMS

STONE STRONG GRAVITY CALCULATIONS - ver 6.6

Project Name: LRFD Methodology
Location: Example Calculations
Job#: 20004.00
Section: Example #2, 3H:1V backslope
Calc by: D Thiele

(AASHTO 9th Edition, 2020)

12/5/23 15:37

Notes 12.0 tall wall, 12 inches of embedment, 9 inch thick base, 3H:1V backslope, battered face, 30 degree sand retained, CIP tail extension on lower 4.5 feet

Internal stability (top 6 feet)

Wall Configuration

unit	w (in)	h (ft)	setback (in) face	setback (in) tail	modular units Wb (lb)	modular units xb (in)	unit fill Wa (lb)	unit fill xa (in)	soil wedge Ws (lb)	soil wedge xs (in)	CIP Extension we (in)	CIP Extension h_t	Internal	Max Utiliization
6-44	44.0	1.50	6.0	6.0	375	26.0	301	28.5					Internal Stability OK!	11%
6-44	44.0	1.50	4.0	4.0	375	24.0	301	26.5					Internal Stability OK!	23%
24-44	44.0	3.00	0.0	0.0	750	20.2	594	23.8						
													Internal Stability OK!	**53%**
	44.0	6.00	6.0	6.0	1,500	22.6	1,196	25.7	0	0.0				

backfill height 6.00 feet

ω= 6.34 deg

ω'= 6.34 deg

interface friction angle

δ 15.0 deg

Retained Soil

γ 120 pcf

ϕ 30 deg

Internal ONLY

Aggregate Unit Fill

γ 110 pcf

Project Name:	LRFD Methodology
Location:	Example Calculations
Job#:	20004.00
Section:	Example #2, 3H:1V backslope
Calc by:	D Thiele

Seismic Load PGA [ ] G site class (A to E or 1) D Fpga 1.60 Fa 1.60 k_h 0.00

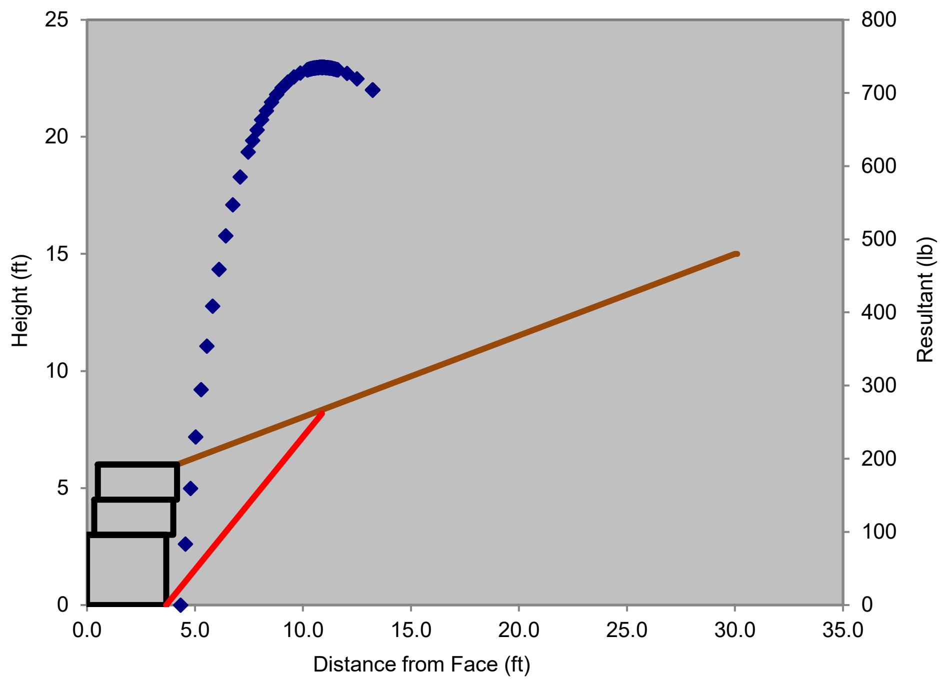
Backfill Slope & Surcharge

			backslope		LL surcharge		tier height	
length 1	30	feet (horizontal)	3	H:1V slope		psf		ft
length 2		feet (horizontal)		H:1V slope		psf		ft
length 3		feet (horizontal)		H:1V slope		psf		ft
length 4		feet (horizontal)		H:1V slope		psf		

effective slope 3.00 H:1V slope β 18.4 deg avg q 0 psf

failure plane α 48.61 deg zone of influence 10.88 ft

Ground Surface & Trial Wedge Plot



Unfactored Loads

K_a =	0.340	K_{AE} =	0.340
P_h =	727 lb	ΔK_{AE} =	0.000
P_v =	111 lb	P_{IR} =	0 lb
Q_{lh} =	0 lb	ΔP_{AEh} =	0 lb
Q_{lv} =	0 lb	ΔP_{AEv} =	0 lb

STONE STRONG GRAVITY CALCULATIONS - ver 6.6

Project Name: LRFD Methodology
Location: Example Calculations
Job#: 20004.00
Section: Example #2, 3H:1V backslope
Calc by: D Thiele

12/5/23 15:37

Load Cases:		Strngth I-a	Strngth I-b	Strngth IV	Extrme I-a (EQ)	Extrme I-b (EQ)	Extrme II (CT)	Service I		
Factored Loading	*Overturning (lb-ft):*	2,180	2,180	2,180	1,453	1,453	1,453	1,453	**OK!**	**Max Utiliization**
	Sliding (lb):	1,090	1,090	1,090	727	727	727	727	**OK!**	53%
	Bearing (psf):								**OK!**	
	e (ft):	0.56	0.37	0.32	0.30	0.30	0.30	0.30	**OK!**	
	Bf' (ft):									
Factored Resistance	*Overturning (lb-ft):*	5,221	6,926	7,632	5,293	5,293	5,293	5,293		**Min Capacity/Demand Ratio**
	Sliding (lb):	2,048	2,647	2,885	2,342	2,342	2,342	2,342		1.88
	Bearing (psf):									
	(@ interface) Max e (ft):	1.61	1.61	1.61	1.43	1.43	1.61	1.61		
Load & Resistance Factors	LL	1.75	1.75	0.00	0.00	0.00	0.50	1.00		
	EH	1.50	1.50	1.50	1.00	1.00	1.00	1.00		
	EQ	0.00	0.00	0.00	1.00	1.00	0.00	0.00		
	CT	0.00	0.00	0.00	0.00	0.00	1.00	0.00		
	LL Surcharge over Wall	0.00	1.75	0.00	0.00	0.00	0.00	1.00		
	DC	0.90	1.25	1.50	1.00	1.00	1.00	1.00		
	EV	1.00	1.35	1.35	1.00	1.00	1.00	1.00		
	BC	0.45	0.45	0.45	1.00	1.00	1.00	1.00		
	ϕt precast to agg	0.90	0.90	0.90	1.00	1.00	1.00	1.00		
	ϕt CIP to agg/soil	0.80	0.80	0.80	1.00	1.00	1.00	1.00		
	ϕt soil to soil	0.90	0.90	0.90	1.00	1.00	1.00	1.00		
	ϕt precast to precast	0.90	0.90	0.90	1.00	1.00	1.00	1.00		
	concrete interface - eccentricity limit	0.45	0.45	0.45	0.40	0.40	0.45	0.45		
	bearing on soil - eccentricity limit	0.33	0.33	0.33	0.40	0.40	0.40	0.33		