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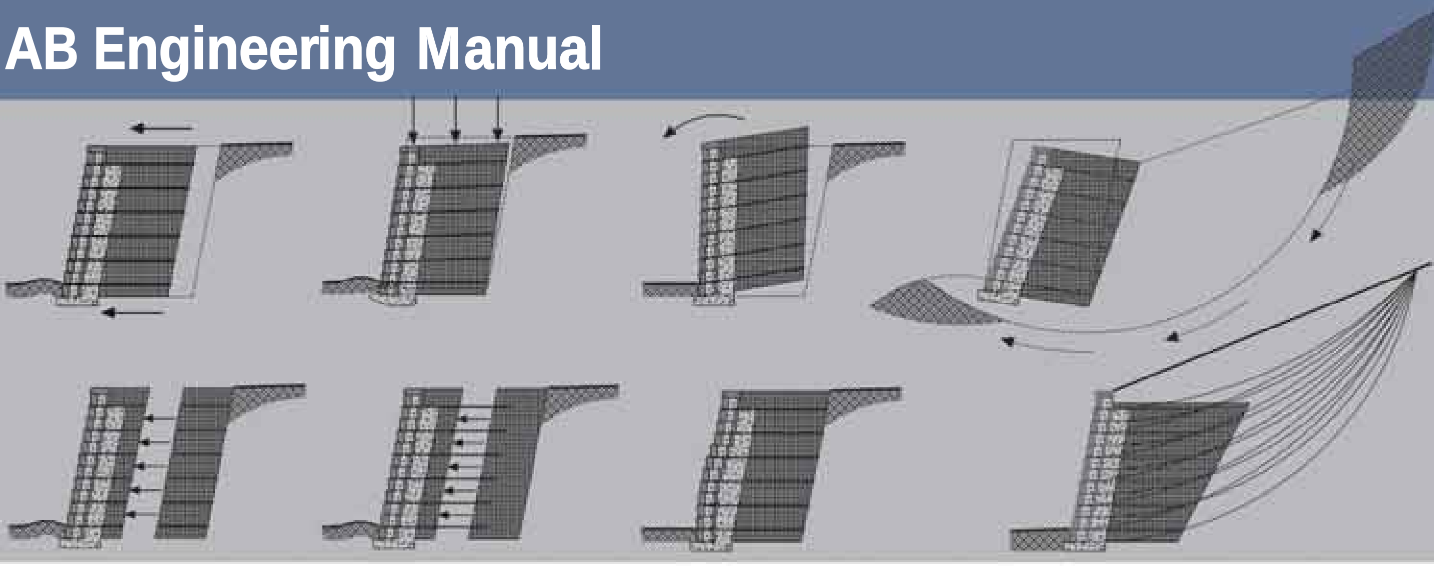
AB Engineering Manual



Allan Block® Retaining Walls

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CHAPTER FIVE

Seismic Analysis

Introduction

In seismic design we take a dynamic force and analyze it as a temporary static load. The forces from seismic activity yield both a vertical and a horizontal acceleration. For our calculations, the vertical acceleration is assumed to be zero (Bathurst, 1998, NCMA Segmental Retaining Walls - Seismic Design Manual, 1998). Due to the temporary nature of the loading, the minimum recommended factors of safety for design in seismic conditions are 75% of the values recommended for static design.

The wall performance during the Northridge earthquake in Los Angeles, California and the Kobe earthquake in Japan proves that a soil mass reinforced with geogrid, which is flexible in nature, performs better than rigid structures in real life seismic situations (Columbia University in Cooperation with Allan Block Corporation and Huesker Geosynthetics. “Executive Summary - Seismic Testing - Geogrid Reinforced Soil Structures Faced with Segmental Retaining Wall Block”, Sandri, Dean, 1994, "Retaining Walls Stand Up to the Northridge Earthquake").

The following design uses the earth pressure coefficient method derived by Mononobe-Okabe (M-O) to quantify the loads placed on the reinforced mass and the internal components of the structure. Since the nature of segmental retaining walls is flexible, an allowable deflection can be accepted resulting in a more efficient design while remaining within accepted factors of safety.

Pressure Coefficients

The calculation of the dynamic earth pressure coefficient is similar to the static earth pressure coefficient derived by Coulomb, with the addition by Mononobe-Okabe of a seismic inertia angle (θ).

$$K_{ae} = \frac{\left[\dfrac{\cos^2(\phi + \omega - \theta)}{\cos(\theta)\cos^2(\omega)\cos(\phi_w - \omega + \theta)}\right]}{\left[1 + \sqrt{\dfrac{\sin(\phi + \phi_w)\sin(\phi - i - \theta)}{\cos(\phi_w - \omega + \theta)\cos(\omega + i)}}\right]^2}$$

Where:

ϕ = peak soil friction angle

ω = block setback

ϕ_w = angle between the horizontal and the sloped back face of the wall

i = back slope angle

θ = seismic inertia angle

The seismic inertia angle (θ) is a function of the vertical and horizontal acceleration coefficients:

$$\theta = \operatorname{atan}\left(\frac{K_h}{1 + K_v}\right)$$

Where:

K_v = vertical acceleration coefficient

K_h = horizontal acceleration coefficient

The vertical acceleration coefficient (K_v) is taken to be zero based on the assumption that a vertical and horizontal peak acceleration will not occur simultaneously during a seismic event (Bathurst et al.). The horizontal acceleration coefficient (K_h) is based on the acceleration coefficient (A_o) and the allowable deflection (d) of the wall system. (See equations below) The acceleration coefficient (A_o) typically varies from 0 to 0.4 in our calculations and is defined as the fraction of the gravitational constant g experienced during a seismic event. AASHTO provides recommendations for the acceleration coefficient based on the seismic zone that the retaining wall is being designed for. The allowable deflection (d) represents the lateral deflection that the retaining wall can be designed to withstand during a seismic event. The amount of deflection allowed in the design is based on engineering judgement. An approximation of the allowable deflection is 10 (A_o) in inches or 254 (A_o) for millimeters. However, the typical allowable deflection (d) is approximately 3 in. (76 mm). The equation used to determine the horizontal acceleration coefficient (K_h) varies depending on the amount of deflection allowed and whether it is calculated for the infill soils or the retained soils.

For **Infill** soils:

If $d = 0$, then

$$K_h = (1.45 - A_o)\,A_o$$

This equation, proposed by Segrestin and Bastic, is used in AASHTO / FHWA guidelines. It is assumed to be constant at all locations in the wall.

If $d > 0$, then

$$K_h = 0.74\,A_o\left(\frac{(A_o)\,(1\text{ in})}{d}\right)^{0.25}$$

$$K_h = 0.74\,A_o\left(\frac{(A_o)\,(25.4\text{ mm})}{d}\right)^{0.25}$$

This is a standard equation for the horizontal acceleration coefficient based on the Mononobe-Okabe methodology (Mononobe, 1929; Okabe, 1926).

For **Retained** soils if:

If $d \leq 1$, then

$$K_h = \frac{A_o}{2}$$

If $d > 1$, then

$$K_h = 0.74\,A_o\left(\frac{(A_o)\,(1\text{ in})}{d}\right)^{0.25}$$

$$K_h = 0.74\,A_o\left(\frac{(A_o)\,(25.4\text{ mm})}{d}\right)^{0.25}$$

The following example illustrates the calculation of the dynamic earth pressure coefficient for the infill and retained soils with a typical allowable deflection of 3 in. (76 mm).

Example 5-1

Given:

ϕ_i	=	34°	ϕ_r	=	28°
ϕ_{wi}	=	2/3(34°) = 23°	ϕ_{wr}	=	2/3(28°) = 19°
d	=	3 in (76 mm)	ω	=	12°
i	=	0°	A_o	=	0.4

Find:

The dynamic earth pressure coefficients (Kae_i, Kae_r) for the infill and retained soils.

$$Kae_i = \frac{\left[\dfrac{\cos^2(\phi + \omega - \theta)}{\cos(\theta)\cos^2(\omega)\cos(\phi_w - \omega + \theta)}\right]}{\left[1+\sqrt{\dfrac{\sin(\phi + \phi_w)\sin(\phi - i - \theta)}{\cos(\phi_w - \omega + \theta)\cos(\omega + i)}}\right]^2}$$

The first step is to calculate the acceleration coefficients.

K_v = 0, based on the assumption that a vertical and horizontal peak acceleration will not occur simultaneously during a seismic event.

To determine K_h, we must look at the allowable deflection (d). Since the allowable deflection is greater than zero, the following equation is used:

$$K_h = 0.74\, A_o \left(\frac{(A_o)(1\ \text{in})}{d}\right)^{0.25} \qquad K_h = 0.74\, A_o \left(\frac{(A_o)(25.4\ \text{mm})}{d}\right)^{0.25}$$

$$K_h = 0.74\,(0.4) \left(\frac{(0.4)(1\ \text{in})}{3\ \text{in}}\right)^{0.25} = 0.179 \qquad K_h = 0.74\,(0.4) \left(\frac{(0.4)(25.4\ \text{mm})}{76\ \text{mm}}\right)^{0.25} = 0.179$$

The seismic inertia angle (θ) is:

$$\theta = \text{atan}\left(\frac{K_h}{1 + K_v}\right) = \text{atan}\left(\frac{0.179}{1 + 0}\right) = 10.1°$$

Finally, the dynamic earth pressure coefficient for the infill is:

$$Kae_i = \frac{\left[\dfrac{\cos^2(34 + 12 - 10.1)}{\cos(10.1)\cos^2(12)\cos(23 - 12 + 10.1)}\right]}{\left[1+\sqrt{\dfrac{\sin(34 + 23)\sin(34 - 0 - 10.1)}{\cos(23 - 12 + 10.1)\cos(12 + 0)}}\right]^2} = 0.289$$

The same process is followed in determining the dynamic earth pressure coefficient for the retained soil. Here again, the vertical acceleration coefficient (K_v) is equal to zero. With the allowable deflection greater than 1 inch (25 mm), the horizontal acceleration coefficient is the following:

$$K_h = 0.74\,A_o \left(\frac{(A_o)\,(1\text{ in})}{d}\right)^{0.25}$$

$$K_h = 0.74\,A_o \left(\frac{(A_o)\,(25.4\text{ mm})}{d}\right)^{0.25}$$

$$K_h = 0.74\,(0.4) \left(\frac{(0.4)\,(1\text{ in})}{3\text{ in}}\right)^{0.25} = 0.179$$

$$K_h = 0.74\,(0.4) \left(\frac{(0.4)\,(25.4\text{ mm})}{76\text{ mm}}\right)^{0.25} = 0.179$$

Next, the seismic inertia angle (θ) can be calculated:

$$\theta = \text{atan}\left(\frac{K_h}{1 + K_v}\right) = \text{atan}\left(\frac{0.179}{1 + 0}\right) = 10.1°$$

The dynamic earth pressure coefficient for the retained soil is:

$$Kae_r = \frac{\left[\dfrac{\cos^2(28 + 12 - 10.1)}{\cos(10.1)\cos^2(12)\cos(19 - 12 + 10.1)}\right]}{\left[1 + \sqrt{\dfrac{\sin(28 + 19)\sin(28 - 0 - 10.1)}{\cos(19 - 12 + 10.1)\cos(12 + 0)}}\right]^2} = 0.377$$

Dynamic Earth Force of the Wall

The dynamic earth force is based on a pseudo-static approach using the Mononobe-Okabe (M-O) method. Figures 5-1 and 5-2 illustrate the pressure distributions for the active force, dynamic earth force increment, and the dynamic earth force. The magnitude of the dynamic earth force is:

$$\text{DFdyn} = F_{ae} - F_a$$

Where:

$$F_a = (0.5)\,(K_a)\,(\gamma)\,(H)^2$$

$$F_{ae} = (0.5)\,(1 + K_v)\,(K_{ae})\,(\gamma)\,(H)^2$$

The magnitude of the resultant force (F_a) acts at 1/3 of the height of the wall. Based on full scale seismic testing DFdyn has been found to act at 1/2 the height of the wall. Based on a rectangular pressure distribution.

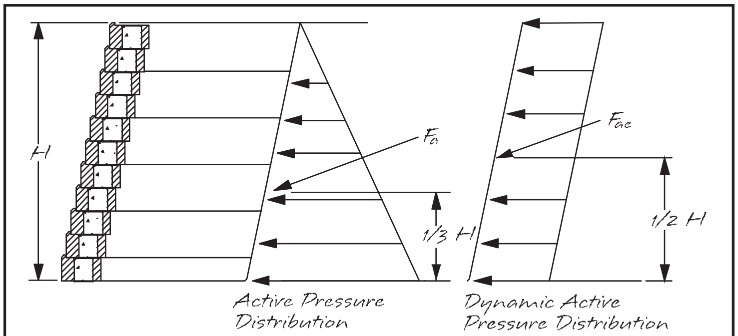

Figure 5-1. Dynamic and Static Active Pressure Distribution

Safety Factors

The minimum accepted factors of safety for seismic design are taken to be 75% of the values recommended for static design.

Sliding > 1.1

Overturning > 1.5

NOTE: The values 1.1 and 1.5 are based on 75% of the recommended minimum factors of safety for design of conventional segmental retaining walls. (Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guide Lines, FHWA NHI-00-043).

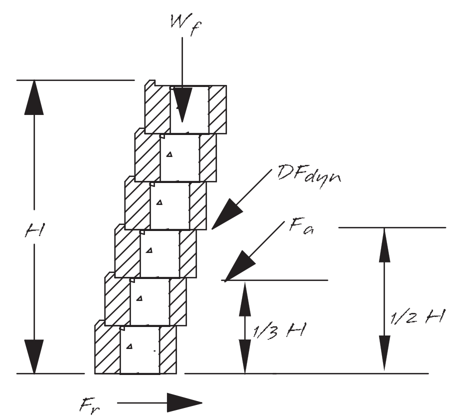

Figure 5-2. Free Body Diagram of Simple Gravity Wall Under Seismic Influence

Simple Gravity Wall with Seismic Influence

In seismic analysis, the weight of a simple gravity wall must counteract the static and temporary dynamic forces of the retained soil. Figure 5-2 illustrates the forces on a simple gravity wall during a seismic event. In the following example, the same equilibrium principles apply as in a static gravity wall analysis with additional consideration for the seismic earth force and the allowed reductions in required factors of safety for sliding and overturning.

Example 5-2:

Given:

ϕ_i	$= \phi_r = 30°$	β	$= 78°$
ω	$= (90 - \beta) = 12°$	i	$= 0°$
A_o	$= 0.4$	d	= 2 in. (51 mm)
Ka_i	$= 0.2197$	H	= 2.54 ft (0.77 m)
Ka_r	$= 0.2197$	ϕ	$= \phi_{wi} = \phi_{wr} = 2/3(\phi) = 20°$
γ_{wall}	= 130 lb/ft³ (2,061 kg/m³)	γ	$= \gamma_i = \gamma_r =$ 120 lb/ft³ (1,923 kg/m³)
Kae_i	$= 0.362$	Kae_r	$= 0.362$

Find:
The safety factor against sliding (SFS) and overturning (SFO).

NOTE: The dynamic earth pressure coefficients Kae_i and Kae_r were determined by following the allowable deflection criteria established at the beginning of the section.

The first step is to determine the driving forces exerted by the soil on the wall:

Active earth force:

F_a = $(0.5)(K_a)(\gamma)(H)^2$
= $(0.5)(0.2197)(120\ lb/ft^3)(2.54\ ft)^2 = 85\ lb/ft$
= $(0.5)(0.2197)(1{,}923\ kg/m^3)(0.67\ m)^2$
= $(95\ kg/m)(9.81\ m/sec^2) = 1{,}229\ N/m$

Dynamic earth force:

F_{ae} = $(0.5)(1 + K_v)(K_{ae})(\gamma)(H)^2$
= $(0.5)(1 + 0)(0.362)(120\ lb/ft^3)(2.54)^2 = 140\ lb/ft$
= $(0.5)(1 + 0)(0.362)(1{,}923\ kg/m^3)(0.77)^2 = 2{,}024.5\ N/m$

Dynamic earth force increment:

$DFdyn$ = $F_{ae} - F_a$
= $140\ lb/ft - 85\ lb/ft = 55\ lb/ft$ = $2{,}024.5\ N/m - 1{,}229\ N/m = 795.5\ N/m$

Resolving the active earth force and the dynamic earth force increment into horizontal and vertical components:

F_{ah} = $(F_a)\cos(\phi_w)$
= $(85\ lb/ft)\cos(20°) = 80\ lb/ft$ = $(1{,}229\ N/m)\cos(20°) = 1{,}155\ N/m$

F_{av} = $(F_a)\sin(\phi_w)$
= $(85\ lb/ft)\sin(20°) = 29\ lb/ft$ = $(1{,}229\ N/m)\sin(20°) = 420\ N/m$

$DFdyn_h$ = $(DFdyn)\cos(\phi_w)$
= $(55\ lb/ft)\cos(20°) = 51.7\ lb/ft$ = $(795.5\ N/m)\cos(20°) = 747.5\ N/m$

$DFdyn_v$ = $(DFdyn)\sin(\phi_w)$
= $(55\ lb/ft)\sin(20°) = 18.8\ lb/ft$ = $(795.5\ N/m)\sin(20°) = 272.1\ N/m$

The next step is to determine the resisting forces:

Sliding Analysis

Weight of the wall facing:

W_f = $(\gamma_{wall})(H)(d)$
= $(130\ lb/ft^3)(2.54\ ft)(0.97\ ft) = 320\ lb/ft$ = $(2{,}061\ kg/m^3)(0.77\ m)(0.296m) = 4{,}608\ N/m$

Maximum frictional resistance to sliding:

F_r = $(W_f + F_{av} + DFdyn_v)\tan(\phi)$
= $(320\ lb/ft + 29\ lb/ft + 18.8\ lb/ft)\tan(30°) = 212.3\ lb/ft$ = $(4{,}608\ N/m + 420\ N/m + 272.1\ N/m)\tan(30°) = 3{,}060\ N/m$

Safety factor against sliding (SFS):

$$SFS_{seismic} = \frac{\text{(Force resisting sliding)}}{\text{(Force driving sliding)}} = \frac{F_r}{F_{ah} + DFdyn_h}$$

$$= \frac{(223 \text{ lb/ft})}{(80 \text{ lb/ft} + 51.7 \text{ lb/ft})} = 1.70 \geq 1.1 \text{ ok}$$

$$= \frac{(3{,}241 \text{ N/m})}{(1{,}155 \text{ N/m} + 747.5 \text{ N/m})} = 1.70 \geq 1.1 \text{ ok}$$

The factor of safety of 1.21 shows that an AB gravity wall during an earthquake in a seismic zone 4 is stable and does not require reinforcement to prevent sliding. As a comparison, the factor of safety in a static condition is the following:

$$SFS_{static} = \frac{\text{(Force resisting sliding)}}{\text{(Force driving sliding)}} = \frac{F_r}{F_{ah}} = \frac{(W_f + F_{av}) \tan \phi}{F_{ah}}$$

$$= \frac{(320 \text{ lb/ft} + 29 \text{ lb/ft}) \tan (30)}{(80 \text{ lb/ft})} = 2.52 \geq 1.5 \text{ ok}$$

$$= \frac{(4{,}608 \text{ N/m} + 420 \text{ N/m}) \tan (30)}{(1{,}155 \text{ N/m})} = 2.52 \geq 1.5 \text{ ok}$$

Overturning Failure Analysis

In seismic analysis, the moments resisting overturning (M_r) must be greater than or equal to 75% of the static requirement for overturning times the moments causing overturning (M_o).

The moments resisting overturning (M_r):

The weight of the wall, the vertical component of the active force, and the vertical component of the dynamic earth increment force contribute to the moment resisting overturning failure of the wall.

$$M_r = (W_f)\,(Wfarm) + (F_{av})\,(Faarm_v) + (DFdyn_v)\,(DFdynarm_v)$$

$$= (W_f)\,[(X_1) + (0.5)\,(H) \tan(\omega)] + F_{av}\,[(L + s) + (0.333)\,(H) \tan(\omega)]$$

$$+ DFdyn_v\,[(L + s) + (0.5)\,(H) \tan(\omega)]$$

$$= (320 \text{ lb/ft})\,[(0.49 \text{ ft}) + (0.5)\,(2.54) \tan(12)] + (29 \text{ lb/ft})\,[(0) + (0.171 \text{ ft})$$

$$+ (0.333)\,(2.54) \tan(12°)] + (18.8 \text{ lb/ft})\,[(0) + (0.171 \text{ ft}) + (0.5)\,(2.54) \tan(12°)]$$

$$= 261.5 \text{ ft-lb/ft}$$

$$= (4{,}608 \text{ N/m})\,[(0.149 \text{ m}) + (0.5)\,(0.77 \text{ m}) \tan(12°)] + (420 \text{ N/m})\,[(0) + (0.053 \text{ m})$$

$$+ (0.333)\,(0.77 \text{ m}) \tan(12°)] + (272.1 \text{ N/m})\,[(0) + (0.053 \text{ m}) + (0.5)\,(0.77 \text{ m}) \tan(12°)]$$

$$= 1{,}147.7 \text{ N-m/m}$$

NOTE: (s = setback per block, L = length of geogrid, X_1 = half the block depth)

The moments causing overturning (M_o):

The horizontal components of the active and dynamic forces contribute to the moment causing overturning failure of the wall.

$$M_o = (F_h)(Faarm_h) + (DFdyn_h)(DFdynarm_h)$$
$$= (F_h)(0.333)(H) + (DFdyn_h)(0.5)(H)$$
$$= (80\ lb/ft)(0.333)(2.54\ ft) + (51.7\ lb/ft)(0.5)(2.54\ ft)$$
$$= 133.3\ ft\text{-}lb/ft$$

$$= (1{,}155\ N/m)(0.333)(0.77\ m) + (747.5\ N/m)(0.5)(0.77\ m)$$
$$= 584.2\ N\text{-}m/m$$

Safety Factor Against Overturning (SFO):

$$SFS_{seismic} = \frac{(\text{Moments resisting overturning})}{(\text{Moments driving overturning})} = \frac{M_r}{M_o} \geq 1.5$$

$$= \frac{(261.5\ ft\text{-}lb/ft)}{(133.3\ ft\text{-}lb/ft)} = 1.96 > 1.5,\ \text{ok}$$

$$= \frac{(1{,}147.7\ N\text{-}m/m)}{(584.2\ N\text{-}m/m)} = 1.96 > 1.5,\ \text{ok}$$

This shows that the gravity wall is adequate with respect to overturning failure. However, if the safety factors were not met, geogrid reinforcement for this wall would be needed to achieve proper factor of safety. Evaluating the wall under static conditions we see that the required factors of safety are also met.

$$M_r = (W_f)(Wfarm) + (F_v)(Faarm_v)$$
$$= (W_f)[(X_1) + (0.5)(H)\tan(\omega)] + (F_v)[(L + s + (0.333)(H)\tan(\omega)]$$
$$= (320\ lb/ft)[(0.49\ ft) + (0.5)(2.54)\tan(12°)] + (29\ lb/ft)[(0) + (0.171\ ft)$$
$$+ (0.333)(2.54)\tan(12°)]$$
$$= 253\ ft\text{-}lb/ft$$

$$= (4{,}608\ N/m)[(0.149\ m) + (0.5)(0.77\ m)\tan(12°)] + (420\ N/m)[(0) + (0.053\ m)$$
$$+ (0.333)(0.77\ m)\tan(12°)]$$
$$= 1{,}108\ N\text{-}m/m$$

$$M_o = (F_h)(Faarm_h)$$
$$= (F_h)(0.333)(H)$$
$$= (80\ lb/ft)(0.333)(2.54\ ft)$$
$$= 68\ ft\text{-}lb/ft$$

$$= (1{,}155\ N/m)(0.333)(0.77\ m)$$
$$= 296\ N\text{-}m/m$$

$$SFO_{static} = \frac{(\text{Moments resisting overturning})}{(\text{Moments driving overturning})}$$

$$= \frac{M_r}{M_o} \geq 2.0$$

$$= \frac{(253\ ft\text{-}lb/ft)}{(68\ ft\text{-}lb/ft)}$$

$$= 3.72 \geq 2.0\ \text{ok}$$

$$= \frac{(1{,}108\ N\text{-}m/m)}{(296\ N\text{-}m/m)}$$

$$= 3.72 \geq 2.0\ \text{ok}$$

COHERENT GRAVITY WALL WITH SEISMIC INFLUENCE

Seismic inertial force (P_{ir})

In the external stability analysis of a geogrid reinforced retaining wall during a seismic event, a seismic inertial force (P_{ir}) is introduced. The seismic inertial force is the sum of the weight components that exert a horizontal inertial force within a reinforced soil mass during a seismic event. The three components exerting this inertial force are the block facing, the reinforced soil mass, and the backslope.

$$P_{ir} = K_{hr} (W_f + W_s + W_i)$$

This force along with the dynamic earth increment force combine with the static earth forces from the retained soil and the weight forces from the wall structure to create the conditions during an earthquake.

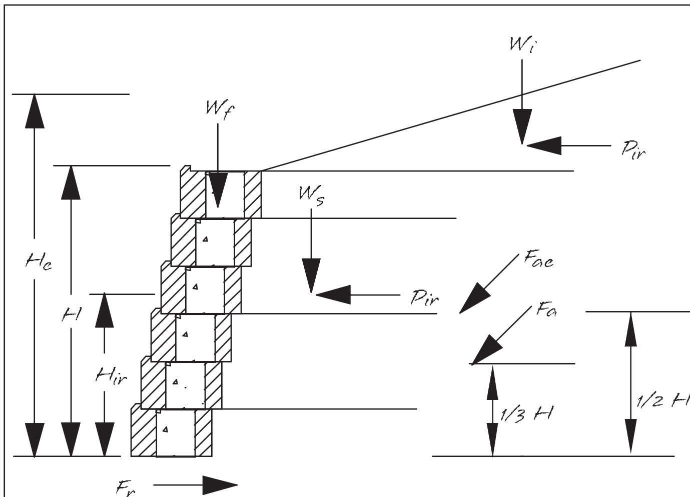

Figure 5-3. Free Body Diagram of a Coherent Gravity Wall Under Seismic Influence

Factor of Safety against Sliding

Calculating the Factor of Safety against Sliding for a coherent gravity wall follows the same stability criteria as a simple gravity wall. The principle being that the forces resisting sliding must be 1.1 times the forces causing sliding (75% of static Factor of Safety). As can be seen below, the formula for calculating the Factor of Safety against Sliding is the same as the gravity wall analysis with the addition of the seismic inertial force (P_{ir}) and the weight of the reinforced soil (W_s).

$$SFS_{seismic} = \frac{Fr_{seismic}}{F_{ah} + DFdyn_h + P_{ir}} \geq 1.1$$

Where:

$$Fr_{seismic} = (F_{av} + DFdyn_v + W_f + W_s) \tan (\phi_i)$$

Factor of Safety against Overturning

The Factor of Safety against Overturning is computed in the same way as a simple gravity wall with the addition of the seismic inertial force (P_{ir}) and the weight of the reinforced soil (W_s). The minimum $SFO_{seismic}$ can be defined as 75% of SFO_{static}.

$$SFO_{seismic} = \frac{M_r}{M_o} = \frac{(W_f)(Wfarm) + (W_s)(Wsarm) + (F_{av})(Faarm_v) + (DFdyn_v)(DFdynarm_v)}{(F_{ah})(Faarm_h) + (DFdyn_h)(DFdynarm_h) + (P_{ir})(H_{ir})} \geq 1.5$$

Example 5-3:

Given:

ϕ_i	=	ϕ_r = 30°	β	=	78°	F_a	=	1,362 lb/ft (19,884 N/m)
W_i	=	0 lb/ft	ω	=	$(90 - \beta)$ = 12°	DFdyn	=	879 lb/ft (12,850 N/m)
i	=	0°	Ka_i	=	0.2197	W_f	=	1,243 lb/ft (18,147 N/m)
d	=	2 in (51 mm)	Ka_r	=	0.2197	W_s	=	6,345 lb/ft (92,632 N/m)
A_o	=	0.4	Kae_i	=	0.362	W_s'	=	5,219 lb/ft (76,269 N/m)
H	=	10.16 ft (3.10 m)	Kae_r	=	0.362	γ_{wall}	=	130 lb/ft³ (2,061 kg/m³)
ϕ_w	=	$\phi_{wi} = \phi_{wr}$ = 2/3(ϕ) = 20°	Grid Lengths	=	6 ft (1.82 m)	H_{ir}	=	5.08 ft (1.548 m)
γ	=	$\gamma_i = \gamma_r$ = 120 lb/ft³ (1,923 kg/m³)						

Find:

The safety factor against sliding and overturning.

Factor of Safety Against Sliding Analysis

Based on the given information, we must first determine the frictional resistance to sliding (F_r).

$$F_r = (F_{av} + DFdyn_v + W_f + W_s)\tan(\phi)$$
$$= [(1{,}362 \text{ lb/ft})\sin(20°) + (879 \text{ lb/ft})\sin(20°) + 1{,}243 \text{ lb/ft} + 6{,}345 \text{ lb/ft}]\tan(30°)$$
$$= 4{,}823 \text{ lb/ft}$$

$$= [(19{,}884 \text{ N/m})\sin(20°) + (12{,}850 \text{ N/m})\sin(20°) + 18{,}147 \text{ N/m} + 92{,}632 \text{ N/m}]\tan(30°)$$
$$= 70{,}437 \text{ N/m}$$

Next, the seismic inertial force is calculated:

$$P_{ir} = K_{hr}(W_f + W_s' + W_i)$$

Since,

d = 2 in (51 mm)

$$K_{hr} = (0.74)(A_o)\left(\frac{(A_o)(1 \text{ in})}{d}\right)^{0.25} \qquad = (0.74)(A_o)\left(\frac{(A_o)(25.4 \text{ mm})}{d}\right)^{0.25}$$

$$= (0.74)(0.4)\left(\frac{(0.4)(1 \text{ in})}{2 \text{ in}}\right)^{0.25} \qquad = (0.74)(0.4)\left(\frac{(0.4)(25.4 \text{ mm})}{51 \text{ mm}}\right)^{0.25}$$

$$= 0.198 \qquad = 0.198$$

$$P_{ir} = 0.198\,(1{,}243 \text{ lb/ft} + 5{,}219 \text{ lb/ft} + 0) = 1{,}279 \text{ lb/ft}$$

$$= 0.198\,(18{,}147 \text{ N/m} + 76{,}269 \text{ N/m} + 0) = 18{,}694 \text{ N/m}$$

Finally, the safety factor against sliding can be calculated:

$$SFS_{seismic} = \frac{\text{(Forces resisting sliding)}}{\text{(Forces driving sliding)}} = \frac{F_r}{F_{ah} + DFdyn_h + P_{ir}} \geq 1.1$$

$$= \frac{(4{,}823 \text{ lb/ft})}{(1{,}362 \text{ lb/ft})\cos 20° + (879 \text{ lb/ft})\cos 20° + 1{,}279 \text{ lb/ft}} = 1.42 \geq 1.1 \text{ ok}$$

$$= \frac{(70{,}437 \text{ N/m})}{(19{,}884 \text{ N/m})\cos 20° + (12{,}850 \text{ N/m})\cos 20° + 18{,}694 \text{ N/m}} = 1.42 \geq 1.1 \text{ ok}$$

Comparing the seismic SFS to the static SFS below, we again see much higher safety values for static.

$$SFS_{static} = \frac{\text{(Forces resisting sliding)}}{\text{(Forces driving sliding)}} = \frac{F_r}{F_{ah}} = \frac{F_r - (DFdyn_v)\tan\phi}{(F_a)\cos(\phi_w)}$$

$$= \frac{(4{,}823\ \text{lb/ft}) - (173.6\ \text{lb/ft})}{(1{,}362\ \text{lb/ft})\cos 20°} = 3.63 \geq 1.5\ \text{ok}$$

$$= \frac{(70{,}437\ \text{N/m}) - (2{,}537\ \text{N/m})}{(19{,}889\ \text{N/m})\cos 20°} = 3.63 \geq 1.5\ \text{ok}$$

Factor of Safety Against Overturning Analysis

The safety factor against overturning is equal to the moments resisting overturning divided by the moments driving overturning (M_r / M_o) and must be greater than or equal to 1.5 (75% of SFO_{static}).

The moments resisting overturning (M_r):

$$M_r = (W_t)(Wt_{arm}) + (F_{av})(Faarm_v) + (DFdyn_v)(DFdynarm_v)$$

Where: $W_t = W_s + W_f$

$$= (W_t)[0.5(L + s) + (0.5)(H)\tan(\omega)] + F_{av}[(L + s) + (0.333)(H)\tan(\omega)]$$
$$+ DFdyn_v[(L + s) + (0.5)(H)\tan(\omega)]$$

$$= (7{,}588\ \text{lb/ft})[0.5(6.0\ \text{ft} + 0.171\ \text{ft}) + (0.5)(10.16\ \text{ft})\tan(12°)]$$
$$+ [(1{,}362\ \text{lb/ft})\sin 20°]\ [6.0\ \text{ft} + 0.171\ \text{ft} + (0.333)(10.16\ \text{ft})\tan(12°)]$$
$$+ [(879\ \text{lb/ft})\sin(20°)]\ [6.0\ \text{ft} + 0.171\ \text{ft} + (0.5)(10.16\ \text{ft})\tan(12°)]$$
$$= 37{,}002\ \text{ft-lb/ft}$$

$$= (110{,}778\ \text{N/m})[0.5(1.82\ \text{m} + 0.053\ \text{m}) + (0.5)(3.10\ \text{m})\tan(12°)]$$
$$+ [(19{,}884\ \text{N/m})\sin 20°][1.82\ \text{m} + 0.053\ \text{m} + (0.333)(3.10\ \text{m})\tan(12°)]$$
$$+ [(12{,}850\ \text{N/m})\sin(20°)][1.82\ \text{m} + 0.053\ \text{m} + (0.5)(3.10\ \text{m})\tan(12°)]$$
$$= 164{,}788\ \text{N-m/m}$$

The moments driving overturning (M_o):

$$M_o = (F_{ah})(Faarm_h) + (DFdyn_h)(DFdynarm_h) + (P_{ir})(H_{ir})$$
$$= (F_{ah})(0.333)(H) + (DFdyn_h)(0.5)(H) + (P_{ir})(5.08\ \text{ft})$$

$$= [(1{,}362\ \text{lb/ft})\cos(20°)](0.333)(10.16\ \text{ft}) + [(879\ \text{lb/ft})\cos(20°)](0.5)(10.16\ \text{ft}) + 1{,}279\ \text{lb/ft}\ (5.08\ \text{ft})$$
$$= 15{,}023\ \text{ft-lb/ft}$$

$$= [(19{,}884\ \text{N/m})\cos(20°)](0.333)(3.10\ \text{m}) + [(12{,}850\ \text{N/m})\cos(20°)](0.5)(3.10\ \text{m}) + 18{,}694\ \text{N/m}\ (1.548\ \text{m})$$
$$= 66{,}943\ \text{N-m/m}$$

Safety Factor Against Overturning (SFO):

$$SFO_{seismic} = \frac{\text{(Moments resisting overturning)}}{\text{(Moments driving overturning)}} = \frac{M_r}{M_o} \geq 1.5$$

$$= \frac{(37{,}002\ \text{ft-lb/ft})}{(15{,}023\ \text{ft-lb/ft})} = 2.46 \geq 1.5\ \text{ok}$$

$$= \frac{(164{,}788\ \text{N-m/m})}{(66{,}943\ \text{N-m/m})} = 2.46 \geq 1.5\ \text{ok}$$

Comparing the seismic (SFO) to the below static (SFO):

$M_r = (W_t)(Wt_{arm}) + (F_{av})(F_{aarm})$

Where: $W_t = W_s + W_f$

$= (W_t)[0.5(L + s) + (0.5)(H)\tan(\omega)] + (F_{av})[(L + s) + (0.333)(H)\tan(\omega)]$

$= (7{,}588 \text{ lb/ft})[0.5(6.0 \text{ ft} + 0.171 \text{ ft}) + (0.5)(10.16 \text{ ft})\tan(12°)]$
$+ [(1{,}362 \text{ lb/ft})\sin 20°][(6.0 \text{ ft} + 0.171 \text{ ft}) + (0.333)(10.16 \text{ ft})\tan(12°)]$
$= 34{,}821$ ft-lb/ft

$= (110{,}778 \text{ N/m})[0.5(1.82 \text{ m} + 0.053 \text{ m}) + (0.5)(3.10 \text{ m})\tan(12°)]$
$+ [(19{,}884 \text{ N/m})\sin 20°][(1.82 \text{ m} + 0.053 \text{ m}) + (0.333)(3.10 \text{ m})\tan(12°)]$
$= 145{,}909$ N-m/m

$M_o = (F_{ah})(Faarm_h)$
$= (F_{ah})(0.333)(H)$
$= [(1{,}362 \text{ lb/ft})\cos(20°)](0.333)(10.16 \text{ ft})$
$= 4{,}334$ ft-lb/ft

$= [(19{,}884 \text{ N/m})\cos(20°)](0.333)(3.10 \text{ m})$
$= 18{,}161$ N-m/m

$$SFO_{static} = \frac{\text{(Moments resisting overturning)}}{\text{(Moments driving overturning)}} = \frac{M_r}{M_o}$$

$$= \frac{(34{,}821 \text{ ft-lb/ft})}{(4{,}334 \text{ ft-lb/ft})} = 8.0 \geq 2.0 \text{ ok}$$

$$= \frac{(145{,}909 \text{ N-m/m})}{(18{,}161 \text{ N-m/m})} = 8.0 \geq 2.0 \text{ ok}$$

Internal Stability

The factor of safety checks for the internal stability of a geogrid reinforced retaining wall under seismic conditions include the geogrid overstress, geogrid / block connection strength, geogrid pullout from the soil, and localized or top of the wall stability. These calculations are identical to those for a static stability analysis with the exception of the seismic forces introduced which affect the tensile loading on the geogrid.

Factor of Safety Geogrid Tensile Overstress

In order to calculate the Factor of Safety for Geogrid Tensile Overstress, the tensile force on each grid must first be determined. In a seismic event, the sum of the active force (F_a), the dynamic earth force increment ($DFdyn_i$), and the seismic inertial force (P_{ir}) represent the tensile force on each layer of geogrid.

$F_{id_i} = F_{a_i} + DFdyn_i + P_{ir_i}$

Where:

$F_{a_i} = (K_a)\cos(\phi_w)(\gamma)(Ac_i)(0.5)$

$DFdyn_i = (0.5)(H_{ei})(K_{ae} - K_a)\cos(\phi_w)(\gamma)(Ac_i)$

NOTE: This equation comes directly from the NCMA SRW Design Manual (3rd Edition) and can be referred to as the trapezoidal method.

Ac_i = The tributary influence area on each grid layer.

and

$P_{ir_i} = (K_h)(\gamma)(Ac_i)$

AASHTO or FHWA projects often use the active wedge method to determine DFdyn.

$$DFdyn_i = (K_h)(WA)\left(\frac{Ac_i}{H_e}\right)$$

AB Walls 2007 allows the user to choose either method but is defaulted to use the greater of the two.

We have used full scale seismic testing to determine that the internal seismic pressure closely matches a rectangle shape where the load is evenly distributed between the grid layers relative to their tributary area. This gives values that are not only more accurate, but are easier to design with. This load value is determined by the soil weight based on either the trapezoidal method shown in Figure 5-4 or by the active wedge method shown in Figure 5-5.

The angle of inclination (αi) of the Coulomb failure surface for the active wedge method:

$$\alpha i = \text{atan}\left[\frac{-\tan(\phi i - i) + \sqrt{[\tan(\phi i - i)(\tan(\phi i - i) + \cot(\phi i + \omega))(1 + \tan(\phi_w - \omega)\cot(\phi i + \omega))]}}{1 + \tan(\phi_w - \omega)(\tan(\phi i - i) + \cot(\phi i + \omega))}\right] + \phi i$$

Determine the Factor of Safety against Tensile Overstress:

$$FS_{overstress} = \frac{(LTADS)(RF_{cr})}{F_{id}}$$

In the calculation of the Factor of Safety Geogrid Tensile Overstress for a seismic event, we do not take a reduction of the geogrid ultimate strength for long-term creep. This is due to the short-term loading during a seismic event.

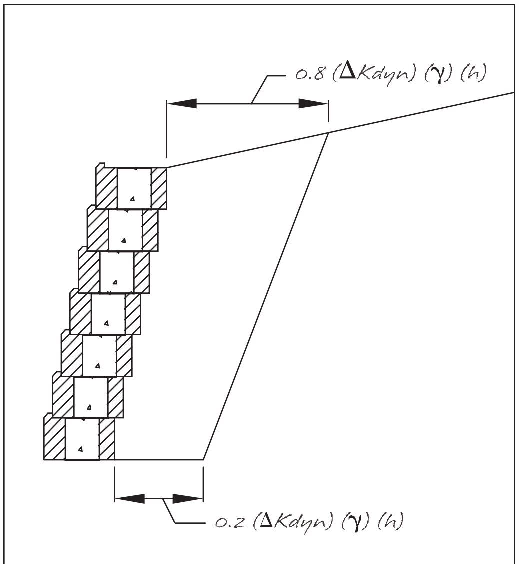

Figure 5-4. Trapezoidal Method

Geogrid / Block Connection Capacity

The Factor of Safety for Connection Strength is equal to the peak connection strength divided by the tensile force on that layer of grid multiplied by 0.666. We take the reduction on the tensile force due to the reality that some of the tensile force is absorbed by the soil in the influence area.

$$FS_{conn} = \frac{F_{cs}}{F_{id}\,(0.667)} \geq 1.1$$

Geogrid Pullout from the Soil

The Factor of Safety for Geogrid Pullout from the Soil is:

$$FS_{pullout} = \frac{F_{gr}}{F_{id}} \geq 1.1$$

where,

$$F_{gr} = 2\,(d_g)\,(\gamma)\,(L_e)\,(C_i)\tan(\phi)$$

The above pullout capacity equation takes into account the geogrid interaction coefficient (C_i) and is calculated based on the length of geogrid embedded beyond the line of maximum tension (L_e).

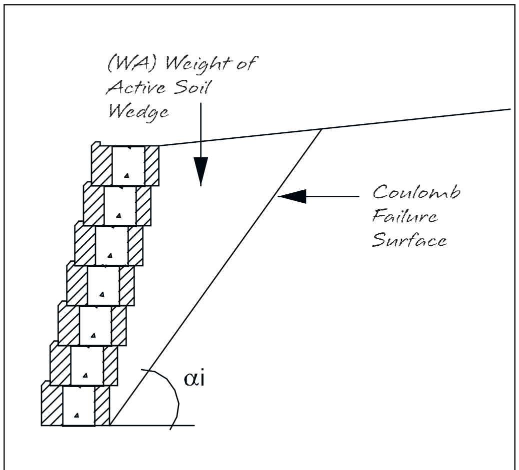

Figure 5-5. Active Wedge Method

Localized Stability, Top of the Wall

To determine local or top of the wall stability (SFS and SFO), the wall parameters and soils forces in the unreinforced portion of the retaining wall are focused on. The unreinforced height of the wall (H_t) is simply the total height of the wall minus the elevation at which the last grid layer is placed. The local weight of the facing is:

$$W_f = (H_t)\,(t)\,(\gamma_{wall})$$

The local sliding resistance (F_r) is an equation based on the Allan Block shear strength, which was developed through empirical test data and is a function of the normal load acting at that point and is the following:

$$F_r = 2{,}671 \text{ lb/ft} + (W_f)\tan(38°) \qquad = 38{,}900 \text{ N/m} + (W_f)\tan(38°)$$

The soil and surcharge forces are as follows:

Active Force: $F_a = (0.5) (K_a) (\gamma) (H_t)^2$

Dynamic Force: $F_{ae} = (0.5) (1 + K_v) (K_{ae}) (\gamma) (H_t)^2$

Dynamic Earth Force Infrement: $DFdyn = F_{ae} - F_a$

Seismic Inertial Force: $P_{ir} = (K_h) (W_f)$

Finally, the safety factor equations are:

$$SFS_{localstatic} = \frac{F_r}{(F_a) \cos (\phi_w)} \geq 1.5$$

$$SFS_{localseismic} = \frac{F_r}{(F_a + DFdyn + P_{ir}) \cos (\phi_w)} \geq 1.1$$

$$SFO_{localstatic} = \frac{W_f \, [(H_t/2) \tan \omega + t/2] + (F_a) \sin (\phi_w) \, [(H_t/3) \tan \omega + t]}{(F_a) \cos (\phi_w) (H_t/3)} \geq 2.0$$

$$SFO_{localseismic} = \frac{W_f \, [(H_t/2) \tan \omega + t/2] + (F_a) \sin (\phi_w) \, [(H_t/3) \tan \omega + t] + (DFdyn) \sin (\phi_w) (0.5 H_t + t)}{(F_a) \cos (\phi_w) (H_t/3) + (DFdyn) \cos (\phi_w) (0.5 H_t) + P_{ir} (H_t/2)}$$

$$\geq 1.5$$

NOTE: Verify local requirements for static and seismic Factors of Safety.

Maximum Allowable Slopes in Seismic Conditions

The Mononobe-Okabe soil mechanics theory gives designers the seismic earth pressure coefficient (K_{ae}) to apply to their retaining wall by combining the effects of soil strength (ϕ_r), weighted friction angle (ϕ_w), slope above the wall (i), wall setback (ω), and seismic inertia angle (θ_r). This equation becomes limited by its mathematics when low strength soils, steep slopes, and high seismic accelerations are combined. This may be translated to say that for specific combinations of slope angles, soil strength and seismic acceleration the project changes from a segmental retaining wall design to a slope stability problem. With a closer look at these three limiting variables the maximum allowable slope in seismic conditions is:

$$i_{max} = \phi_r - \theta_r$$

See reference: Engineering Implications of the Relation between Static and Pseudo-Static Slope Stability Analysis, Robert Shukha, Rafael Baker and Dov Leshchinsky, EJGE Paper 2005-616)

PHI	A_o	Maximum Allowable Slope
34	0.2	30.1
34	0.4	24.7
32	0.2	28.1
32	0.4	22.7
30	0.2	26.1
30	0.4	20.7
28	0.2	24.1
28	0.4	18.7

For slopes that are planned to exceed the maximum allowable value, the M-O equation does not provide for accurate loading values and therefore does not accurately evaluate pseudo-static loading. We recommend consulting a geotechnical engineer for a more in depth analysis and possible solutions.

This technical specification manual will allow a wall designer to source and reference specific information for use in developing project documents. The information shown here is for use with Allan Block products only. Visit allanblock.com for the most current information.

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