GRAVITY WALL DESIGN - ASD
STONE STRONG PRECAST MODULAR BLOCK

This engineering section presents information for design of Stone Strong retaining walls in a gravity configuration using conventional procedures with safety factors.

The design methodologies presented conform substantially to AASHTO specifications (Standard Specifications for Highway Bridges - 2002). This section includes the following documents:

- Gravity Wall Design Methodology (15 pages)
- Example Gravity Wall Calculations (9 pages)
- Example 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 DESIGN METHODOLOGY (ASD)
STONE STRONG PRECAST MODULAR BLOCK

Evaluate gravity retaining wall using allowable stress design approach following AASHTO and NCMA analytical techniques. Additional requirements, analytical methods, and theories are taken from the International Building Code, other AASHTO versions, and FHWA publications. Refer to:

NCMA Design Manual for Segmental Retaining Wall, 3rd Edition
FHWA Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines, NHI-00-043
International Building Code

Properties of Soil/Aggregate

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

unit fill - \( \gamma_u = 110 \text{pcf (17.3 kN/m}^3) \) max (see AASHTO 5.9.2) & \( \phi_u \)
leveling base - \( \gamma_b \) & \( \phi_b \) for typical aggregate base (or concrete base may be substituted)
retained soil - \( \gamma \) & \( \phi \) by site conditions (where select backfill is used, select material must encompass entire retained soil influence zone)
foundation soil - \( \gamma \phi \) & c by site conditions
interface angle (see AASHTO 5.9.2)

For stepped modules, when the block width varies within a vertical section, \( \delta = \frac{3}{4} \phi \)

For cases where all blocks are substantially uniform width, \( \delta = \frac{1}{2} \phi \)

Note: infill weight is reduced to account for infill material not engaged by modular units in overturning. Only 80% of the weight of aggregate is included in the overturning calculations, \( W' \) (see AASHTO 5.9.2)
Precast Modular Unit Geometric Properties

Block Library – Imperial Units

<table>
<thead>
<tr>
<th>Block Type</th>
<th>Description</th>
<th>Conc. Wt. (lbs)</th>
<th>Void Vol. (ft³)</th>
<th>Length (ft)</th>
<th>Height (ft)</th>
<th>Unit Width (in)</th>
<th>Conc. Cen. of Gravity x₀ (in)</th>
<th>Void Cen. of Gravity xₐ (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-28</td>
<td>6SF-28 unit (6 square feet)</td>
<td>950</td>
<td>6.65</td>
<td>4</td>
<td>1.50</td>
<td>28</td>
<td>12.8</td>
<td>14.0</td>
</tr>
<tr>
<td>6SF</td>
<td>6SF unit (6 square feet)</td>
<td>1,500</td>
<td>10.95</td>
<td>4</td>
<td>1.50</td>
<td>44</td>
<td>21.0</td>
<td>23.5</td>
</tr>
<tr>
<td>24SF</td>
<td>24SF unit (24 square feet)</td>
<td>6,000</td>
<td>43.21</td>
<td>8</td>
<td>3.00</td>
<td>44</td>
<td>21.0</td>
<td>24.8</td>
</tr>
<tr>
<td>24-ME</td>
<td>24SF Mass Extender unit</td>
<td>10,000</td>
<td>44.94</td>
<td>8</td>
<td>3.00</td>
<td>56</td>
<td>32.7</td>
<td>25.8</td>
</tr>
<tr>
<td>24-62</td>
<td>24SF-62 unit</td>
<td>6,800</td>
<td>76.05</td>
<td>8</td>
<td>3.00</td>
<td>62</td>
<td>29.1</td>
<td>33.0</td>
</tr>
<tr>
<td>24-86</td>
<td>24SF-86 unit</td>
<td>7,600</td>
<td>117.90</td>
<td>8</td>
<td>3.00</td>
<td>86</td>
<td>40.0</td>
<td>45.1</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Block Type</th>
<th>Description</th>
<th>Conc. Wt. (kN)</th>
<th>Void Vol. (m³)</th>
<th>Length (m)</th>
<th>Height (m)</th>
<th>Unit Width (mm)</th>
<th>Conc. Cen. of Gravity x₀ (mm)</th>
<th>Void Cen. of Gravity xₐ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-28</td>
<td>6SF-28 unit (6 square feet)</td>
<td>4.23</td>
<td>0.19</td>
<td>1.22</td>
<td>0.46</td>
<td>711</td>
<td>324</td>
<td>356</td>
</tr>
<tr>
<td>6SF</td>
<td>6SF unit (6 square feet)</td>
<td>6.67</td>
<td>0.31</td>
<td>1.22</td>
<td>0.46</td>
<td>1,118</td>
<td>533</td>
<td>597</td>
</tr>
<tr>
<td>24SF</td>
<td>24SF unit (24 square feet)</td>
<td>26.69</td>
<td>1.22</td>
<td>2.44</td>
<td>0.91</td>
<td>1,118</td>
<td>538</td>
<td>630</td>
</tr>
<tr>
<td>24-ME</td>
<td>24SF Mass Extender unit</td>
<td>44.48</td>
<td>1.28</td>
<td>2.44</td>
<td>0.91</td>
<td>1,422</td>
<td>831</td>
<td>655</td>
</tr>
<tr>
<td>24-62</td>
<td>24SF-62 unit</td>
<td>30.25</td>
<td>2.16</td>
<td>2.44</td>
<td>0.91</td>
<td>1,575</td>
<td>739</td>
<td>838</td>
</tr>
<tr>
<td>24-86</td>
<td>24SF-86 unit</td>
<td>33.8</td>
<td>3.35</td>
<td>2.44</td>
<td>0.91</td>
<td>2,184</td>
<td>1,016</td>
<td>1,146</td>
</tr>
</tbody>
</table>

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.
Typical gravity wall configuration, variables, and nomenclature:

Note that surcharge loads over the top of the wall are a stabilizing force and are neglected as conservative.
Typical gravity wall configuration, 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**

In common applications, the block units are installed in a battered configuration. In a typical batter, the 24 SF, 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 SF 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)  
- 2 in. setback per 6 SF block (18 in. tall)

The face batter is calculated as:

\[ \theta = \arctan\left(\frac{4}{36}\right) = 6.34° \]
\[ \theta = \arctan\left(\frac{102}{914}\right) = 6.34° \]
\[ \theta = \arctan\left(\frac{2}{18}\right) = 6.34° \]
\[ \theta = \arctan\left(\frac{51}{457}\right) = 6.34° \]

In some applications, the units may be installed with no batter to create a vertical face, \( \omega = 0° \)

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. Use \( \omega' \) in Coulomb equation and earth pressure component calculations. To calculate \( \omega' \) 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:

\[ \omega' = \arctan\left(\frac{w_s}{H_w}\right) \]

**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 (225 mm) 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:

\[ h_e = \frac{H'}{(20*S/6)} \]

where \( S \) is the run of the toe slope per unit fall and \( H' \) is the exposed height of the wall

A minimum embedment of 6 to 9 inches (150 to 225 mm) is recommended for private projects. A minimum embedment of 20 inches (500 mm) or more may be required for roadway applications.
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:

\[ W_{te} = (w_{te} \times H_{te}) \times 145 \text{ pcf (22.8 kN/m}^3) \]  
(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, \( \omega_s \), is calculated:

\[ \omega_s = \arctan\left(-\frac{w_s}{H_{wedge}}\right) \]

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:

\[ h_s = \text{height of the soil trapezoid behind the block (may differ from height of the block)} \]
\[ w_u = \text{width of the block} \]
\[ h_1 = \text{dist. from the top of wall to top of the soil trapezoid behind the block} \]
\[ h_2 = \text{dist. from the top of wall to bottom of the soil trapezoid behind the block} \]
\[ s = \text{dist. from the face of wall to face of the block} \]
\[ s_u = \text{dist. from the face of wall to back of the block} = s + w_u \]
\[ s_T = \text{dist. from the face of wall to the back of top-most block of wall} \]
\[ b_1 = \text{length of top side of trapezoid of soil behind block} = h_1 \tan(\omega_s) + (s_T - s_u) \]
\[ b_2 = \text{length of bottom side of trapezoid of soil behind block} = h_2 \tan(\omega_s) + (s_T - s_u) \]

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:

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

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

\[ x_s = [(b_1^2 \times b_2 + (b_2^2 - 2 \times b_1 \times b_2 + b_1^2) / 3) / (b_1 + b_2)] + s + w_u \]
\[ y_s = [h_s / 3 \times (2b_1 + b_2) / (b_1 + b_2)] + H - h_2 \]

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

Coulomb active earth pressure coefficient (see AASHTO 5.5.2-1)

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

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 5.5.2-1)

Vertical forces:

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

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

Horizontal forces:

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

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

Resultants of earth load components:

\[ y_{P} = \frac{H}{3} \]

\[ x_{P} = \left( \frac{H}{3} \right) \tan(\omega') + w_u \]

\[ y_{Q_l} = \frac{H}{2} \]

\[ x_{Q_l} = \left( \frac{H}{2} \right) \tan(\omega') + w_u \]

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:

\[
x_b = \frac{\sum (W_{b1} \cdot x_{b1} + W_{b2} \cdot x_{b2} + \cdots + W_{bn} \cdot x_{bn})}{\sum (W_{b1} + W_{b2} + \cdots + W_{bn})}
\]
\[
y_b = \frac{\sum (W_{b1} \cdot y_{b1} + W_{b2} \cdot y_{b2} + \cdots + W_{bn} \cdot y_{bn})}{\sum (W_{b1} + W_{b2} + \cdots + W_{bn})}
\]

The center of mass of the aggregate fill is:

\[
x_a = \frac{\sum (W_{a1} \cdot x_{a1} + W_{a2} \cdot x_{a2} + \cdots + W_{an} \cdot x_{an})}{\sum (W_{a1} + W_{a2} + \cdots + W_{an})}
\]
\[
y_a = \frac{\sum (W_{a1} \cdot y_{a1} + W_{a2} \cdot y_{a2} + \cdots + W_{an} \cdot y_{an})}{\sum (W_{a1} + W_{a2} + \cdots + W_{an})}
\]

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

\[
x_s = \frac{\sum (W_{s1} \cdot x_{s1} + W_{s2} \cdot x_{s2} + \cdots + W_{sn} \cdot x_{sn})}{\sum (W_{s1} + W_{s2} + \cdots + W_{sn})}
\]
\[
y_s = \frac{\sum (W_{s1} \cdot y_{s1} + W_{s2} \cdot y_{s2} + \cdots + W_{sn} \cdot y_{sn})}{\sum (W_{s1} + W_{s2} + \cdots + W_{sn})}
\]

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

\[
x_{te} = \frac{\sum (W_{te1} \cdot x_{te1} + W_{te2} \cdot x_{te2} + \cdots + W_{ten} \cdot x_{ten})}{\sum (W_{te1} + W_{te2} + \cdots + W_{te})}
\]
\[
y_{te} = \frac{\sum (W_{te1} \cdot y_{te1} + W_{te2} \cdot y_{te2} + \cdots + W_{ten} \cdot y_{ten})}{\sum (W_{te1} + W_{te2} + \cdots + W_{te})}
\]

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

\[
x_{b+te} = \frac{(W_b \cdot x_b + W_{te} \cdot x_{te})}{(W_b + W_{te})}
\]
\[
y_{b+te} = \frac{(W_b \cdot y_b + W_{te} \cdot y_{te})}{(W_b + W_{te})}
\]

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

\[
x_{a+s} = \frac{(W_a \cdot x_a + W_s \cdot x_s)}{(W_a + W_s)}
\]
\[
y_{a+s} = \frac{(W_a \cdot y_a + W_s \cdot y_s)}{(W_a + W_s)}
\]
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:

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

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

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

Seismic Earth load components

$k_v$ is generally taken as 0. $k_n$ 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:

$$k_n = 1.66 * A_m * [A_m/(d*C)]^{0.25}$$

d is the maximum horizontal displacement, and is typically set at 2 inches (50 mm) as conservative. Note that this equation has embedded units of mm, and $C$ is a conversion factor (25.4 when $d$ is in units of inches, and 1 when $d$ is in units of mm).

$A_m = (1.45-PGA)*PGA$

Note that when PGA is not provided, it can be calculated from seismic response values provided in the International Building Code. IBC 1802.2.7 allows for PGA to be taken as $S_{DS}/2.5$. Following IBC Eq. 16-37 and 16-39:

$$PGA = 0.267 * S_s F_a$$

The horizontal inertial force $P_r$ is calculated as follows:

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

The seismic thrust is calculated as follows:

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

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

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

Resultants of Seismic Earth load components

In overturning analysis, the inertial force is applied at the vertical center of gravity of the wall, while the seismic thrust is applied at 60% of the wall height.
$y_{Pa} = 0.6*H$

$x_{Pa} = 0.6*H*\tan(\alpha') + w_u$

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

Since the inertial and thrust forces are generally not in sync and do not peak simultaneously, the full inertial force is applied along with 50% of the seismic thrust (FHWA 4.2h).

Stability including seismic load conditions should be separately verified for sliding, overturning/eccentricity, and bearing. Live loads are typically excluded from seismic analysis.

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

For base to foundation soil failure, use:

$$R_s(\text{foundation soil}) = (W_b + W_{te} + W_a + W_s + P_v + w_u*t_b*\gamma) \tan \phi + B_w*c$$

where $\phi$ represents foundation soil friction angle, $B_w$ is base width (bottom block width including any tail extension plus $\frac{1}{2}H:1V$ distribution through base), and $c$ represents foundation soil cohesion. The weight of the base is included in the wall weight.

For block to base material sliding, use:

$$R_s(\text{footing}) = \mu_b (W_b + W_{te} + W_a + W_s + P_v)$$

where $\mu_b$ 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:

$$\%_{\text{void}} = \frac{V_{\text{void}}}{V_{\text{void}}+V_{\text{concrete}}}$$

$$\%_{\text{concrete}} = \frac{V_{\text{concrete}}}{V_{\text{void}}+V_{\text{concrete}}}$$

If a 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:

$$\mu_b = (\%_{\text{void}}*W_u(\text{bottom}) + \%_{\text{concrete}}*W_u(\text{bottom}) + W_{te} + \mu_{\text{p - extension/base}})/(W_u(\text{bottom}) + W_{te})$$
Partial friction coefficients can be interpreted from the following table:

<table>
<thead>
<tr>
<th>Block to Aggregate Base</th>
<th>Coefficient of Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>formed precast surface on compacted aggregate surface (includes Mass Extender)</td>
<td>(0.8 \times \tan \phi_b)</td>
</tr>
<tr>
<td>Unit Fill to Aggregate Base</td>
<td>lower (\tan \phi_b) or (\tan \phi_u)</td>
</tr>
<tr>
<td>screened aggregate (loose to moderate relative density - dumped) on compacted aggregate surface</td>
<td></td>
</tr>
<tr>
<td>Block to Concrete Base</td>
<td>0.60</td>
</tr>
<tr>
<td>formed precast surface on floated concrete surface (includes Mass Extender)</td>
<td></td>
</tr>
<tr>
<td>Unit Fill Aggregate to Concrete Base</td>
<td>(0.8 \times \tan \phi_u)</td>
</tr>
<tr>
<td>screened aggregate (loose to moderate relative density - dumped) on floated concrete surface</td>
<td></td>
</tr>
<tr>
<td>Concrete Tail Extension to Aggregate Base</td>
<td>(\tan \phi_b)</td>
</tr>
<tr>
<td>cast in place concrete on aggregate surface</td>
<td></td>
</tr>
<tr>
<td>Concrete Tail Extension to Concrete Base</td>
<td>0.75</td>
</tr>
<tr>
<td>cast in place concrete on floated concrete surface</td>
<td></td>
</tr>
<tr>
<td>Concrete Tail Extension Directly on Foundation Soil (Sand)</td>
<td>(\tan \phi_f)</td>
</tr>
<tr>
<td>cast in place concrete on granular soil</td>
<td></td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Friction Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Graded, Aggregate, Densely Compacted</td>
</tr>
<tr>
<td>Crushed Hard Aggregate &gt;75% w/ 2 fractured faces, hard natural rock</td>
</tr>
<tr>
<td>Crushed Aggregate &gt;75% w/ 2 fractured faces, medium natural rock or recycled concrete</td>
</tr>
<tr>
<td>Cracked Gravel &gt;90% w/ 1 fractured face</td>
</tr>
</tbody>
</table>

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.
### Table of Forces & Moments

<table>
<thead>
<tr>
<th>Force Arm Moment about toe</th>
<th>Force (lb) or (kN)</th>
<th>Arm (ft) or (m)</th>
<th>Moment about toe (lb*ft) or (kN *m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertical Forces</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>weight of blocks</td>
<td>( W_b + W_{te} )</td>
<td>( x_{b+te} )</td>
<td>((W_b + W_{te}) * x_{b+te})</td>
</tr>
<tr>
<td>weight of agg. &amp; soil over tail</td>
<td>( W_a + W_s )</td>
<td>( x_{a+s} )</td>
<td>((W_a + W_s) * x_{a+s})</td>
</tr>
<tr>
<td>modified weight of a &amp; s (80%)</td>
<td>0.8*(( W_a + W_s ))</td>
<td>( x_{a+s} )</td>
<td>0.8*(( W_a + W_s )) * ( x_{a+s} )</td>
</tr>
<tr>
<td>earth pressure</td>
<td>( P_v )</td>
<td>( x_P )</td>
<td>( P_v * x_P )</td>
</tr>
<tr>
<td>seismic thrust</td>
<td>( P_{aev/2} )</td>
<td>( x_{Pae} )</td>
<td>( P_{aev/2} * x_{Pae} )</td>
</tr>
<tr>
<td>LL surcharge</td>
<td>( Q_{lv} )</td>
<td>( x_{Qi} )</td>
<td>( Q_{lv} * x_{Qi} )</td>
</tr>
<tr>
<td><strong>Horizontal Forces</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>earth pressure</td>
<td>( P_h )</td>
<td>( y_{Ph} )</td>
<td>( P_h * y_{Ph} )</td>
</tr>
<tr>
<td>seismic thrust</td>
<td>( \Delta P_{aeh/2} )</td>
<td>( y_{Pae} )</td>
<td>( \Delta P_{aeh/2} * y_{Pae} )</td>
</tr>
<tr>
<td>inertial force</td>
<td>( P_{ir} )</td>
<td>( y_{Pir} )</td>
<td>( P_{ir} * y_{Pir} )</td>
</tr>
<tr>
<td>LL surcharge</td>
<td>( Q_{lh} )</td>
<td>( y_{Qi} )</td>
<td>( Q_{lh} * y_{Qi} )</td>
</tr>
</tbody>
</table>
Overturning

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

\[
\begin{array}{|c|c|}
\hline
M_V' & \Sigma \text{ moments from vertical forces (using 80\% } W_s \& W_a) \\
M_H & \Sigma \text{ moments from horizontal forces} \\
FS & \frac{M_V'}{M_H} \\
\hline
\end{array}
\]

The overturning safety factor should be greater than 1.5 for private projects (NCMA 4.3 and IBC 1806.1). A minimum safety factor of 2.0 may be required for highway applications (AASHTO 5.5.5).

check that \(FS > 1.5\) with static earth pressure loads and surcharge loads

Safety factors are typically reduced 25% for seismic loading due to the extreme nature of these events. Surcharge loads are generally not applied concurrent with seismic loads.

check that \(FS > 1.13\) with static earth pressure loads and seismic loads

Sliding

The minimum value for sliding resistance is calculated as follows:

\[
\begin{array}{|c|c|}
\hline
F_H & \Sigma \text{ horizontal forces} \\
F_V & \Sigma \text{ vertical forces (using 100\% } W_s \& W_a) \\
R_s \text{ (footing)} & \mu_b F_V \\
R_s \text{ (foundation soil)} & (F_V + t_b \cdot w_b \cdot g_b) \cdot \tan(\phi) + B_w \cdot c \\
\text{min } R_s & \text{smaller of } R_s \text{ (footing)} \text{ or } R_s \text{ (foundation soil)} \\
FS & \text{min } R_s' / F_H \\
\hline
\end{array}
\]

The safety factor for sliding should be greater than 1.5

check that \(FS > 1.5\) with static earth pressure loads and surcharge loads

check that \(FS > 1.13\) with static earth pressure loads and seismic loads
### Bearing/Eccentricity

Bf' 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.

\[
B_f' = w_u + w_{te} + t_b - 2*e \quad \text{or} \quad B_f' = w_u + w_{te} + 2*t_b - 2*e \quad \text{(for concrete base)}
\]

<table>
<thead>
<tr>
<th>(F_V)</th>
<th>(\Sigma) vertical forces (using 100% (W_s) &amp; (W_a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight of base</td>
<td>(t_b \cdot \gamma_b)</td>
</tr>
<tr>
<td>(M_V)</td>
<td>(\Sigma) moments from vertical forces (using 100% (W_s) &amp; (W_a))</td>
</tr>
<tr>
<td>(M_H)</td>
<td>(\Sigma) moments from horizontal forces</td>
</tr>
<tr>
<td>(e)</td>
<td>((w_u + w_{te})/2 - (M_V - M_H)/F_V)</td>
</tr>
<tr>
<td>(B_f') (granular base)</td>
<td>(w_u + w_{te} + t_b - 2*e)</td>
</tr>
<tr>
<td>(B_f') (concrete base)</td>
<td>(w_u + w_{te} + 2<em>t_b - 2</em>e)</td>
</tr>
<tr>
<td>contact pressure (q_c)</td>
<td>(F_V / B_f' + t_b \cdot \gamma_b)</td>
</tr>
<tr>
<td>bearing resistance (q_{ut})</td>
<td>([c*N_c + (h_{te} + t_b)\gamma_{found}<em>N_q + 0.5</em>\gamma_{found}*B_f'*N_{r}])</td>
</tr>
</tbody>
</table>

FS \(q_{ut} / q_c\)

The safety factor for bearing should be greater than 2

- check that \(FS > 2.0\) with static earth pressure loads and surcharge loads
- check that \(FS > 1.5\) with static earth pressure loads and seismic loads
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 topping 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.

\[ FS = \frac{M'_{V}}{M_{H}} \]

check that \( FS > 1.5 \) with static earth pressure loads and surcharge loads

check that \( FS > 1.13 \) with static earth pressure loads and seismic loads

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

\[ R_s = [S_i + (W + P_v +Q_{iv})^* \tan (35.2^\circ)] \]

where \( S_i = 362 \text{ lb/ft or 5.28 kN/m} \)

\[ FS = \frac{R_s}{F_H} \]

check that \( FS > 1.5 \) with static earth pressure loads and surcharge loads

check that \( FS > 1.13 \) with static earth pressure loads and seismic loads

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.
EXAMPLE GRAVITY WALL CALCULATIONS
ALLOWABLE STRESS METHOD USING IBC SAFETY FACTORS

Example 1: 13.5 feet tall wall, level back slope, 150 psf parking surcharge

Retained Soil: sand with $\gamma = 120$ pcf and $\phi = 30$ degrees
Foundation Soil: clay with $\gamma = 125$ pcf, $\phi = 26$ degrees, and $c' = 150$ psf
Infill Aggregate: screened crushed aggregate with $\gamma = 110$ pcf and $\phi = 35$ degrees
Base Aggregate: well graded crushed aggregate with $\gamma = 125$ pcf and $\phi = 40$ degrees
Wall Configuration (all weights per foot along length of wall)

### External Stability Analysis

<table>
<thead>
<tr>
<th>Modular Units</th>
<th>Setback (in)</th>
<th>Concrete (/ft.)</th>
<th>Unit Fill (/ft.)</th>
<th>Soil Wedge (/ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>unit</td>
<td>w (in)</td>
<td>h (ft)</td>
<td>face</td>
<td>tail</td>
</tr>
<tr>
<td>6-28</td>
<td>28.0</td>
<td>1.50</td>
<td>16.0</td>
<td>-42.0</td>
</tr>
<tr>
<td>6-28</td>
<td>28.0</td>
<td>1.50</td>
<td>14.0</td>
<td>-44.0</td>
</tr>
<tr>
<td>6</td>
<td>44.0</td>
<td>1.50</td>
<td>12.0</td>
<td>-30.0</td>
</tr>
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<td>44.0</td>
<td>3.00</td>
<td>8.0</td>
<td>-34.0</td>
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<td>24-86</td>
<td>86.0</td>
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<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>24-86</td>
<td>86.0</td>
<td>3.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Weight and Center of Gravity of Wall Components**

\[
W_b = 950 + 950 + 750 + 375 + 238 + 238 = 3,500 \text{ lb/ft} \\
W_a = 1,621 + 1,621 + 594 + 301 + 183 + 183 = 4,503 \text{ lb/ft} \\
W_s = 792 + 151 + 217 + 63 = 1,224 \text{ lb/ft} \\
\text{Total Wall Weight} = 3,500 + 4,503 + 1,224 = 9,227 \text{ lb/ft} \\
\]

\[
x_b = \frac{(950 \times 40.0 + 950 \times 44.0 + 750 \times 29.2 + 375 \times 33.0 + 238 \times 26.8 + 238 \times 28.8)}{3,500} = 36.4 \text{ in} \\
x_a = \frac{(1,621 \times 45.1 + 1,621 \times 49.1 + 594 \times 32.8 + 301 \times 35.5 + 183 \times 28.0 + 183 \times 30.0)}{4,503} = 43.0 \text{ in} \\
x_s = \frac{(792 \times 66.9 + 151 \times 61.8 + 217 \times 50.1 + 62 \times 47.1)}{1,224} = 62.3 \text{ in} \\
\]

**Earth Pressure Components**

\[
\omega' = \arctan(-42/12/13.5) = -14.53^\circ \\
\delta = 0.75 \times 30 = 22.5^\circ \\
\]

\[
K_a = \frac{\cos^2(30-14.53)}{\cos^2(-14.53) \cos(-14.53-22.5) \left[1 + \frac{\sin(30+22.5) \sin(30-0)}{\cos(-14.53-22.5) \cos(-14.53+0)}\right]^2} \\
K_a = 0.421 \\
P_h = 0.5 \times 0.421 \times 120 \times (12.0)^2 \cos(22.5 + 14.53) = 3,679 \text{ lb} \\
P_v = 0.5 \times 0.421 \times 120 \times (12.0)^2 \sin(22.5 + 14.53) = 2,776 \text{ lb} \\
Q_{bh} = 0.421 \times 150 \times 12.0 \times \cos(22.5 + 14.53) = 681 \text{ lb} \\
Q_{bv} = 0.421 \times 150 \times 12.0 \times \sin(22.5 + 14.53) = 514 \text{ lb} \\
\]

\[
x_p = \frac{(13.5/3) \times \tan(-14.53) + 86/12}{6.00} = 6.00 \text{ ft} \\
y_p = \frac{13.5}{3} = 4.50 \text{ ft} \\
x_{Ql} = \frac{(13.5/2) \times \tan(-14.53) + 86/12}{5.42} = 5.42 \text{ ft} \\
y_{Ql} = \frac{13.5}{2} = 6.75 \text{ ft} \\
\]
Base Friction

Use the smaller sliding resistance, R, of the following:

Determine composite friction coefficient across base:

\[
\%_{\text{void}} = \frac{1,621/110}{950/145+1,621/110} = 0.6922 \\
\%_{\text{concrete}} = \frac{950/145}{950/145+1,621/110} = 0.3078 \\
\mu_b = 0.6922 \tan(35) + 0.3078 \times 0.8 \tan(40) = 0.691 \\
\]

\[
R_{\text{footing}} = 0.691 \times (9,227+2,776+514) = 8,653 \text{ lb/ft} \\
R_{\text{soil}} = (9,227+2,776+514+(86/12 \times 9/12) \times 125) \times \tan(26) + ((86+9)/12) \times 150 \\
= 7,620 \text{ lb/ft} \\
\]

Factors of Safety

Overturning

\[
FS = \frac{[3,500 \times (36.4/12)+0.8 \times 4,503 \times (43.0/12)+0.8 \times 1,224 \times (62.3/12)+2,776 \times 6.00+514 \times 5.42]}{(3,679 \times (4.50)+681 \times 6.75)} = 2.27 > 1.5 \quad \text{OK!!} \\
\]

Sliding

\[
FS = \frac{7,620}{(3,679+681)} = 1.75 > 1.5 \quad \text{OK!!} \\
\]

Bearing

\[
e = \frac{(86/12)-[(3,500 \times (36.4/12)+4,503 \times (43.0/12)+1,224 \times (62.3/12)+2,776 \times 6.00+514 \times 5.42) - (3,679 \times 4.50+681 \times 6.75)]}{(3,500+4,503+1,224+2,776+514)} = 1.08 \text{ ft} \\
B'_f = (86+9)/12 - 2 \times 1.08 = 5.76 \text{ ft.} \\
q_c = (9,227+2,776+514) / 5.76 + 9/12 \times 125 = 2,266 \text{ psf} \\
\]

Bearing Factors (Vesci):

\[
N_c = 22.25 \quad N_q = 11.85 \quad N_r = 12.54 \\
q_{ult} = 150 \times 22.25 + ((9+9)/12) \times 125 \times 11.85 + 0.5 \times 125 \times 5.76 \times 12.54 = 10,076 \text{ psf} \\
\]

\[
FS = \frac{10,076}{2,266} = 4.45 > 2.0 \quad \text{OK!!} \\
\]
Internal Stability Analysis

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 24SF. Internal stability of the block stack above this interface is calculated as follows:

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

<table>
<thead>
<tr>
<th>Modular Units</th>
<th>Setback (in)</th>
<th>Concrete (/ft.)</th>
<th>Unit Fill (/ft.)</th>
<th>Soil Wedge (/ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>unit</td>
<td>w (in)</td>
<td>h (ft)</td>
<td>face</td>
<td>tail</td>
</tr>
<tr>
<td>6-28</td>
<td>28.0</td>
<td>1.50</td>
<td>8.0</td>
<td>-8.0</td>
</tr>
<tr>
<td>6-28</td>
<td>28.0</td>
<td>1.50</td>
<td>6.0</td>
<td>-10.0</td>
</tr>
<tr>
<td>6</td>
<td>44.0</td>
<td>1.50</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>24</td>
<td>44.0</td>
<td>3.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Weight and Center of Gravity of Wall Components

\[
W_b = 750 + 375 + 238 + 238 = 1,600 \text{ lb/ft}
\]
\[
W_a = 594 + 301 + 183 + 183 = 1,261 \text{ lb/ft}
\]
\[
W_s = 151 + 41 = 193 \text{ lb/ft}
\]
Total Wall Weight = 1,600 + 1,261 + 193 = 3,054 lb/ft

\[
x_b = \frac{(750 \times 20.2 + 375 \times 24.0 + 238 \times 17.8 + 238 \times 19.8)}{1,600} = 20.7 \text{ in}
\]
\[
x_a = \frac{(594 \times 23.8 + 301 \times 26.5 + 183 \times 19.0 + 183 \times 21.0)}{1,261} = 23.3 \text{ in}
\]
\[
x_s = \frac{(151 \times 38.6 + 41 \times 37.0)}{193} = 38.3 \text{ in}
\]

Earth Pressure Components

\[
\omega' = \arctan(-8/12/7.5) = -5.08^\circ
\]
\[
\delta = 0.75 \times 30 = 22.5^\circ
\]
\[
K_a = \frac{\cos^2(30+5.08)}{\cos^2(-5.08) \cos(-5.08-22.5) \left[ 1 + \sqrt{\frac{\sin(30+22.5) \sin(30-0)}{\cos(-5.08-22.5) \cos(-5.08+0)}} \right]^2}
\]
\[
K_a = 0.335
\]
\[
P_h = 0.5 \times 0.335 \times 120 \times (7.5)^2 \cos(22.5 + 5.08) = 1,003 \text{ lb}
\]
\[
P_v = 0.5 \times 0.335 \times 120 \times (7.5)^2 \sin(22.5 + 5.08) = 524 \text{ lb}
\]
\[
Q_{lh} = 0.335 \times 150 \times 7.5 \cos(22.5 + 5.08) = 334 \text{ lb}
\]
\[
Q_{lv} = 0.335 \times 150 \times 7.5 \sin(22.5 + 5.08) = 175 \text{ lb}
\]
\[
x_p = (7.5/3) \tan(-5.08) + 43/12 = 3.36 \text{ ft}
\]
\[
y_p = 7.5/3 = 2.5 \text{ ft}
\]
\[
x_{Ql} = (7.5/2) \tan(-5.08) + 43/12 = 2.61 \text{ ft}
\]
\[
y_{Ql} = 7.5/2 = 3.75 \text{ ft}
\]
Interface Shear
\[ R_s = 362 + (3,054 + 524 + 175) \tan(35.2) = 3,009 \]

Factors of Safety

Overturning/Toppling
\[ FS = \frac{[1,600 \times (20.7/12) + 0.8 \times 1,261 \times (23.3/12) + 0.8 \times 193 \times (38.3/12) + 524 \times 3.36 + 175 \times 2.61]}{(1,003 \times 2.50 + 334 \times 3.75)} = 2.00 > 1.5 \quad \text{OK!!} \]

Sliding/Internal Shear
\[ FS = \frac{3,009}{1,003 + 334} = 2.25 > 1.5 \quad \text{OK!!} \]

All other interfaces \textbf{OK!!}
Example 2: 13.5 feet tall wall, 3H:1V back slope, CIP tail extension

Retained Soil: sand with $\gamma = 120$ pcf and $\phi = 30$ degrees
Foundation Soil: clay with $\gamma = 125$ pcf, $\phi = 26$ degrees, and $c' = 150$ psf
Infill Aggregate: screened crushed aggregate with $\gamma = 110$ pcf and $\phi = 35$ degrees
Base Aggregate: well graded crushed aggregate with $\gamma = 125$ pcf and $\phi = 40$ degrees
Tail Extension: 30 inches wide by 72 inches tall, placed on aggregate base
Wall Configuration including CIP tail extension (all weights per foot along length of wall)

<table>
<thead>
<tr>
<th>Modular Units</th>
<th>Setback (in)</th>
<th>Concrete (/ft.)</th>
<th>Unit Fill (/ft.)</th>
<th>Soil Wedge (/ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w (in)</td>
<td>h (ft)</td>
<td>face</td>
<td>tail</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wb (lb)</td>
<td>Wa (lb)</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>xb (in)</td>
<td>xa (in)</td>
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<tr>
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<td></td>
<td></td>
<td>Ws (lb)</td>
<td>xs (in)</td>
</tr>
<tr>
<td>unit</td>
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</tr>
<tr>
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<td>61.2</td>
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<td>750</td>
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<td>61.8</td>
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<td>44.0</td>
<td>3.00</td>
<td>8.0</td>
<td>-22.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>750</td>
<td>594</td>
</tr>
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<td>1,838</td>
<td>594</td>
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<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

External Stability Analysis

Weight and Center of Gravity of Wall Components

\[
W_b + W_t = 750 + 2.5 \times 3.0 \times 145 + 750 + 2.5 \times 3.0 \times 145 + 750 + 2.5 \times 3.0 \times 145 + 750 + 375 = 5,550 \text{ lb/ft}
\]

\[
W_a = 594 + 594 + 594 + 301 = 2,678 \text{ lb/ft}
\]

\[
W_s = 616 + 308 + 25 = 949 \text{ lb/ft}
\]

Total Wall Weight = 5,500 + 2,678 + 949 = 9,176 lb/ft

\[
x_{b+t} = \frac{(1,838 \times 43.6 + 1,838 \times 47.6 + 750 \times 29.2 + 750 \times 33.2 + 375 \times 37.0)}{5,550} = 41.1 \text{ in}
\]

\[
x_a = \frac{(594 \times 24.8 + 594 \times 28.8 + 594 \times 32.8 + 594 \times 36.8 + 301 \times 39.5)}{2,678} = 31.8 \text{ in}
\]

\[
x_s = \frac{(616 \times 63.3 + 308 \times 61.8 + 25 \times 61.2)}{949} = 62.8 \text{ in}
\]

Earth Pressure Components

\[
\omega' = \arctan(-14/12/13.5) = -4.94^\circ
\]

\[
\delta = 0.75 \times 30 = 22.5^\circ
\]

\[
K_a = \frac{\cos^2(30+4.94)}{\cos^2(-4.94) \cos(-4.94-22.5) \left[1+\frac{\sin(30+22.5) \sin(30-18.4)}{\cos(-4.94-22.5) \cos(-4.94+18.4)}\right]^2}
\]

\[
K_a = 0.456
\]

\[
P_h = 0.5 \times (0.456) \times 120 \times (13.5)^2 \cos(22.5+4.94) = 4,425 \text{ lb}
\]

\[
P_v = 0.5 \times (0.456) \times 120 \times (13.5)^2 \sin(22.5+4.94) = 2,298 \text{ lb}
\]

\[
x_p = (13.5/3) \tan(-4.94)+(74/12) = 5.78 \text{ ft}
\]

\[
y_p = (13.5/3) = 4.5
\]
Base Friction
Use the smaller sliding resistance, R, of the following:

Determine composite friction coefficient across base:
\[
\%_{\text{void}} = \frac{1,621/110}{750/145 + 2.0*3.0 + 1,621/110} = 0.5688
\]
\[
\%_{\text{prescast}} = \frac{750/145}{750/145 + 2.0*3.0 + 1,621/110} = 0.1996
\]
\[
\%_{\text{CIP}} = \frac{2.0*3.0}{750/145 + 2.0*3.0 + 1,621/110} = 0.2316
\]
\[
\mu_b = 0.5688 \cdot \tan(35) + 0.1996 \cdot 0.8 \cdot \tan(40) + 0.2316 \cdot \tan(40) = 0.606
\]
\[
R_{\text{footing}} = 0.606 \cdot (9,176 + 2,298) = 6,953 \text{ lb/ft}
\]
\[
R_{\text{soil}} = (9,176 + 2,289 + (74/12 \cdot 9/12) \cdot 125) \cdot \tan(26) + ((74 + 9)/12) \cdot 150 = 6,916 \text{ lb/ft}
\]

Factors of Safety
Overturning
\[
FS = \frac{[5,550(41.1/12) + 0.8 \cdot 2,678(31.8/12) + 0.8 \cdot 949(62.8/12) + 2,298 \cdot 5.78]}{(4,425 \cdot 4.5)} = 2.11 > 1.5 \quad \text{OK!!}
\]
Sliding
\[
FS = 6,916/4,425 = 1.56 > 1.5 \quad \text{OK!!}
\]
Bearing
\[
e = (74/12)/2 - \{(5,550(41.1/12) + 2,678(31.8/12) + 949(62.8/12) + 2,298 \cdot 5.78) - (4,425 \cdot 4.5)\}/(5,550 + 2,678 + 949 + 2,298) = 0.95
\]
\[
B' = (74+9)/12 \cdot 2.0 \cdot 0.95 = 5.01 \text{ ft.}
\]
\[
q_c = ((5,550 + 2,678 + 949 + 2,298) / 5.01) + (9/12) \cdot 125 = 2,385 \text{ psf}
\]
Bearing Factors (Vesic):
\[
N_c = 22.25 \quad N_q = 11.85 \quad N_t = 12.54
\]
\[
q_{ult} = 150 \cdot 22.25 + ((9+9)/12) \cdot 125 \cdot 11.85 + 0.5 \cdot 125 \cdot 5.01 \cdot 12.54 = 9,485 \text{ psf}
\]
\[
FS = 9,485/2,385 = 3.98 > 2.0 \quad \text{OK!!}
\]
**Internal Stability Analysis**
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 change from 24SF unit with tail extension to a 24SF unit. Internal stability of the block stack above this interface is calculated as follows:

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

<table>
<thead>
<tr>
<th>Modular Units</th>
<th>Setback (in)</th>
<th>Concrete (/ft.)</th>
<th>Unit Fill (/ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>unit</td>
<td>w (in)</td>
<td>h (ft)</td>
<td>face</td>
</tr>
<tr>
<td>6</td>
<td>44.0</td>
<td>1.50</td>
<td>8.0</td>
</tr>
<tr>
<td>24</td>
<td>44.0</td>
<td>3.00</td>
<td>4.0</td>
</tr>
<tr>
<td>24</td>
<td>44.0</td>
<td>3.00</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Weight and Center of Gravity of Wall Components**

\[
W_b = 750+750+375 = 1,875 \text{ lb/ft} \\
W_a = 594+594+301 = 1,489 \text{ lb/ft} \\
\text{Total Wall Weight} = 1,875+1,489 = 3,364 \text{ lb/ft}
\]

\[
x_b = \frac{(750*20.2+750*24.2+375*28.0)}{1,875} = 23.4 \text{ in} \\
x_a = \frac{(594*248+594*28.8+296*35.5)}{1,489} = 26.8 \text{ in}
\]

**Earth Pressure Components**

\[
\omega' = 6.34^\circ \\
\delta = 0.5*30 = 15.0^\circ \\
K_a = \frac{\cos^2(30+6.34)}{\cos^2(6.34) \cos(6.34-15.0) \left[ 1+\frac{\sin(30+15.0) \sin(30-18.4)}{\cos(6.34-15.0) \cos(6.34+18.4)} \right]^2}
\]

\[
K_a = 0.340 \\
P_h = 0.5*0.340*120*(7.5)^2*\cos(15-6.34) = 1,135 \text{ lb} \\
P_v = 0.5*0.340*120*(7.5)^2*\sin(15-6.34) = 173 \text{ lb}
\]

\[
x_P = (7.5/3)*\tan(6.34)+(44/12) = 3.94 \text{ ft} \\
y_P = 7.5/3 = 2.5 \text{ ft}
\]

**Interface Shear**

\[
R_s = 362+(3,364+173)*\tan(35.2) = 2,857 \text{ lb}
\]

**Factors of Safety**

**Overturning/Toppling**

\[
FS = \frac{[1.875*(23.4/12)+0.8*1,489*(26.7/12)+173*3.94]}{1,135*2.5} = 2.46 > 1.5 \quad \text{OK!!}
\]

**Sliding/Internal Shear**

\[
FS = \frac{2,857/1,135}{2.52} = 1.5 \quad \text{OK!!}
\]

All other interfaces **OK!!**
### Wall Configuration

<table>
<thead>
<tr>
<th>unit</th>
<th>w (in)</th>
<th>h (ft)</th>
<th>setback (in)</th>
<th>modular units</th>
<th>soil wedge</th>
<th>CIP Extension</th>
<th>Internal Stability FS</th>
<th>Seismic Internal FS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>face</td>
<td>tail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wb (lb)</td>
<td>Wa (lb)</td>
<td>Ws (lb)</td>
<td>xb (in)</td>
<td>h_t</td>
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<td></td>
<td></td>
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<td></td>
<td>xa (in)</td>
<td>xs (in)</td>
<td>we (in)</td>
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<td>6-28</td>
<td>28.0</td>
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<td>238</td>
<td>183</td>
<td>63</td>
<td>47.1</td>
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<td>14.0</td>
<td>-44.0</td>
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<td>183</td>
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<td>8.0</td>
<td>-34.0</td>
<td>750</td>
<td>594</td>
<td>792</td>
<td>66.9</td>
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<td>24-86</td>
<td>86.0</td>
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<td>950</td>
<td>1,621</td>
<td>49.1</td>
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<td>24-86</td>
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<td>0.0</td>
<td>0.0</td>
<td>950</td>
<td>1,621</td>
<td>45.1</td>
<td>0</td>
</tr>
</tbody>
</table>

### Notes
- 13.5 tall wall with extended precast units, battered face
- Level back slope, 150 psf parking lot surcharge
- External Stability OK!
Seismic Load  Ss  G  site class (A to E or 1)  D  Fpga  1.60  Fa  1.60  k_h  0.00

Backfill Slope & Surcharge
length 1  30 feet (horizontal)  rise in grade  ft  LL surcharge  150 psf  tier height  ft
length 2  ft  ft  psf  ft
length 3  ft  ft  psf  ft
length 4  ft  ft  psf  ft

Analysis

Analysis

Results

Overturning: Desired FS = 1.5  Actual FS = 2.27  OK!

Sliding: Desired FS = 1.5  Actual FS = 1.75  OK!

Bearing Capacity: Desired FS = 2  Actual FS = 4.45  OK!

q_{all} = 5,038 psf  q_c = 2,266 psf

Internal Safety Factors

Desired FS = 1.5  Actual FS = 1.5
**Project Name:** Example Calculations  
**Location:**  
**Job #:** 20004.00  
**Section:** Example #1  
**Calc by:** D Thiele

### Notes
- 13.5 tall wall with extended precast units, battered face  
- level back slope, 150 psf parking lot surcharge  
- Internal Stability

#### Wall Configuration

<table>
<thead>
<tr>
<th>unit</th>
<th>setback (in)</th>
<th>modular units</th>
<th>unit fill</th>
<th>soil wedge</th>
<th>CIP Extension</th>
<th>Internal Stability FS</th>
<th>Seismic Internal FS</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>w (in)</td>
<td>h (ft)</td>
<td>face</td>
<td>tail</td>
<td>Wb (lb)</td>
<td>xb (in)</td>
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<td>6.0</td>
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<td>183</td>
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<td>1.50</td>
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<td>4.0</td>
<td>375</td>
<td>24.0</td>
<td>301</td>
</tr>
<tr>
<td>24</td>
<td>44.0</td>
<td>3.00</td>
<td>0.0</td>
<td>0.0</td>
<td>750</td>
<td>20.2</td>
<td>594</td>
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</table>

**Internal Stability OK!**

### Retained Soil
- $\gamma = 120$ pcf  
- $\phi = 30$ deg

### Aggregate Unit Fill
- $\gamma = 110$ pcf

**backfill height:** 7.50 feet  
$\omega = 6.34$ deg  
$\omega' = -5.08$ deg  
$\delta = 22.5$ deg
Seismic Load

<table>
<thead>
<tr>
<th>Site class (A to E or 1)</th>
<th>G</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fpga</td>
<td>1.60</td>
<td>Fa</td>
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</tbody>
</table>

Backfill Slope & Surcharge

<table>
<thead>
<tr>
<th>Length</th>
<th>feet (horizontal)</th>
<th>Rise in grade</th>
<th>LL surcharge</th>
<th>tier height</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>ft</td>
<td>150 psf</td>
<td>ft</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>ft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>ft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>ft</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Effective slope H:1V | 0.0 deg |

Failure plane | 57.31 deg |
Zone of influence | 8.48 ft |
Avg q | 150 psf |

Analysis

<table>
<thead>
<tr>
<th>$Q_{lh}$</th>
<th>334 lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{v}$</td>
<td>175 lb</td>
</tr>
<tr>
<td>$P_h$</td>
<td>1,003 lb</td>
</tr>
<tr>
<td>$P_v$</td>
<td>524 lb</td>
</tr>
</tbody>
</table>

$K_a$ = 0.335

$Q_{lh} = 334 lb$
$Q_{v} = 175 lb$
$P_h = 1,003 lb$
$P_v = 524 lb$
$\Delta K_{AE} = 0.000$
$e = 0.62 ft$

Internal Safety Factors

Internal Overturning:
Desired FS = 1.5
Actual FS = 2.00 OK!

Interface Shear:
Desired FS = 1.5
Actual FS = 2.25 OK!
Notes: 13.5 tall wall with CIP tail extension, battered face
3H:1V backslope
External Stability

Wall Configuration

<table>
<thead>
<tr>
<th>unit</th>
<th>w (in)</th>
<th>h (ft)</th>
<th>setback (in)</th>
<th>modular units</th>
<th>unit fill</th>
<th>soil wedge</th>
<th>CIP Extension</th>
<th>Internal Stability FS</th>
<th>Seismic Internal FS</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>face</td>
<td>tail</td>
<td>Wb (lb)</td>
<td>xb (in)</td>
<td>Wa (lb)</td>
<td>xa (in)</td>
<td>Ws (lb)</td>
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<td>37.0</td>
<td>301</td>
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<td>12.0</td>
<td>-18.0</td>
<td>750</td>
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<td>4.0</td>
<td>4.0</td>
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<td>0</td>
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<td>3.00</td>
<td>0.0</td>
<td>0.0</td>
<td>1,838</td>
<td>43.6</td>
<td>594</td>
<td>24.8</td>
<td>0</td>
</tr>
</tbody>
</table>

External Stability OK!

backfill height 13.50 feet  ω = 6.34 deg  interface friction angle
exposed height 12.75 feet  ω’ = -4.94 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 9 in
base thickness 9 in
base material agg
toe slope H:1V slope

Aggregate Unit Fill
γ = 110 pcf
(if specified)

allowable bearing pressure n/a psf
composite friction coefficient μb 0.61
### Seismic Load
- **Ss**
- **G**
- **D**
- **Fpga**
- **Fa**
- **k_h**

### Backfill Slope & Surcharge
- **length 1**: 30 feet (horizontal)
- **length 2**: feet (horizontal)
- **length 3**: feet (horizontal)
- **length 4**: feet (horizontal)
- **effective slope**: 3.00 H:1V slope
- **β**: 18.4 deg
- **avg q**: 0 psf
- **zone of influence**: 22.45 ft

### Analysis
- **Q_{lh}** = 0 lb
- **Q_{v}** = 0 lb
- **P_{h}** = 4,425 lb
- **P_{v}** = 2,298 lb
- **q_{ult}** = 9,485 psf

### Results
- **Overturning**: Desired FS = 1.5  
  Actual FS = 2.11  OK!
- **Sliding**: Desired FS = 1.5  
  Actual FS = 1.56  OK!
- **Bearing Capacity**: Desired FS = 2  
  Actual FS = 3.98  OK!

### Internal Safety Factors
- Desired FS = 1.5

---

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**Notes**
13.5 tall wall with CIP tail extension, battered face
3H:1V backslope
Internal Stability

### Wall Configuration

<table>
<thead>
<tr>
<th>Setback (in)</th>
<th>Modular Units</th>
<th>Unit Fill</th>
<th>Soil Wedge</th>
<th>CIP Extension</th>
<th>Topple Shear</th>
<th>Seismic Internal FS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w (in) h (ft)</td>
<td>Wb (lb)</td>
<td>Wa (lb)</td>
<td>Ws (lb)</td>
<td>xb (in)</td>
<td>xs (in)</td>
</tr>
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<td>0.0 0.0</td>
<td>750 20.2</td>
<td>594 23.8</td>
<td></td>
<td></td>
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</tbody>
</table>

### Retained Soil
- γ = 120 pcf
- φ = 30 deg

### Aggregate Unit Fill
- γ = 110 pcf

Backfill height: 7.50 feet
- ω = 6.34 deg (interface friction angle)
- ω' = 6.34 deg
- δ = 15.0 deg

Internal Stability OK!
Seismic Load  
Ss G site class (A to E or 1) D  
Fpga 1.60  Fa 1.60  k_h 0.00

Backfill Slope & Surcharge  
length 1 30 feet (horizontal) backslope 3 H:1V slope  LL surcharge  psf  tier height  
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  ft  
effective slope 3.00 H:1V slope  β 18.4 deg  avg q 0 psf  
failure plane α 48.61 deg  zone of influence 12.68 ft  

Analysis  
Q_{lh} = 0 lb  ΔK_{AE} = 0.000  e = 0.43 ft  
K_a = 0.340  Q_v = 0 lb  P_{IR} = 0 lb  B_f = 3.46 ft  
P_h = 1,135 lb  R_s = 2,857 lb  ΔP_{AEh} = 0 lb  e_{eq} = 0.43 ft  
P_v = 173 lb  q_{ult} = 8,275 psf  ΔP_{AEv} = 0 lb  B_{f(eq)} = 3.46 ft

Results  
Internal Overturning: Desired FS = 1.5  Actual FS = 2.46  OK! 
Interface Shear: Desired FS = 1.5  Actual FS = 2.52  OK!

Internal Safety Factors  
Desired FS = 1.5

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