LESSON 5

TOPIC 1

Slope Stability

SLOPE STABILITY

Lesson 5 - Topic 1

Slide 5-1-1

Instructor should note that the previous lessons represent the data-gathering phase of the geotechnical process. The remaining lessons will build on this information to develop design information for a project. Stress again that the reliability of any design work will depend on the quality and quantity of subsurface data.

The first design lesson is slope stability. This lesson will be subdivided in two sections; embankment stability and cut slopes.

SLOPE STABILITY

1. *Compute Resisting & Driving Forces*
2. *Explain Effects of Water Pressure on Frictional Resistance*

ACTIVITIES: Circular Arc Analysis
Sliding Block Analysis

Slide 5-1-2

Explain objectives. Mention that hands on student exercises will be used to develop computation skills in stability analysis.

Embankments:
Major Design Considerations

- *Stability*
- *Settlement*
- *Effects on the Structure*

Slide 5-1-3

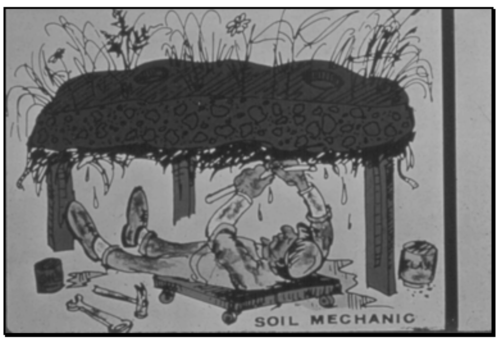
Begin the embankment stability session with a review of the major considerations for embankment design.

Embankment Stability Problem Soils

- *Low Strength Clays*
- *Low Strength Silts*
- *Peats*
- *Organic Silts and Organic Clays*
- *Thin, Weak Seams (Clay, Silt, Sand)*

Slide 5-1-4

Introduce stability problem soils. Relate back to what was observed in the lab exercise and why lab testing is usually concentrated on these soils.



Slide 5-1-5

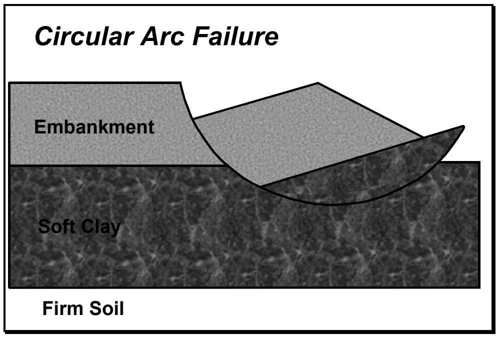
Funny slide to show that we work below ground.

Major Stability Problems

Circular and Sliding Block Failures

Slide 5-1-6

Introduce circular and sliding block failure types. Mention that these are the most common failure modes for embankments.

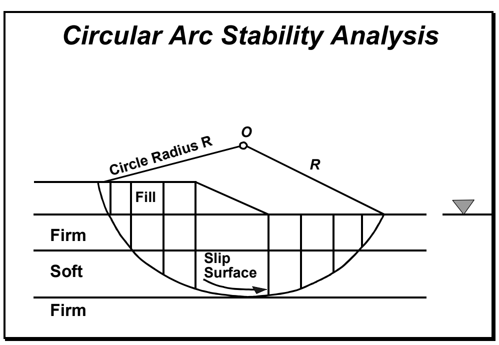


Slide 5-1-7

Describe circular failure. Note that the failed mass rotates in a circular shape with the top dropping and the toe rising. Ask what causes the failed mass to stop rotating?

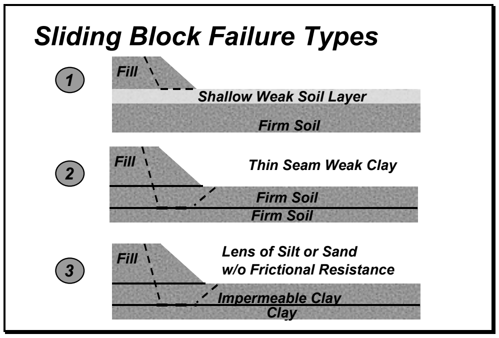
Slide 5-1-8

Show case history. Note the head scarp to the left and the relative height compared to the size of the man standing below the scarp. Note the mud wave at the toe and the relative scale compared to the man near the toe.



Slide 5-1-9

Spend a few minutes on this slide to show the mechanics of a slip circle analysis. Mention how the circular mass is subdivided into a series of slices. Note that certain rules govern where the slices are placed; breaks in ground line, water table, or subsurface layers. Hand methods of analysis commonly require 10-15 slices. Computer methods generally select the number of slices as a function of circle geometry.

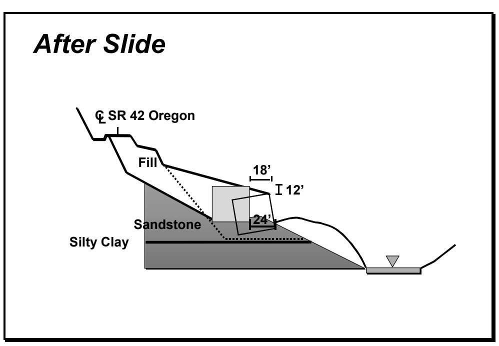


Slide 5-1-10

Describe the three common conditions for a sliding block failure. Note that the presence of water or increased water pressure is frequently a contributing factor to sliding block problems.

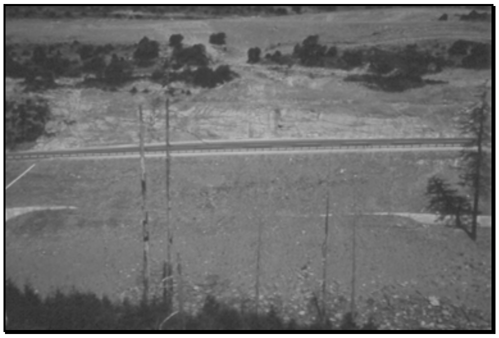
Slide 5-1-11

Show sliding block case history for failure of Reinforced Earth wall at Coos Bay Oregon. This wall was built to prevent a sliver fill section for a road widening from spilling into a river. The failure occurred during placement of a fill slope above the top of the wall. Also note how well the reinforced system withstood the failure movement. The wall actually prevented the failed mass from sliding into the river.



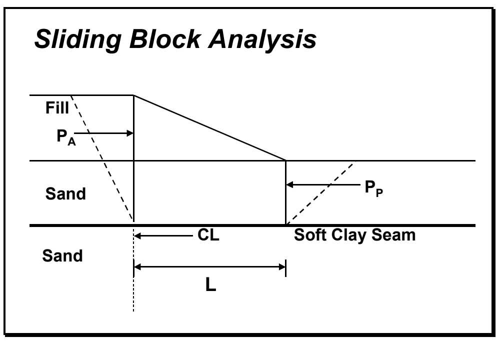
Slide 5-1-12

Describe the mechanism that caused the sliding block failure and the amount of movement associated with the failure. The cause of the failure was a thin seam of silty clay that was not found during the initial subsurface investigation.



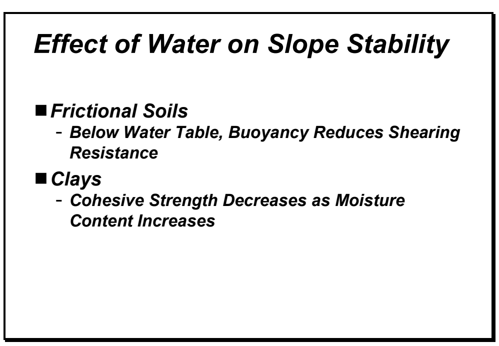
Slide 5-1-13

The remedy for the failure was to place a buttress in front of the failed section of the wall. (Funny line to use is that we employed a method commonly associated with doctors; we buried the wall.) This buttress only resulted in a minor encroachment into the river as the length of the failed section was short.



Slide 5-1-14

Describe mechanics of a sliding block failure. Point to the active wedge, central block, and passive wedge. Note that factor of safety for stability analysis is defined as resisting forces over driving forces.



Slide 5-1-15

Emphasize the water effect on various soil types.

Effect of Water on Slope Stability (Cont'd)

- ***Fills on Clays and Silts***
  - *Soil Consolidates as Water is Squeezed Out - Factor of Safety Increases With Time*
- ***Cuts in Clay***
  - *Soil Absorbs Water When Overburden Pressure Removed - Factor of Safety Decreases With Time*

Slide 5-1-16

Emphasize the water effect on various soil types.

Effect of Water on Slope Stability (Cont'd)

- ***Shales, Claystones, Siltstones, Etc.***
  - *Weak Rock Materials "Slake" When Exposed to Water - Embankments Undergo Internal Settlement or Failure*

Slide 5-1-17

Emphasize the water effect on various soil types.

Embankments: Recommended Safety Factors

$$\text{Safety Factor} = \frac{\text{Resisting}}{\text{Driving}}$$

- ***End Slope Conditions***
  - *Minimum Safety Factor = 1.30*
- ***Side Slope Conditions***
  - *Minimum Safety Factor = 1.25*

Slide 5-1-18

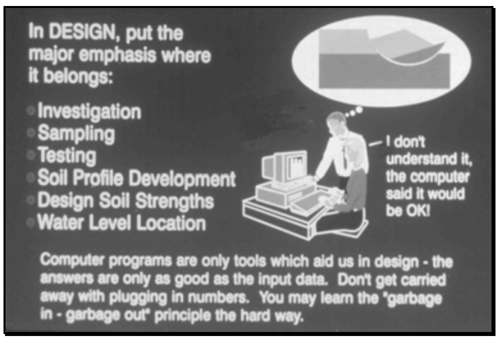
State the recommend safety factors for both end and side slopes. Ask why the safety factor is higher for end slopes?

Basis for Selection of Design Safety Factor

- ***Confidence in Subsurface Data (Particularly Soil Strength Value)***
- ***Stability Analysis Method***
- ***Consequences of Failure***

Slide 5-1-19

Explain that safety factors for specific projects may be increased above the minimum recommended values due to several conditions including those in this list. Caution the audience that a designer should not indiscriminately increase the safety factor. The economic consequence of safety factor increase can be significant to the point where projects are not feasible. The cost of an adequate site investigation and a competent design are far less than use of excessive safety factors.



Slide 5-1-20

Funny slide to show that garbage in equals garbage out. Relate back to how important data collection was in previous lessons.

SOILS AND FOUNDATIONS WORKSHOP

Circular Arc Failure Analysis Methods

- ***Rule of Thumb***
- ***Hand Solutions***
- ***Computer Programs***

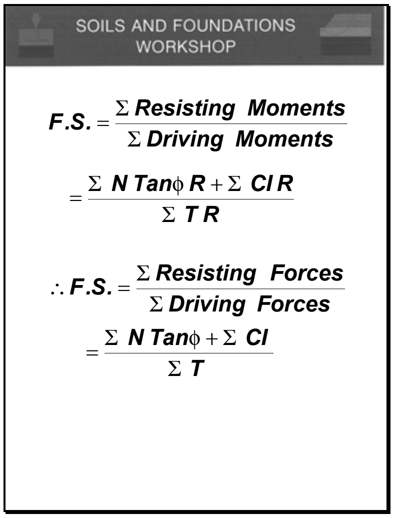
Slide 5-1-21

Comment on the three methods of performing circular analysis.

The rule of thumb is only used for preliminary estimates and to see if more comprehensive analysis is needed.

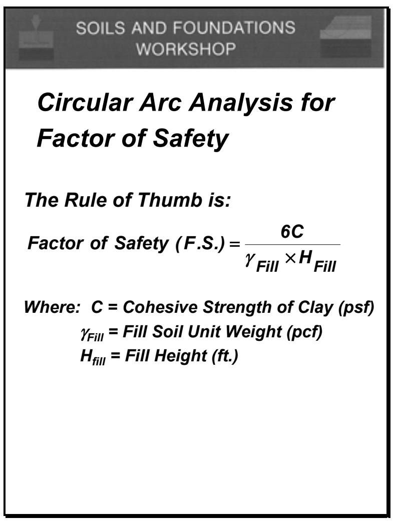
Hand solutions are only possible for the most simplistic type of circular analysis and even then cannot be used for final design due to the extreme amount of computation effort needed to find the critical failure surface. Hand solutions are most commonly used to provide a check on the results of computer analyses.

Numerous computer program exist for circular stability analysis of slopes. The instructor will later demonstrate a program offered by FHWA for stability analysis.



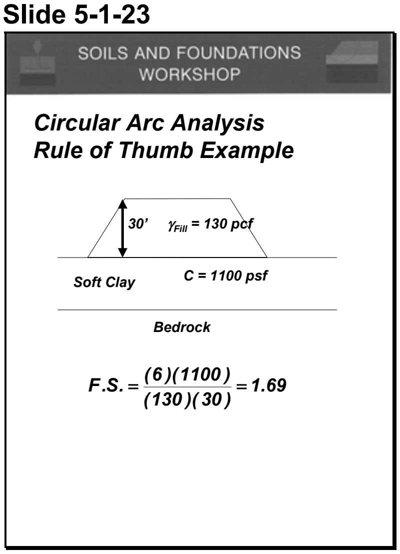
Slide 5-1-22

Explain that circular analysis is based on the concept that a rigid block can fail on a circular shear plane. Rotation occurs about an assumed center of rotation. The factor of safety against failure is found by calculating the driving and resisting moments about an assumed center of rotation. However in simplistic hand analyses, the lever arm for all moments is equal for the circle shape and the safety factor computed from a comparison of driving and resisting forces. The resisting forces are the sum of frictional and cohesion forces. The driving (overturning) force is the net of positive and negative driving forces on either side of the center of rotation.



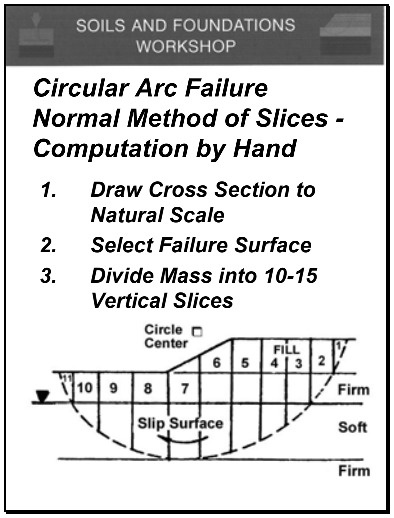
Slide 5-1-23

Explain the rule of thumb concept and the example computation. Mention that any rule of thumb must be used with caution. In this case, a safety factor less than 2.5 is a flag to the designer that a more sophisticated analysis is required. Do not rely on rules of thumb for final design.



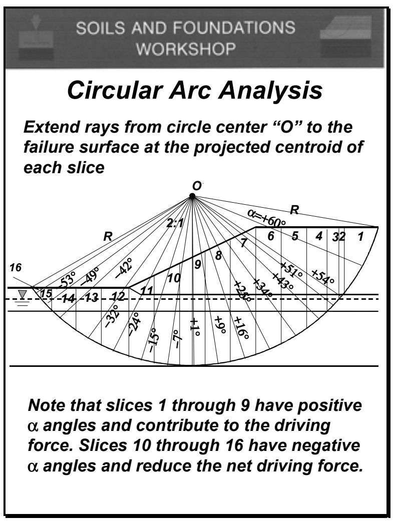
Slide 5-1-24

Demonstrate the computation of embankment safety factor using the rule of thumb. Ask students what errors they see connected with this method of analysis.



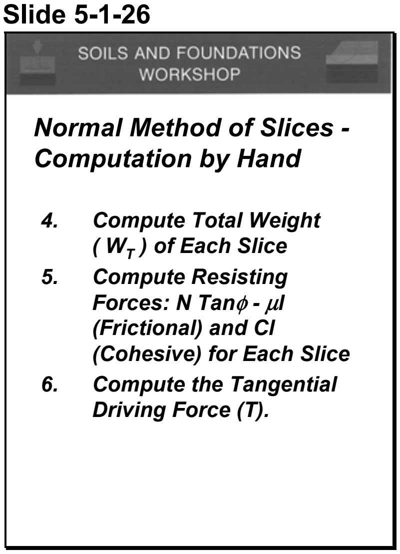
Slide 5-1-25

Introduce the normal method of slices. State that this method is the most basic circular procedure that can be performed by hand. The method has some theoretical shortcomings which tend to make the results conservative; particularly where granular soil layers are present. However the method is straightforward and was selected for this course as computation of both driving and resisting forces can be easily understood. Selection of the first trial circle location is done by experience with the circle center positioned above the mid-point of slope and the radius extending to the base of soft material. Many trials are needed to approach the critical failure location.



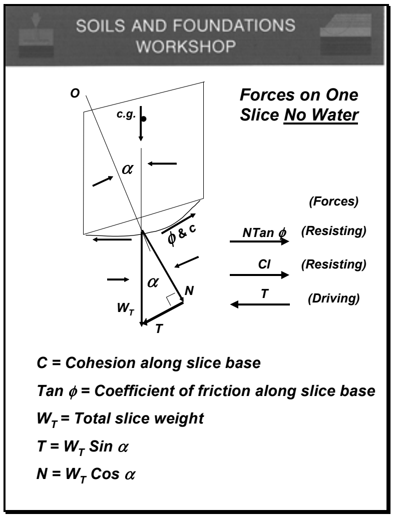
Slide 5-1-26

The magnitude of both the normal and tangential forces will depend on the angle measured in both directions from a vertical line drawn from the circle center.



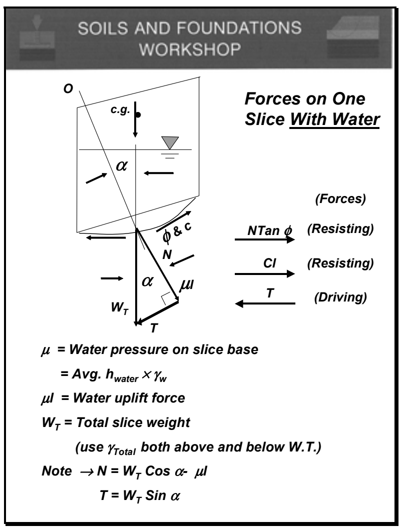
Slide 5-1-27

Explain the computation of resisting and driving forces. Stress that these computations are based on a 1' thick slice, i.e., a 2-dimensional analysis.



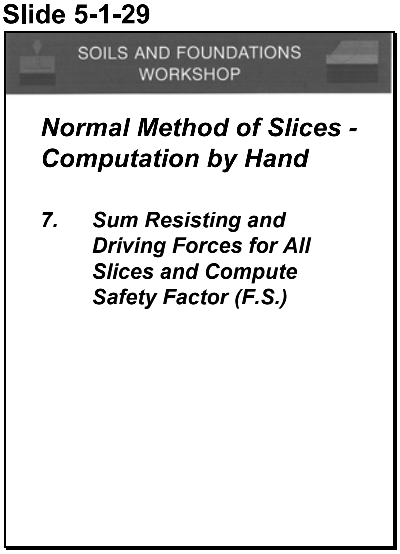
Slide 5-1-28

Explain the graphical concept of driving and resisting forces. Note that we will first consider a situation where no water table exists within the failure mass. Explain that the block (slice) shown is on the driving side of the circle center and will tend to move down to the left due to the weight component acting down the incline. However frictional and cohesive forces at the interface between the block and the material on which the block is rotating will resist that movement.



Slide 5-1-29

Explain the water table affects only the frictional resisting force. Note that the water force is proportional to the average height of water above the base of the slice. The water force reduces the frictional resistance.



Slide 5-1-30

Explain that resisting forces for all slices are always positive and are simply summed. Driving forces are positive on the driving side of the circle center and negative on the resisting side of the circle center. The driving forces for each slice are summed algebraically to find the net driving force. Students can also observe the net amount of driving and resisting associated with each slice to find which slices have the greatest impact on stability.

Instructor: * Go to Flip Chart or Chalkboard. Repeat information shown in slides 25 through 30 by drawing an embankment cross section, dividing the slices, drawing the rays and α angle, and showing the W_t, N and T vectors

SOILS AND FOUNDATIONS WORKSHOP

Normal Method of Slices - Example for One Slice with No Water

Assume:

- ***γ_{total} = 120 pcf, slice height = 10', slice width = 10', ϕ = 25°, α = 20°, l =11', C = 200 psf.***
- ***Find: Resisting and Driving Forces***

Slide 5-1-31

Explain the example problem. Mention that the instructor will compute the component forces and that the group will then sum the appropriate forces to find the total resisting and driving forces.

After explaining the example, ask the group if this slice is located on the driving side of the center or the resisting side of the center. Answer is the driving side as the α angle is positive. A negative angle denotes the slice is on the resisting side.

SOILS AND FOUNDATIONS WORKSHOP

Normal Method of Slices - Example Solution

$W_T = \gamma_{total}$ x slice area (x 1' thick)
= 120 pcf x 10' x 10'
= 12000 lbs

$N = W_T \cos\alpha - \mu l$
= 12000 lbs x Cos 20°
= 11276 lbs

Slide 5-1-32

Proceed with the computation of the component forces on the slice. Note that the computation for is based on the assumption that a one foot thick slice is being analyzed.

SOILS AND FOUNDATIONS WORKSHOP

Normal Method of Slices - Example Solution (Cont'd)

$N \tan\phi$ = 11276 x Tan 25°
= 5258 lbs

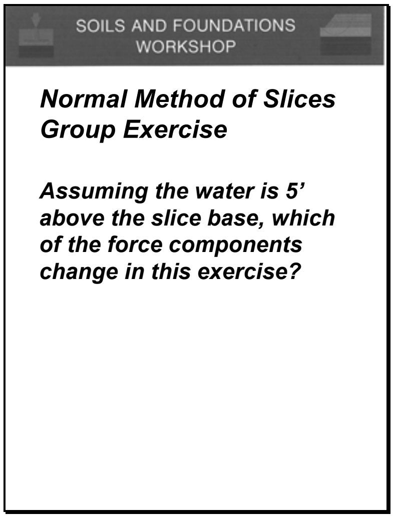
Cl = 200 psf x 11' x 1'
= 2200 lbs

$T = W_t \sin\alpha$
= 12000 lbs x Sin 20°
= 4104 lbs

Slide 5-1-33

After completing the explanation of the computation, ask the group what are the total resisting and driving forces for this slice. Ask if the total forces indicate that this slice is tending to resist movement or promote movement. Answer is resist as the total resisting force is greater than the total driving force.

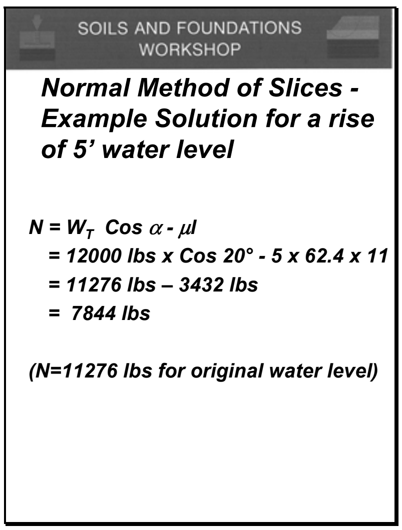
Also remind the group that this is only one of the 10-15 slices that comprise a hand analysis. The forces from all slices need to be calculated and totaled to find the safety factor for this trial circle. Students need to understand that much time and effort is needed to do hand analysis and that many trials are needed to find the most critical circle for a given problem.



Slide 5-1-34

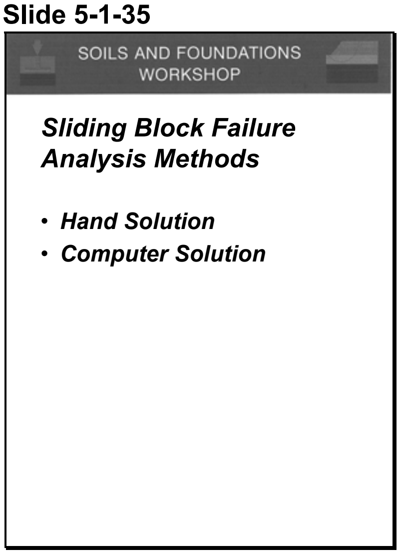
After explaining the exercise, put the previous overhead on the screen. When the group produces the answer (frictional force) ask how the 5' water height would be accounted for in the equations. The correct answer is to include the μ_L term in the Normal Force N.

Also be prepared to field questions on why the cohesion and driving force are not affected by the change in water table, (cohesion based on bond between particles, not seasonal change; driving force based on total weights, not effective weights).



Slide 5-1-35

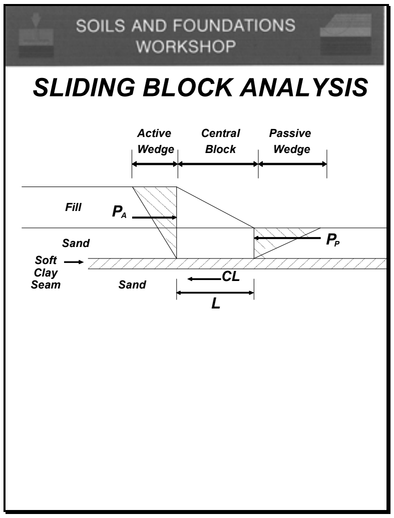
Proceed with the computation (N=11276 lbs for original water level) of the component forces on the slice. Note that the computation for is based on the assumption that a one foot thick slice is being analyzed.



Slide 5-1-36

The sliding block method is a simple, straightforward analysis that can be performed quickly by hand analysis. The block analysis is directly related to the earth pressure concepts used in retaining wall design. This makes the block analysis a good teaching tool to explain basic stability concepts. Mention that a student exercise will follow the explanation of the block method.

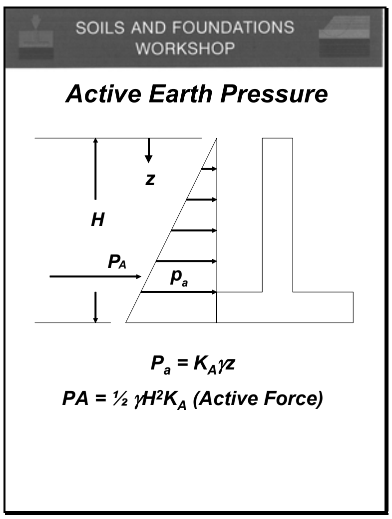
Multiple trials are generally required to find the most critical failure surface, similar to the circular method. Since the block analysis is most commonly used for thin weak layers, the number of trials is usually less than for circular procedures. However computer programs for block stability analysis are recommended for final design. We will demonstrate an FHWA program after completion of this topic.



Slide 5-1-37

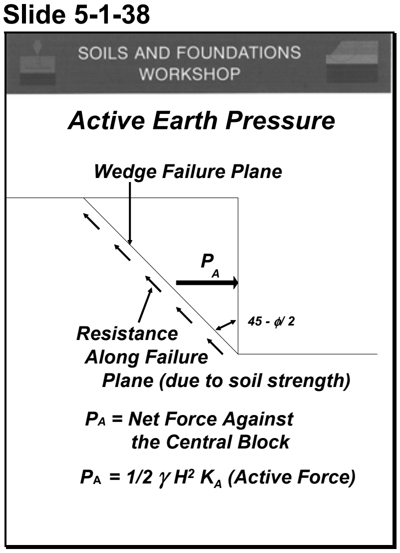
Mention that the sliding block analysis has three component sections that affect the overall stability of the mass; the active wedge that drives the failure, the central block that slides in the soft clay, and the passive wedge that resists movement of the central block. Mention again that this is the situation that you will ask the students to analyze in the student exercise.

Relate the simple Rankine sliding block analysis to basic retaining wall theory where the central block is the wall mass that is acted on by the active and passive forces. Ask who is familiar with retaining wall analysis and then proceed to the next series of overheads to explain the theory.



Slide 5-1-38

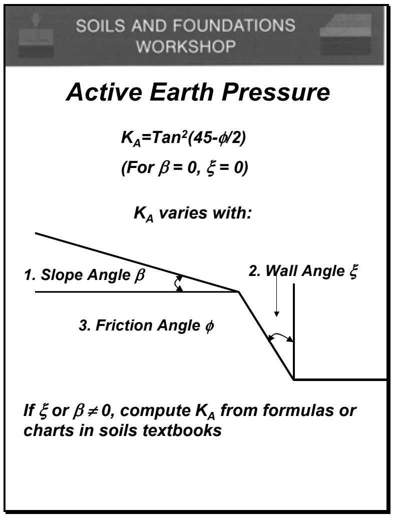
The active earth pressure against a wall is commonly shown as a pressure diagram. This diagram is similar to an overburden pressure diagram except the vertical pressure has been transformed into a horizontal pressure, p_a, by multiplying P_o times the lateral earth pressure coefficient, K_A. The active force against the wall is the area of the pressure diagram for the height of the wall.



Slide 5-1-39

The basis of the active earth pressure concept is that the soil behind the wall will try to fail in a wedge shape. The wedge creates the triangular pressure diagram against the wall. In the case of the sliding block analysis, the pressure diagram is applied to the central block. Note that the force against the central block is calculated the same way as for a wall analysis.

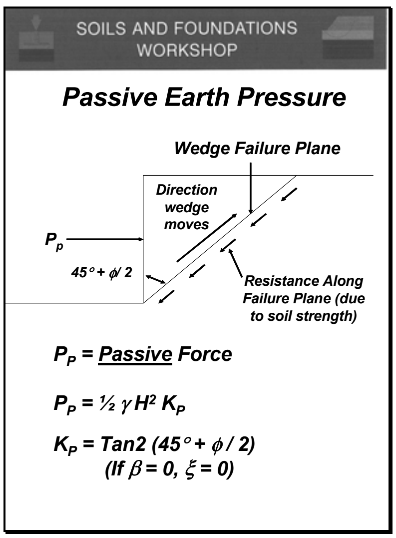
Note that the angle of the failure surface is directly related to the friction angle.



Slide 5-1-40

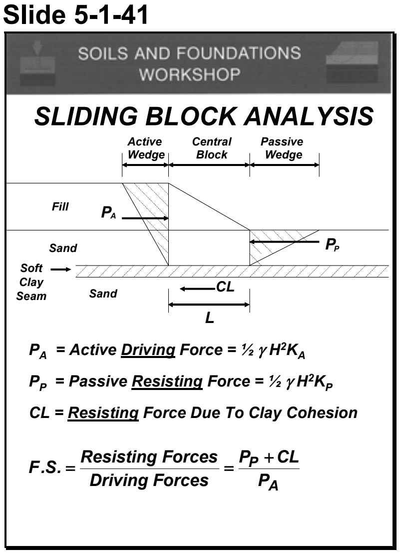
The formula for the Rankine earth pressure coefficient, K_A, is shown for the most basic case, I.e., vertical face and horizontal backslope. This equation will be used in this class. Note that the coefficient is directly related to the friction angle.

Also note that the coefficient varies depending on the angle of the wall and the angle of the backslope. Formulas and charts for these situations are beyond the scope of this course but can be found in most textbooks.



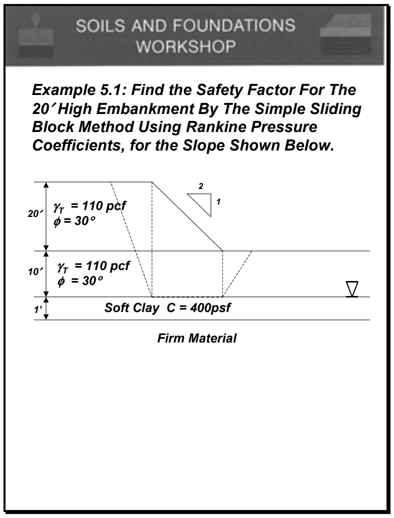
Slide 5-1-41

A similar explanation can be made for the passive pressure. In this case the wall or central block must move the passive wedge up the failure plane before failure can occur. Explain the equation shown and note the equation is the same for both wall analysis and for the sliding block analysis.



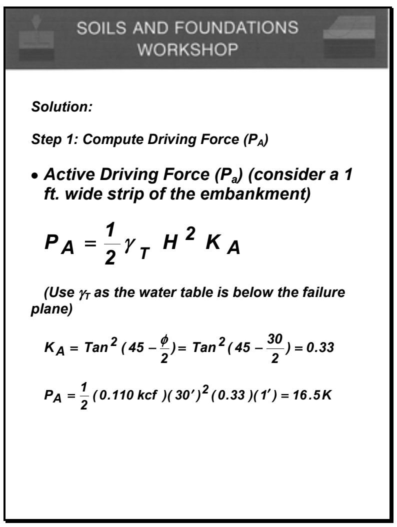
Slide 5-1-42

Complete the conceptual explanation of the sliding block analysis by returning to the block overhead and applying the active and passive concepts that were just explained. Focus on computation of resisting and driving forces to find the safety factor for the block.



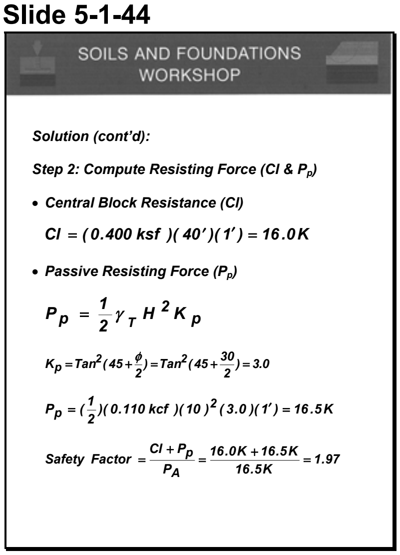
Slide 5-1-43

Demonstrate the solution process for a simple sliding block problem in an example. Get students thinking about the impact of driving and resisting forces on stability.



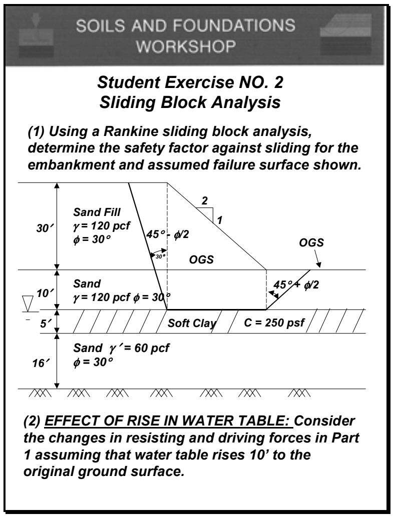
Slide 5-1-44

Demonstrate the solution process for a simple sliding block problem in an example. Get students thinking about the impact of driving and resisting forces on stability.



Slide 5-1-45

Demonstrate the solution process for a simple sliding block problem in an example. Get students thinking about the impact of driving and resisting forces on stability.



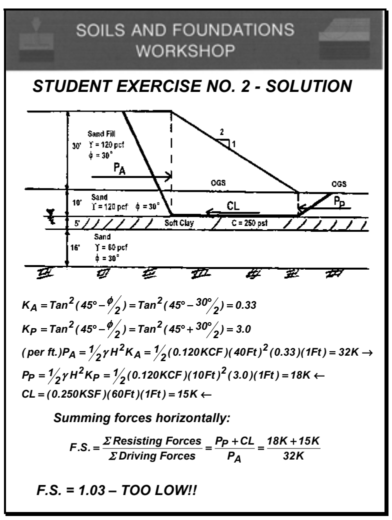
Slide 5-1-46

Ask students to do exercise 2. The exercise involves computation of the safety factor for both a simple embankments over soft ground and then consideration of a situation where the water table rises.

This exercise will test the students on simple stability analysis concepts and computational procedures. Instructor selects one team to put the answer to part 1 on a flip chart and explain to the group. Pertinent questions should be used to test learning of the team and the audience.

Then question the group on the effect of the water table rise. Then show solution for part 2. Do not explain in detail but focus on why water table rise decreases safety factor (resisting forces decrease much more than driving forces). The exercise shows how water can dramatically affect slope stability. Underlying message is that the water level must be determined accurately during site investigation.

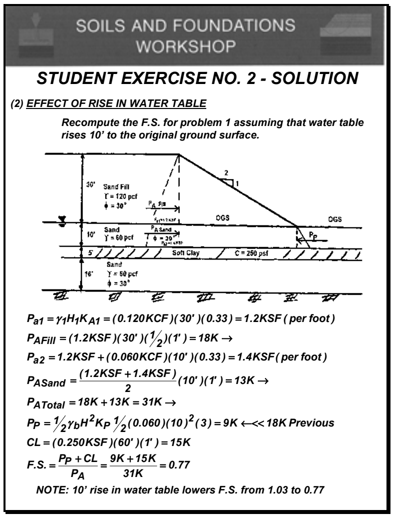
Please refer to the end of the lesson for this exercise.



Slide 5-1-47

Solution to exercise 2 part 1.

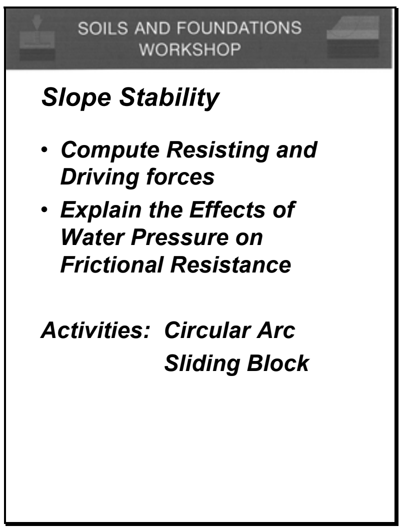
Please refer to the end of the Participant Workbook for the solution to this exercise.



Slide 5-1-48

Show solution to part 2 of the exercise 2. Do not focus on the details of the solution.

Please refer to the end of the Participant Workbook for the solution to this exercise.



Slide 5-1-49

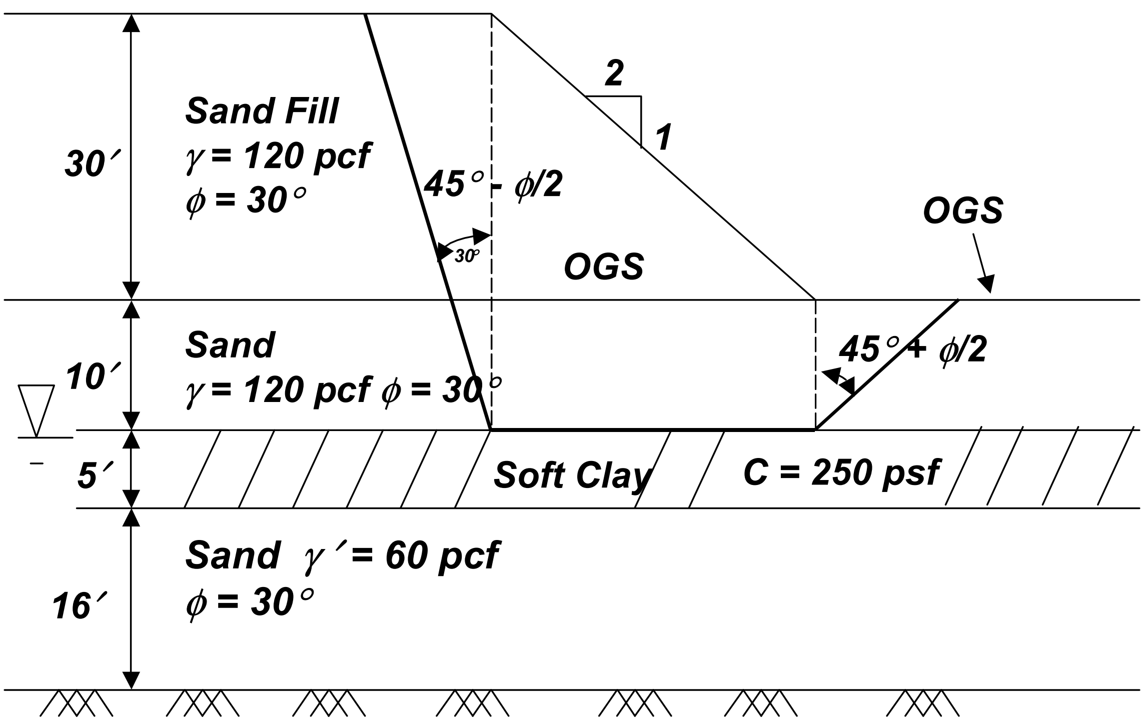
Restate the objectives of this lesson topic. Then proceed to demonstrate the FHWA RSS program and the proprietary XSTABL program. Stress the need to use computerized solution to stability problems but mention that hand analysis is still the best method to check the results of a computer solution.

This demonstration is best done after a break if possible as the equipment set-up can be time consuming (particularly for the video display device). The instructor should prepare for this demonstration the previous day if possible to iron out any kinks in the operation of the equipment or compatibility of the computer to the software.

SOILS AND FOUNDATIONS WORKSHOP

Student Exercise NO. 2
Sliding Block Analysis

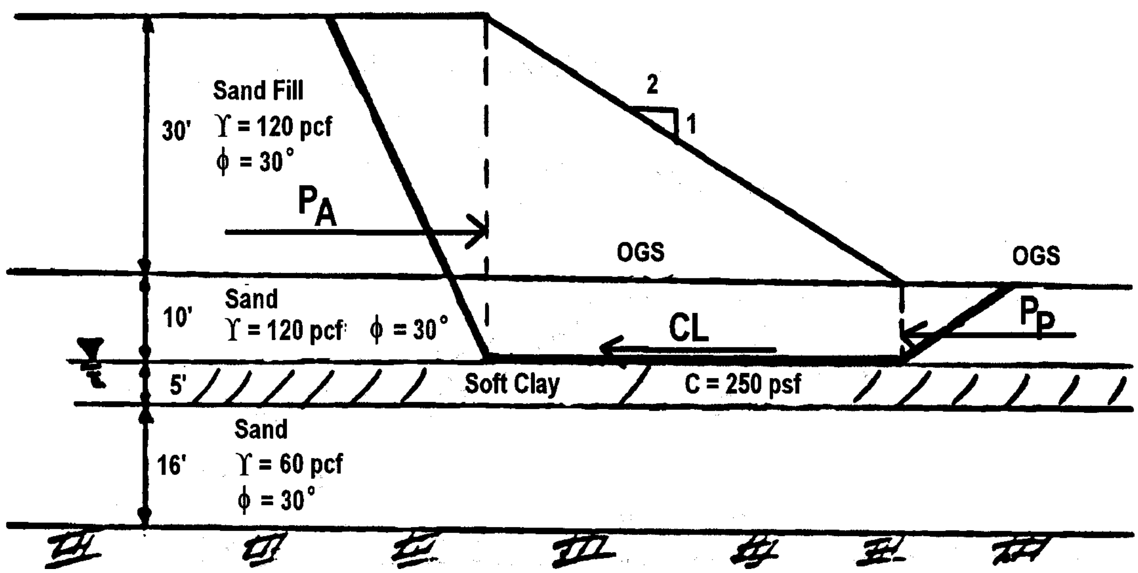
(1) Using a Rankine sliding block analysis, determine the safety factor against sliding for the embankment and assumed failure surface shown.



(2) <u>EFFECT OF RISE IN WATER TABLE:</u> Consider the changes in resisting and driving forces in Part 1 assuming that water table rises 10' to the original ground surface.

SOILS AND FOUNDATIONS WORKSHOP

STUDENT EXERCISE NO. 2 - SOLUTION



$$K_A = Tan^2(45° - \phi/2) = Tan^2(45° - 30°/2) = 0.33$$

$$K_P = Tan^2(45° - \phi/2) = Tan^2(45° + 30°/2) = 3.0$$

$$(per\ ft.)P_A = 1/2\,\gamma H^2 K_A = 1/2(0.120KCF)(40Ft)^2(0.33)(1Ft) = 32K \rightarrow$$

$$P_P = 1/2\,\gamma H^2 K_P = 1/2(0.120KCF)(10Ft)^2(3.0)(1Ft) = 18K \leftarrow$$

$$CL = (0.250KSF)(60Ft)(1Ft) = 15K \leftarrow$$

Summing forces horizontally:

$$F.S. = \frac{\Sigma\ Resisting\ Forces}{\Sigma\ Driving\ Forces} = \frac{P_P + CL}{P_A} = \frac{18K + 15K}{32K}$$

F.S. = 1.03 – TOO LOW!!

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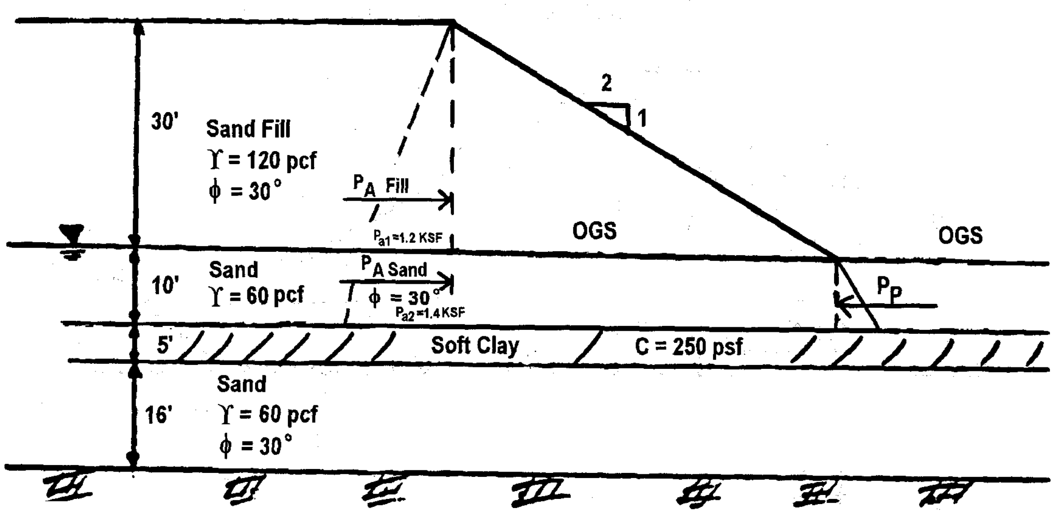
STUDENT EXERCISE NO. 2 - SOLUTION

(2) EFFECT OF RISE IN WATER TABLE

Recompute the F.S. for problem 1 assuming that water table rises 10' to the original ground surface.



$$P_{a1} = \gamma_1 H_1 K_{A1} = (0.120KCF)(30')(0.33) = 1.2KSF\ (per\ foot)$$

$$P_{AFill} = (1.2KSF)(30')(1/2)(1') = 18K \rightarrow$$

$$P_{a2} = 1.2KSF + (0.060KCF)(10')(0.33) = 1.4KSF\ (per\ foot)$$

$$P_{ASand} = \frac{(1.2KSF + 1.4KSF)}{2}(10')(1') = 13K \rightarrow$$

$$P_{ATotal} = 18K + 13K = 31K \rightarrow$$

$$P_P = 1/2\, \gamma_b H^2 K_P\ 1/2 (0.060)(10)^2 (3) = 9K \leftarrow << 18K\ Previous$$

$$CL = (0.250KSF)(60')(1') = 15K$$

$$F.S. = \frac{P_P + CL}{P_A} = \frac{9K + 15K}{31K} = 0.77$$

NOTE: 10' rise in water table lowers F.S. from 1.03 to 0.77