Earth Pressure Theory

Thursday, March 11, 2010
11:43 AM

Examples of Retaining Walls

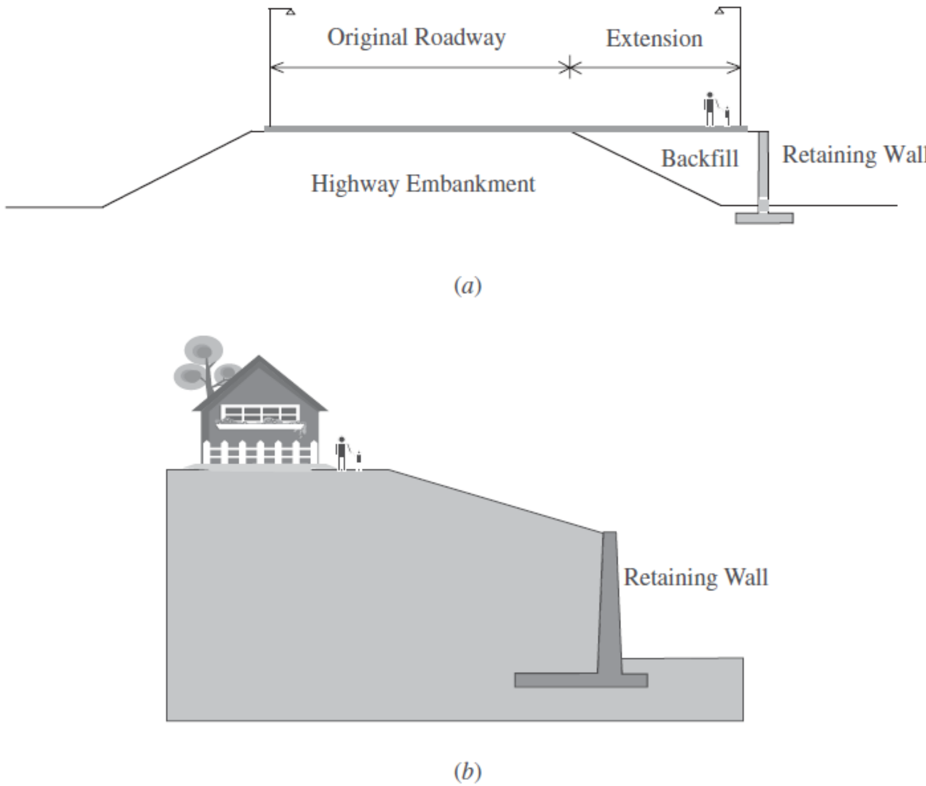
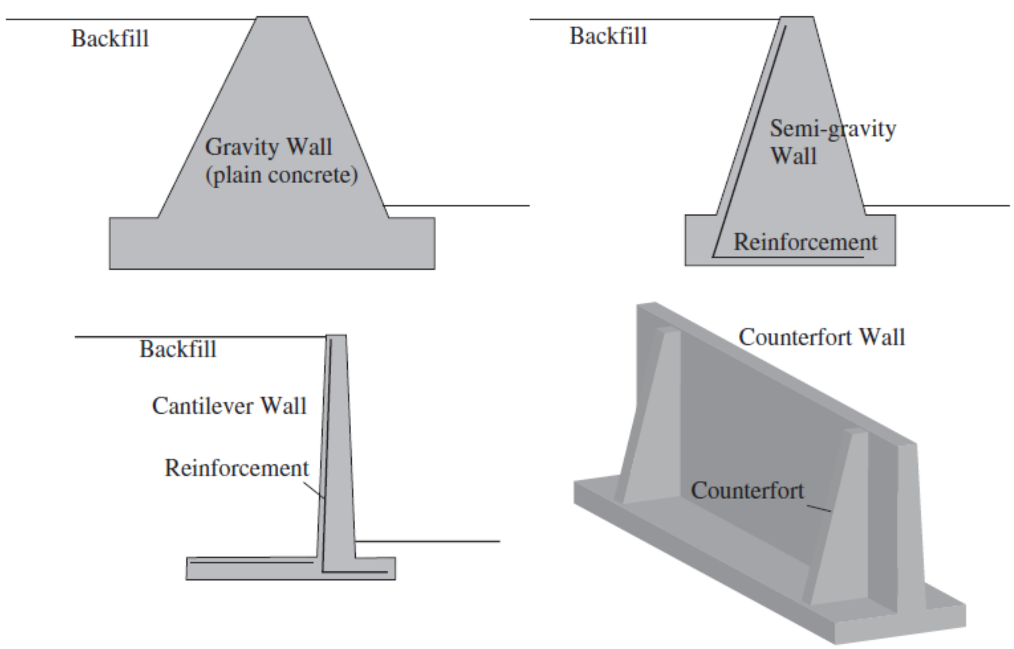


FIGURE 7.1 Retaining walls.



At-Rest, Active and Passive Earth Pressure

Wednesday, August 17, 2011
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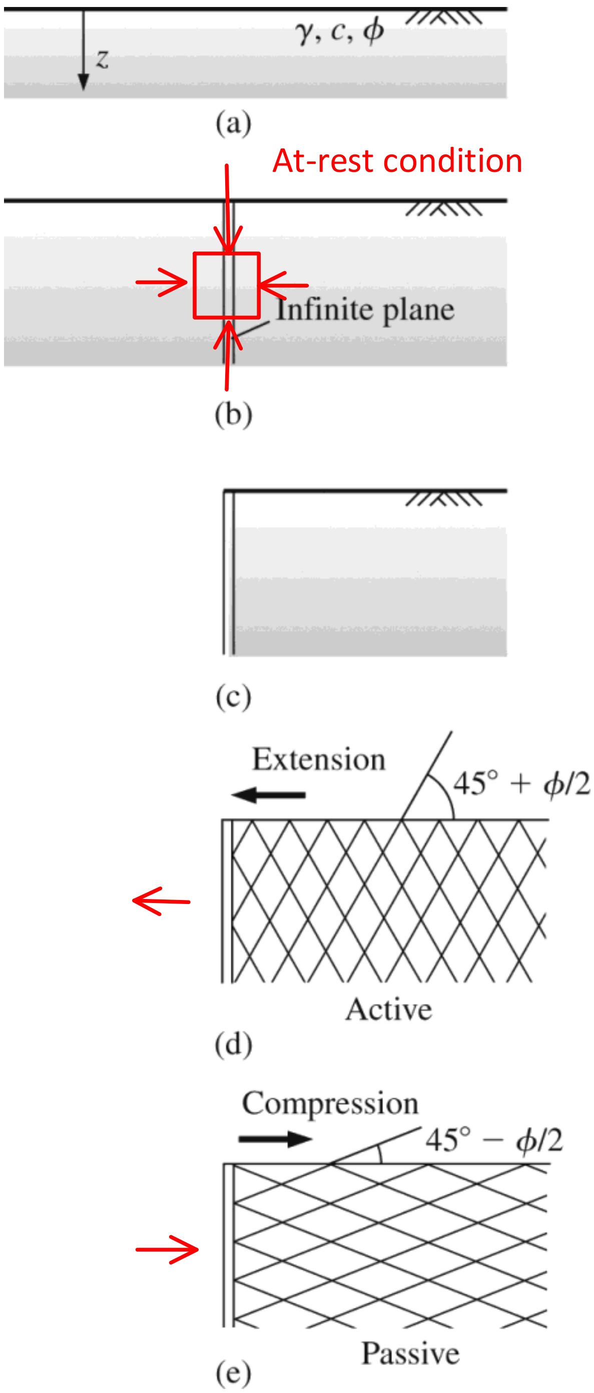


At-rest earth pressure:

a. Shear stress are zero.
b. $\sigma_V = \sigma_1$
c. $\sigma_H = \sigma_3$
d. $\sigma_H = K_o\sigma_1$
e. $K_0 = 1 - \sin\phi$ (Normally consolidated
f. $K_0 = (1 - \sin\phi)\ OCR^{-1/2}$
g. $OCR = \sigma'_{vp}/\sigma'_v$
h. $K_0 = \nu / (1-\nu)$

Let us assume that:

a) wall is perfectly smooth (no shear stress develop on the interface between wall and the retained soil)
b) no sloping backfill
c) back of the wall is vertical
d) retained soil is a purely frictional material (c=0)

At-Rest, Active and Passive Earth Pressure (cont.)

Thursday, March 11, 2010
11:43 AM

Earth pressure is the lateral pressure exerted by the soil on a shoring system. It is dependent on the soil structure and the interaction or movement with the retaining system. Due to many variables, shoring problems can be highly indeterminate. Therefore, it is essential that good engineering judgment be used.

At-Rest Earth Pressure

At rest lateral earth pressure, represented as K_0, is the *in situ* horizontal pressure. It can be measured directly by a dilatometer test (DMT) or a borehole pressure meter test (PMT). As these are rather expensive tests, empirical relations have been created in order to predict at rest pressure with less involved soil testing, and relate to the angle of shearing resistance. Two of the more commonly used are presented below.

Jaky (1948) for normally consolidated soils:

$$K_{0(NC)} = 1 - \sin \phi'$$

Mayne & Kulhawy (1982) for overconsolidated soils:

$$K_{0(OC)} = K_{0(NC)} * OCR^{(\sin \phi')}$$

The latter requires the OCR profile with depth to be determined

Pasted from <http://en.wikipedia.org/wiki/Lateral_earth_pressure>

Earth Pressure Theory (cont)

Thursday, March 11, 2010
11:43 AM

The at-rest earth pressure coefficient (K_o) is applicable for determining the in situ state of stress for undisturbed deposits and for estimating the active pressure in clays for systems with struts or shoring. Initially, because of the cohesive property of clay there will be no lateral pressure exerted in the at-rest condition up to some height at the time the excavation is made. However, with time, creep and swelling of the clay will occur and a lateral pressure will develop. This coefficient takes the characteristics of clay into account and will always give a positive lateral pressure. This method is called the Neutral Earth Pressure Method and is covered in the text by Gregory Tschebotarioff. This method can be used in FLAC to establish the at-rest condition in the numerical model.

$$K_o = \frac{v}{1 - v}$$

v = The Poisson's Ratio. It is determined by a Laboratory test (Maximum value = 0.5)

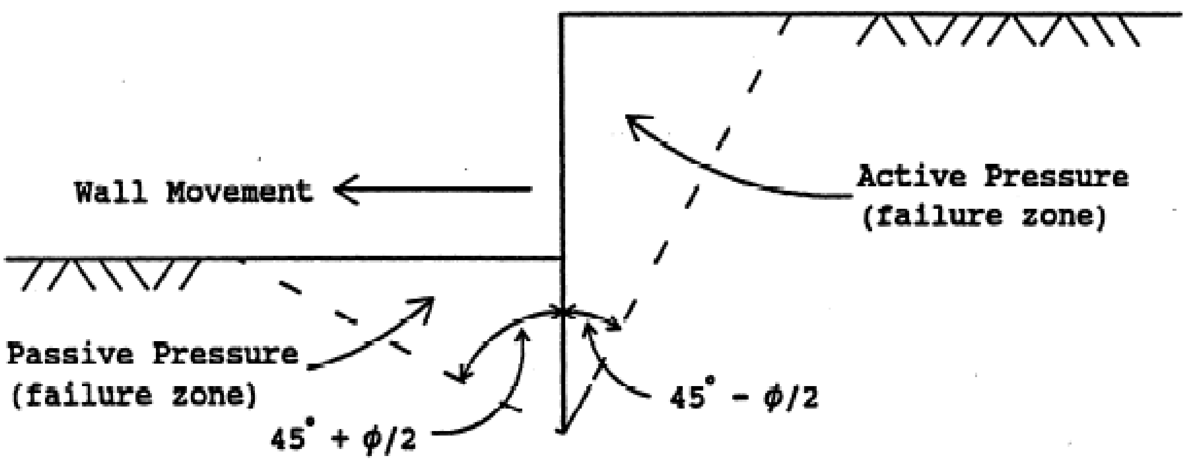
A Poisson's ratio of 0.5 means that there is no volumetric change during shear (i.e., completely undrained behavior).

Soil Type	Typical Value for Poisson's Ratio *	K_o
Clay, saturated	0.40 - 0.50	0.67 - 1.00
Clay, unsaturated	0.10 - 0.30	0.11 - 0.42
Sandy Clay	0.20 - 0.30	0.25 - 0.42
Silt	0.30 - 0.35	0.42 - 0.54
Sand		
Dense	0.20 - 0.40	0.25 - 0.67
Coarse		
(void ratio 0.4 - 0.7)	0.15	0.18
Fine-grained		
(void ratio 0.4 - 0.7)	0.25	0.33
Rock	0.10 - 0.40	0.11 - 0.67

Active and Passive Cases

Thursday, March 11, 2010
11:43 AM

Active and passive earth pressures are the two stages of stress in soils which are of particular interest in the design or analysis of shoring systems. Active pressure is the condition in which the earth exerts a force on a retaining system and the members tend to move toward the excavation. Passive pressure is a condition in which the retaining system exerts a force on the soil. Since soils have a greater passive resistance, the earth pressures are not the same for active and passive conditions. When a state of oil failure has been reached, active and passive failure zones, approximated by straight planes, will develop as shown in the following figure (level surfaces depicted).



Rankine Theory - Active and Passive Cases

Thursday, March 11, 2010
11:43 AM

The Rankine theory assumes that there is no wall friction and the ground and failure surfaces are straight planes, and that the resultant force acts parallel to the backfill slope (i.e., no friction acting between the soil and the backfill). The coefficients according to Rankine's theory are given by the following expressions:

$$K_a = \cos\beta \left[\frac{\cos\beta - [\cos^2\beta - \cos^2\phi]^{1/2}}{\cos\beta + [\cos^2\beta - \cos^2\phi]^{1/2}} \right]$$

$$K_p = \cos\beta \left[\frac{\cos\beta + [\cos^2\beta - \cos^2\phi]^{1/2}}{\cos\beta - [\cos^2\beta - \cos^2\phi]^{1/2}} \right]$$

If the backslope of the embankment behind the wall is level (i.e., $\beta = 0$) the equations are simplified as follows:

$$K_a = \frac{1 - \sin\phi}{1 + \sin\phi} = \tan^2(45^\circ - \phi/2)$$

$$K_p = \frac{1 + \sin\phi}{1 - \sin\phi} = \tan^2(45^\circ + \phi/2)$$

The Rankine formula for passive pressure can only be used correctly when the embankment slope angle equals zero or is negative. If a large wall friction value can develop, the Rankine Theory is not correct and will give less conservative results. Rankine's theory is not intended to be used for determining earth pressures directly against a wall (friction angled does not appear in equations above).
The theory is intended to be used for determining earth pressures on a vertical plane within a mass of soil.

Rankine Theory - Active Case and Displacements

Thursday, March 11, 2010
11:43 AM

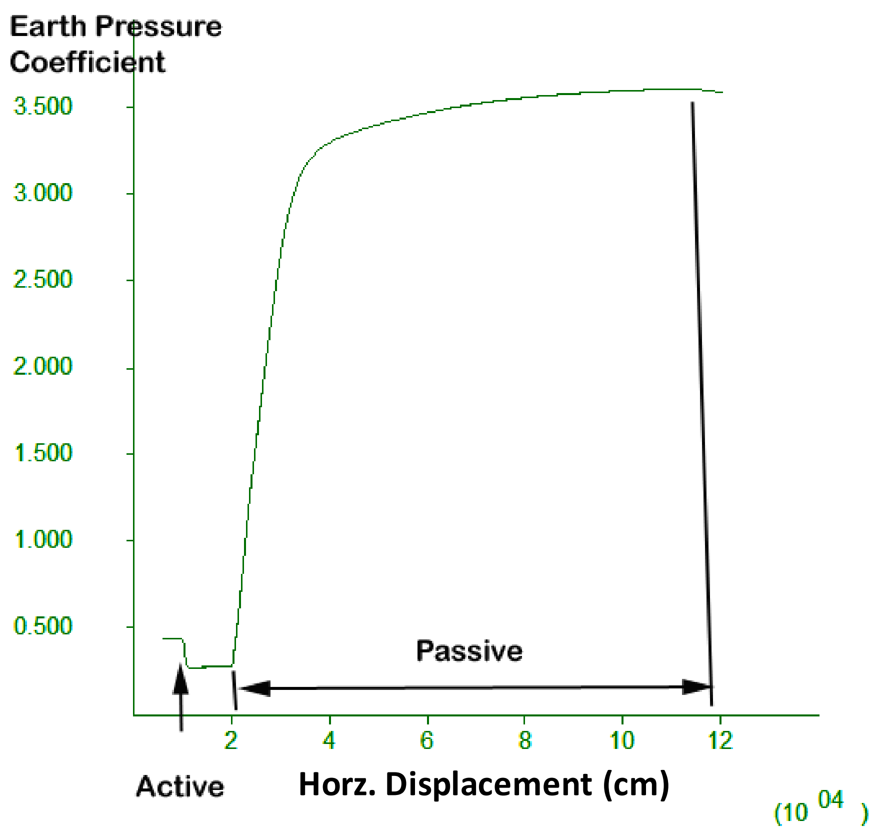
MOVEMENT OF WALL NECESSARY TO PRODUCE ACTIVE PRESSURES

Soil Type	Wall Yield
Cohesionless, dense	0.001 H
Cohesionless, loose	0.001 - 0.002 H
Clay, firm	0.010 - 0.020 H
Clay, soft	0.020 - 0.050 H

* New Zealand Department of Public Works Retaining Wall Manual

H = height of wall

The amount of displacement to mobilize full passive resistance is about 10 times larger than active (see below).



Coulomb Theory

Thursday, March 11, 2010
11:43 AM

Coulomb theory provides a method of analysis that gives the resultant horizontal force on a retaining system for any slope of wall, wall friction, and slope of backfill provided This theory is based on the assumption that soil shear resistance develops along the wall and failure plane. The following coefficient is for a resultant pressure acting at angle δ.

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

The passive K_p value for sloping embankment is not listed since this value can be drastically overestimated.

The following coefficients are for a horizontal resultant pressure and a vertical wall:

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

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

δ is the interface friction angle between the soil and the backwall.
β is the angle of the backslope

Interface Friction Angles and Adhesion

Thursday, March 11, 2010
11:43 AM

Wall friction angle (δ) varies from 0° to 22°, but is always less than the internal angle of friction of the soil (ϕ). It is accepted practice to assume a value of δ = 1/3(ϕ) to 2/3(ϕ). For systems subject to dynamic loading (adjacent railroads, pile driving operations, etc.) use δ= 0. It is important to note that as wall friction increases, lateral pressures decrease, but the vertical load on the shoring system increase. Vertical load components must be considered in shoring design. TABLE 14 lists friction of select soil types acting against various structural materials.

Interface Friction Angles and Adhesion

Thursday, March 11, 2010
11:43 AM

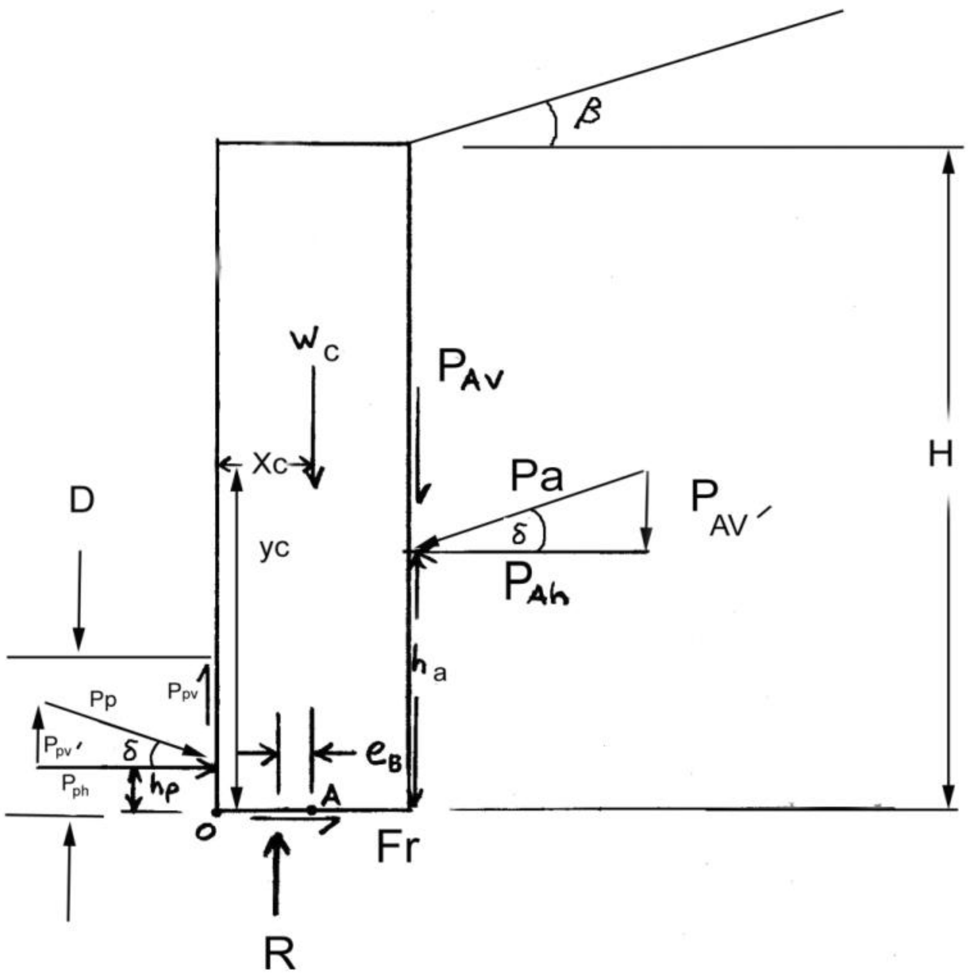
ULTIMATE FRICTION FACTORS AND ADHESION FOR DISSIMILAR MATERIALS

INTERFACE MATERIALS	FRICTION ANGLE, δ DEGREES
Steel sheet piles against the following soils:	
Clean gravel, gravel-sand mixtures, well-graded rock fill with spalls	22
Clean sand, silty sand-gravel mixture, single size hard rock fill	17
Silty sand, gravel or sand mixed with silt or clay	14
Fine sandy silt, nonplastic silt	11
Formed concrete or concrete sheet piling aginst the following soils:	
Clean gravel, gravel-sand mixture, well-graded rock fill with spalls	22 to 26
Clean sand, silty sand-gravel mixture, single size hard rock fill	17 to 22
Silty sand, gravel or sand mixed with silt or clay	17
Fine sandy silt, nonplastic silt	14
Mass concrete on the following materials:	
Clean sound rock	35
Clean gravel, gravel-sand mixtures, coarse sand	29 to 31
Clean fine to medium sand, silty medium to coarse sand, silty or clayey gravel	24 to 29
Clean fine sand, silty or clayey fine to medium sand	19 to 24
Fine sandy silt, nonplastic silt	17 to 19
Very stiff and hard residual or preconsolidated clay	22 to 26
Medium stiff and stiff clay and silty clay	17 to 19
(Masonry on foundation materials has same friction factors.)	
Various structural materials:	
Masonry on masonry, ingneous and metamorphic rocks:	
Dressed soft rock on dressed soft rock	35
Dressed hard rock on dressed soft rock	33
Dressed hard rock on dressed hard rock	29
Masonry on wood (cross grain)	26
Steel on steel at sheet pile interlocks	17

INTERFACE MATERIALS (COHESION)	ADHESION C_a (PSF)
Very soft cohesive soil (0 - 250 psf)	0 - 250
Soft cohesive soil (250 - 500 psf)	250 - 500
Medium stiff cohesive soil (500 - 1000 psf)	500 - 750
Stiff cohesive soil (1000 - 2000 psf)	750 - 950
Very stiff cohesive soil (2000 - 4000 psf)	950 - 1,300

Gravity Wall Design

Thursday, March 11, 2010
11:43 AM



Wall Dimensions				**Fill Properties**			
Top	3	ft		$\beta_{backfill}$ deg	20	0.349	radians
Bottom	3	ft		β_{toe} deg	0	0.000	radians
$\gamma_{concrete}$	150	pcf		φ deg	40	0.698	radians
H	10	ft		δ deg	20	0.349	radians
D	2	ft		$Q_{backwall}$ deg	0	0.000	radians
				$Q_{frontwall}$ deg	0	0.000	radians
x_c	1.500	ft		$\gamma_{backfill}$	100		pcf
y_c	5.000	ft					

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Gravity Wall Design (cont.)

Thursday, March 11, 2010
11:43 AM

Earth Pressures	Coulomb Theory			
K_A	0.2504			
K_P	11.7715			
Forces				
Pa	1252.1	lb/ft		
P_{ah}	1176.6	lb/ft		
$P_{av'}$	428.2	lb/ft		
P_{av}	428.2	lb/ft		
W_c	4500	lb/ft		
R	4928.2	lb/ft	$W_c + P_{av'}$	
F_r	4135.3	lb/ft	R tan (d or f)	
0.5Pp	1177.1	lb/ft	(half of P_p)	
P_{ph}	1106.16	lb/ft		
$P_{pv'}$	402.6	lb/ft		
P_{pv}	402.6	lb/ft		

Resisting Moments on Wall		
P_{av} * B	1284.7	
P_{ph} * D/3	737.4	
W_c * x_c	6750	
SM_r	**8772.2**	
Overturning Moments on Wall		
P_{ah} * h_a	**3921.9**	
SM_o	**3921.9**	
Factors of Safety		
$FS_{sliding}$	**4.455**	
FS_{oturn}	**2.237**	

Building Systems Incrementally

Thursday, March 11, 2010
11:43 AM

For multilayer systems or systems constructed in lifts or layers, it is sometimes preferable to place each layer and allow FLAC to come to equilibrium under the self weight of the layer before the next layer is placed.

This incremental placement approach is particularly useful when trying to determine the initial state of stress in multilayered systems with marked differences in stiffness (e.g., pavements).

It can also be used to replicate the construction process or to determine how the factor of safety may vary versus fill height when analyzing embankments or retaining wall.

This approach is shown in the following pavement system example

Note this approach is not required for homogenous media.

Building Systems Incrementally (cont.)

Thursday, March 11, 2010
11:43 AM

```
;flac 1 - incremental loading
config
grid 17,15
model mohr
gen same 0 20 10 20 same i 1 11 j 1 6
gen same 0 25 10 25 same i 1 11 j 6 11
gen same 0 30 10 30 same i 1 11 j 11 16
gen same same 38 20 38 0 i 11 18 j 1 6
gen same same 38 25 same i 11 18 j 6 11
gen same same 38 30 same i 11 18 j 11 16
mark j 6 ; marked to determine regions
mark j 11 ;marked to determine regions
prop density=2160.5 bulk=133.33E6 shear=44.4444E6 cohesion=0 friction=35.0 reg i 2 j 2 ; region
command
prop density=2400.5 bulk=41.67E6 shear=19.23E6 cohesion=25e3 friction=25.0 reg i 2 j 8
prop density=2240.5 bulk=833.33E6 shear=384.6E6 cohesion=0 friction=30.0 reg i 2 j 12
set gravity=9.81
fix x i=1
fix x i=18
fix y j=1
his unbal
; nulls out top two layers
model null reg i 2 j 8 ; second layer
model null reg i 2 j 12 ; third layer
step 2000 ; solves for stresses due to first layer
model mohr reg i 2 j 8; assign properties to 2nd layer
prop density=2400.5 bulk=41.67E6 shear=19.23E6 cohesion=25e3 friction=25.0 reg i 2 j 8
step 2000
model mohr reg i 2 j 12; assign properties to 3rd layer
prop density=2240.5 bulk=833.33E6 shear=384.6E6 cohesion=0 friction=30.0 reg i 2 j 12
step 2000
save incremental load.sav 'last project state'
```

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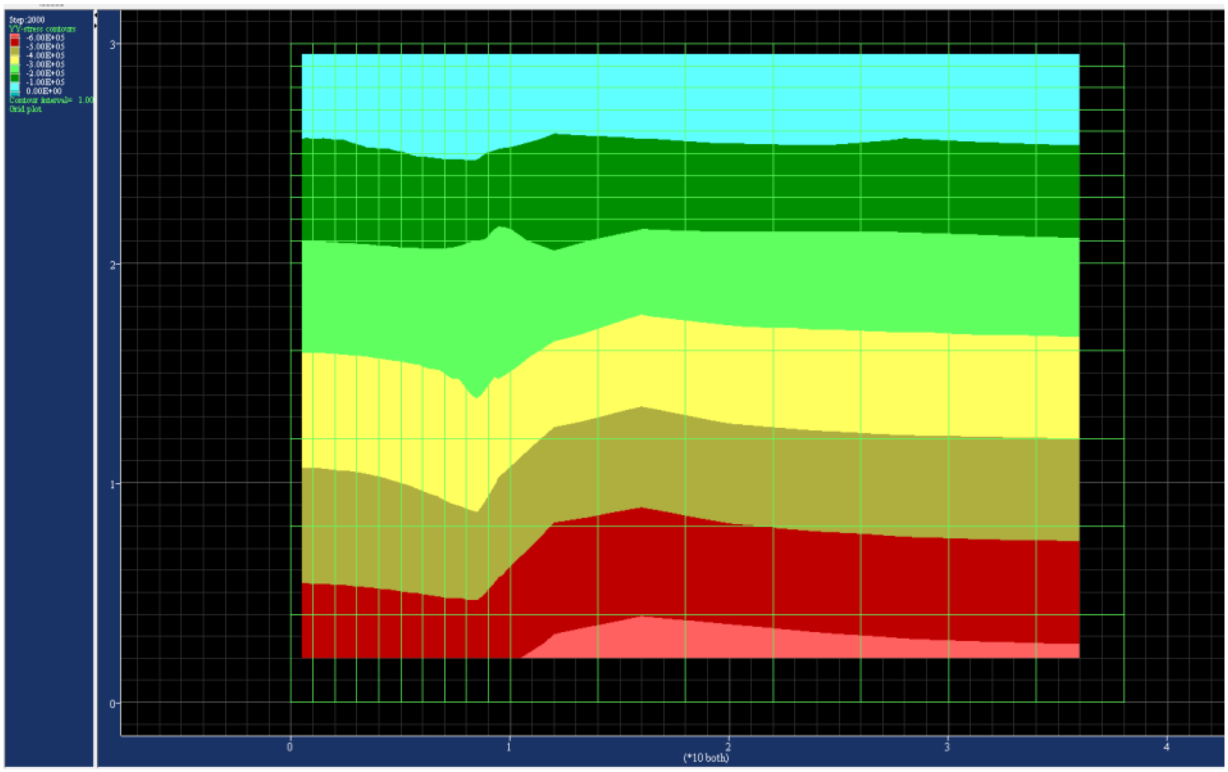
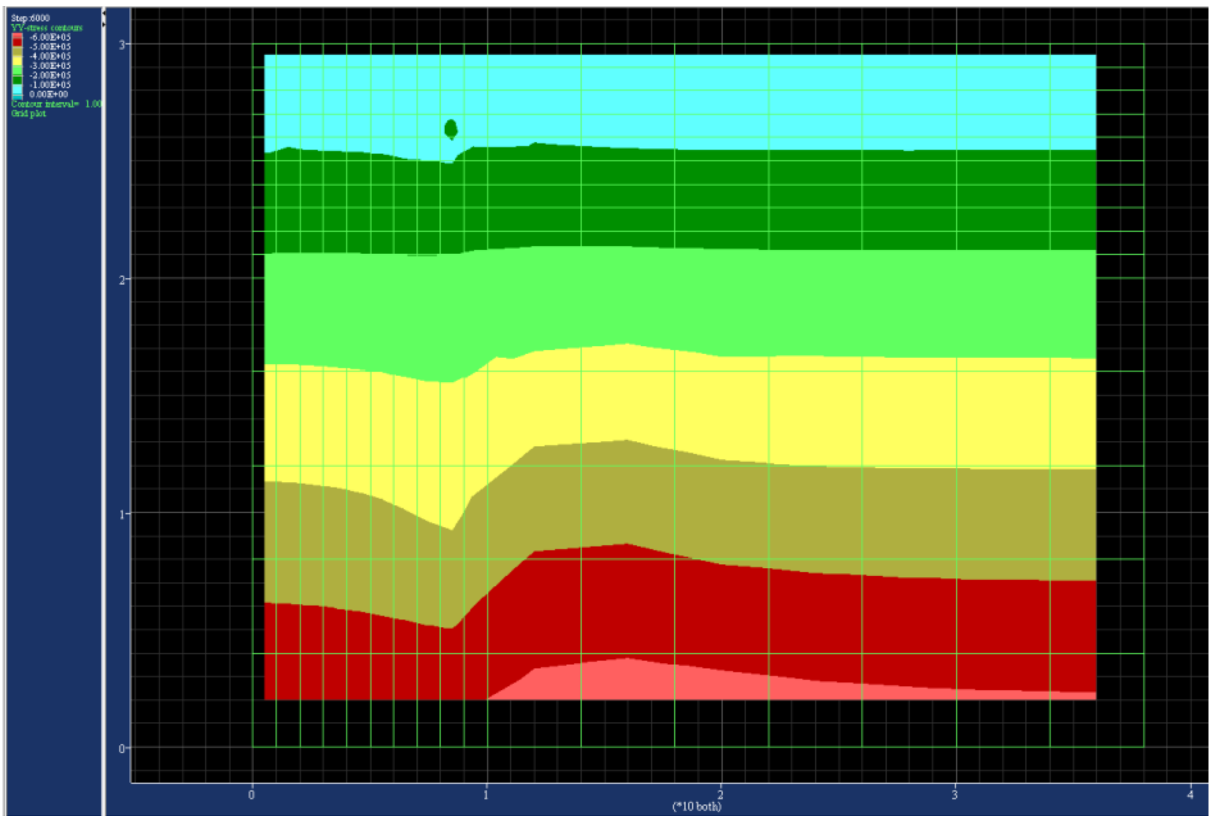
Building Systems Incrementally

Thursday, March 11, 2010
11:43 AM



Vertical stress for 3 layers placed all at one time



Vertical stress for 3 layers placed incrementally

More Reading

Thursday, March 11, 2010
11:43 AM

- Applied Soil Mechanics with ABAQUS Applications, Ch. 7

Assignment 7

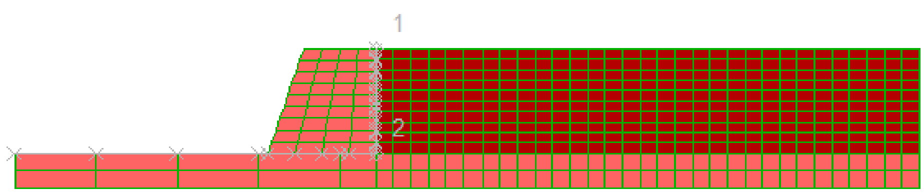
Thursday, March 11, 2010
11:43 AM

1. Develop a FLAC model of a concrete gravity wall (3-m high, 2-m wide (top) 3-m wide (base)) resting on a concrete foundation. Use the model to calculate the earth pressures for the cases shown below using the given soil properties. To do this, show a plot of the average earth pressure coefficient that develops against the backwall versus dytime. Report your modeling answers to 3 significant figures (30 points). Compare the modeling results with those obtained from Rankine theory.

   a. At-rest
   b. Active
   c. Passive

   Backfill (Mohr-Coulomb)
   Density = 2000 kg/m^3
   Bulk modulus = 25 Mpa
   Friction angle = 35 degrees
   Dilation angle = 5 degrees
   Cohesion = 0

   Concrete (Elastic)
   prop density=2400.0 bulk=1.5625E10 shear=1.27119E10



2. Repeat problem 1a, b and c but assume that the friction acting against the back wall of the retaining wall is phi (backfill) divided by 2. (10 points). Compare your results with Coulomb theory.

Assignment 7

Thursday, March 11, 2010
11:43 AM

3. Using the results of problem 1 from FLAC, calculate the factor of safety against sliding and overturning assuming that there is no friction acting between the backfill and the back wall.

   To calculate the factors of safety, you must use the horizontal stresses (converted to forces) that act on the back wall of the gravity wall from the FLAC results. This can be obtained by using histories commands and converted to forces by multiplying by the contributing area. You can also calculate the basal stresses along the bottom of the wall in a similar manner (10 points).

4. Repeat problem 3, but use limit equilibrium methods to calculate the appropriate forces from Rankine theory (10 points).

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Thursday, March 11, 2010
11:43 AM