

# **SEACAP 21/004 Landslide Management**

## **Mainstreaming Slope Stability Management**

### **Theme 8 Remedial Measures: Design**

#### **8.1 Slope stability analysis**

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## Theme 8 Contents

### Part 1 - Slopes

- 1) Overview of basic soil mechanics (Introduction),
- 2) Soil Slope stability analysis (Theme 8.1).
  - why slopes fail,
  - failure shapes
  - how each is analysed
  - Use of slope stability analysis programs.
  - Forward and backanalysis to diagnose problems.
- 3) Rock Slope stability (Theme 8.2)
- 4) Cross section design (Theme 8.3)
- 5) Earthworks design
  - new cuttings and embankments (Theme 8.4)
  - Remedial works to improve stability (Theme 8.4)

### Part 2 – Retaining walls

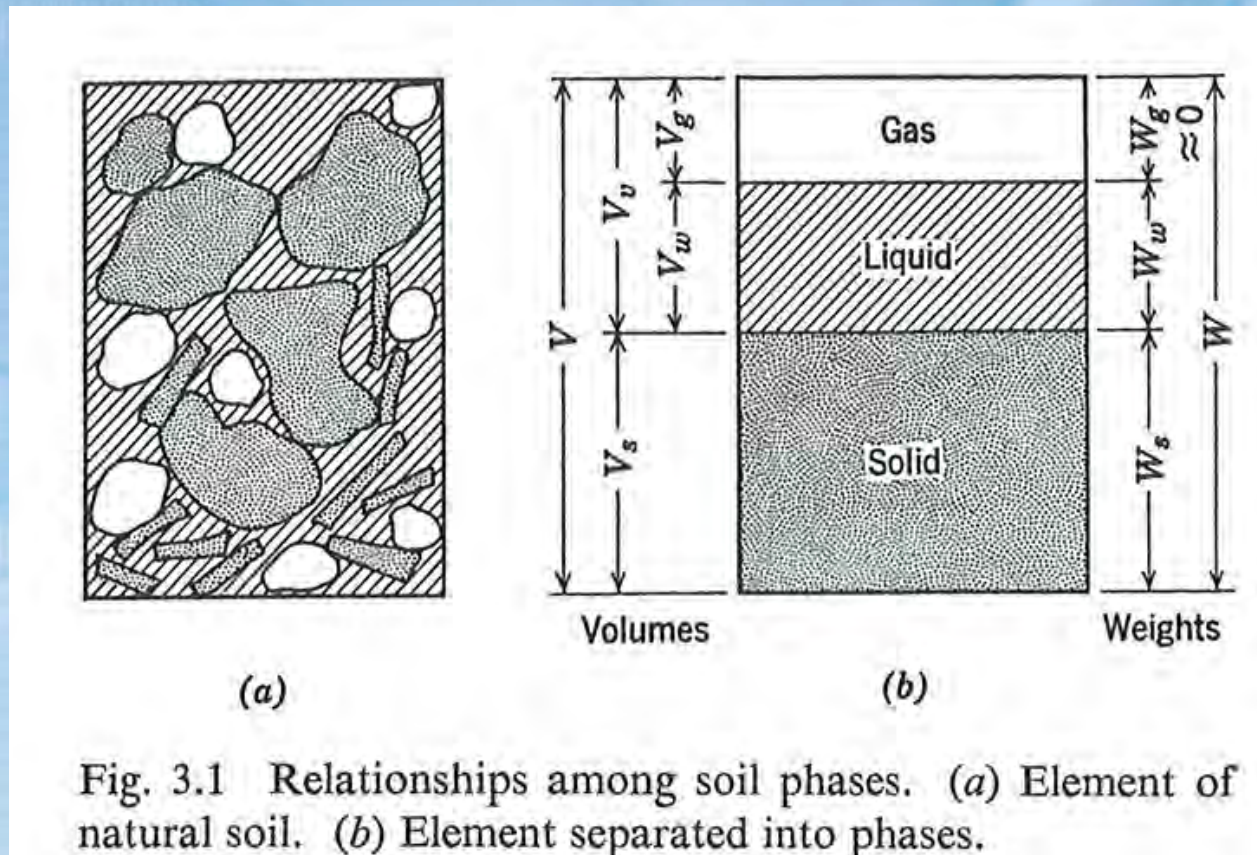
- 6) Overview of soil mechanics (Introduction)
- 7) Gravity retaining wall design (Themes 8.5 and 8.6)
- 8) Embedded retaining walls (Themes 8.5 and 8.6)
- 9) Reinforced soil walls (Themes 8.5 and 8.6)

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# Introduction

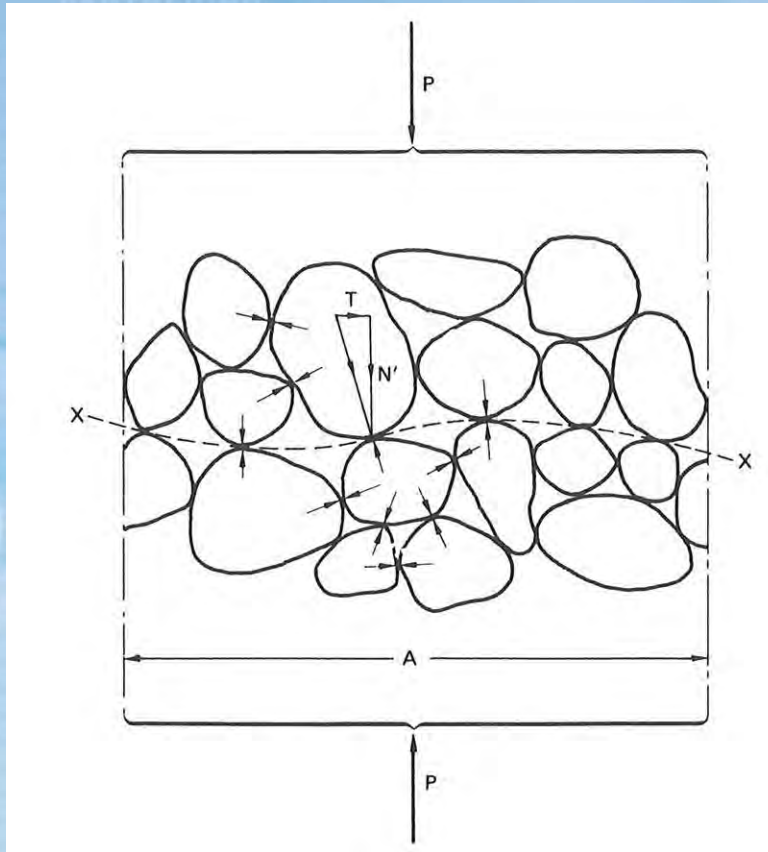
Overview of basic soil mechanics

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Soil – a three phase system

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$$\sigma = u + \sigma'$$

$\sigma$  is the total stress =  $P/A$

$u$  is the pore water pressure

$\sigma'$  is the effective stress =  
stress due to soil particle to  
soil particle contact

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Total vertical stress on block of soil

$$\sigma_v = \gamma_b z$$

Pore pressure (if water is static)

$$u = \gamma_w d$$

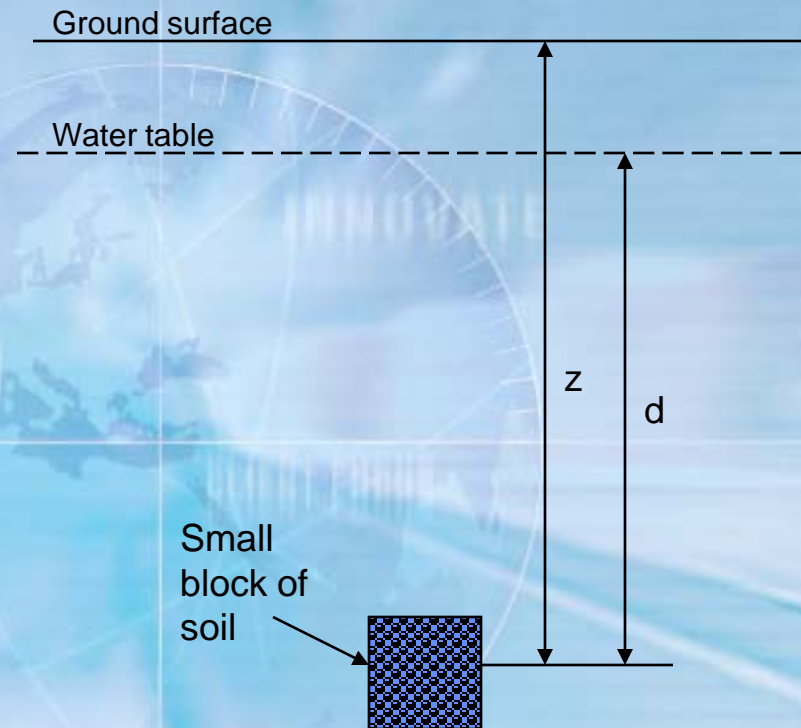
Effective vertical stress on block of soil

$$\sigma_v' = \sigma_v - u$$

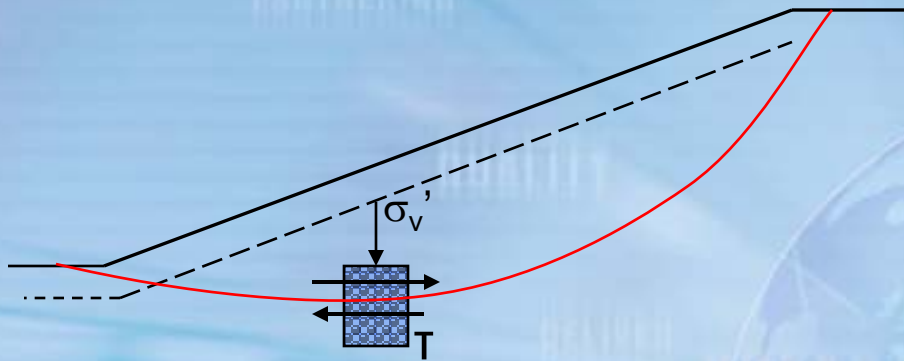
$$\sigma_v' = \gamma_b z - \gamma_w d$$

Where  $\gamma_b$  = Bulk unit weight of soil

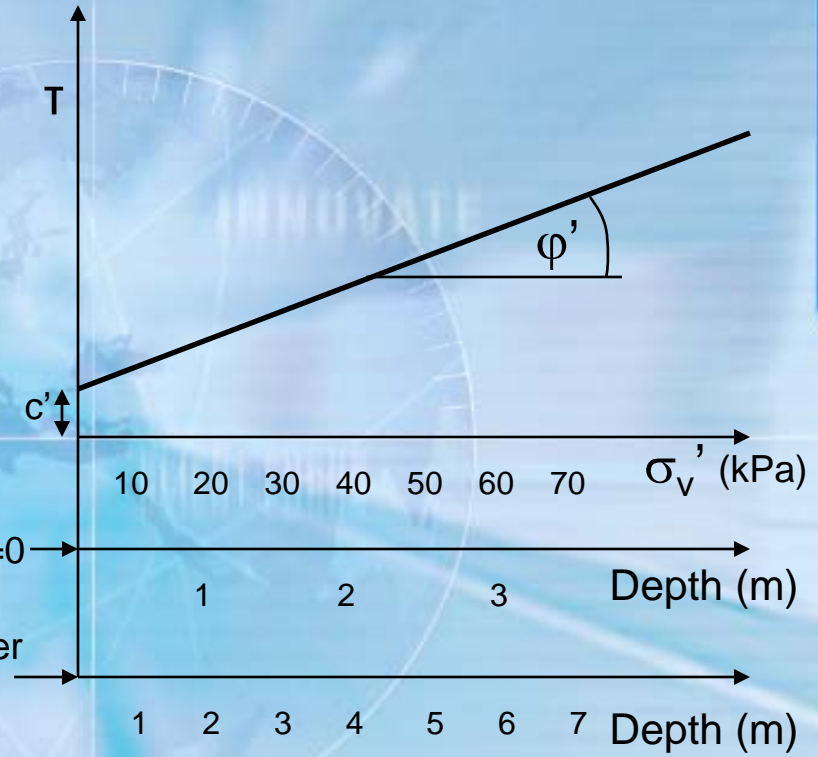
And  $\gamma_w$  = Unit weight of water (= 10kN/m<sup>3</sup>)



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$$\tau = c' + \sigma_v' \tan \phi'$$



If  $\gamma_b = 20 \text{ kN/m}^3$  and  $u=0$

If  $\gamma_b = 20 \text{ kN/m}^3$  and water at ground surface

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Unit weights of soils (and similar materials)				
Material	$\gamma$ : moist bulk density (kN/m <sup>3</sup> )		$\gamma_{sat}$ : saturated bulk density (kN/m <sup>3</sup> )	
	Loose	Dense	Loose	Dense
<b>A - Granular</b>				
Gravel	16.0	18.0	20.0	21.0
Well graded sand and gravel	19.0	21.0	21.5	23.0
Coarse or medium sand	16.5	18.5	20.0	21.5
Well graded sand	18.0	21.0	20.5	22.5
Fine or silty sand	17.0	19.0	20.0	21.5
Rock fill	15.0	17.5	19.5	21.0
Brick hardcore	13.0	17.5	16.5	19.0
Slag fill	12.0	15.0	18.0	20.0
Ash fill	6.5	10.0	13.0	15.0
<b>B - Cohesive</b>				
Peat (very variable)	12.0		12.0	
Organic clay	15.0		15.0	
Soft clay	17.0		17.0	
Firm clay	18.0		18.0	
Stiff clay	19.0		19.0	
Hard clay	20.0		20.0	
Stiff or hard glacial clay	21.0		21.0	

Bulk unit weights ( $\gamma_b$ ) of some typical soils

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Soil type	$\phi'$ peak	C' (kPa)	factors affecting $\phi'$
Clays and Silts (long term)*	20-30	0-20	Plasticity Mineralogy
Sands and Gravels	30 – 40	~0	Density Grading Angularity Fines content

\* Short term strength for clay will be covered later

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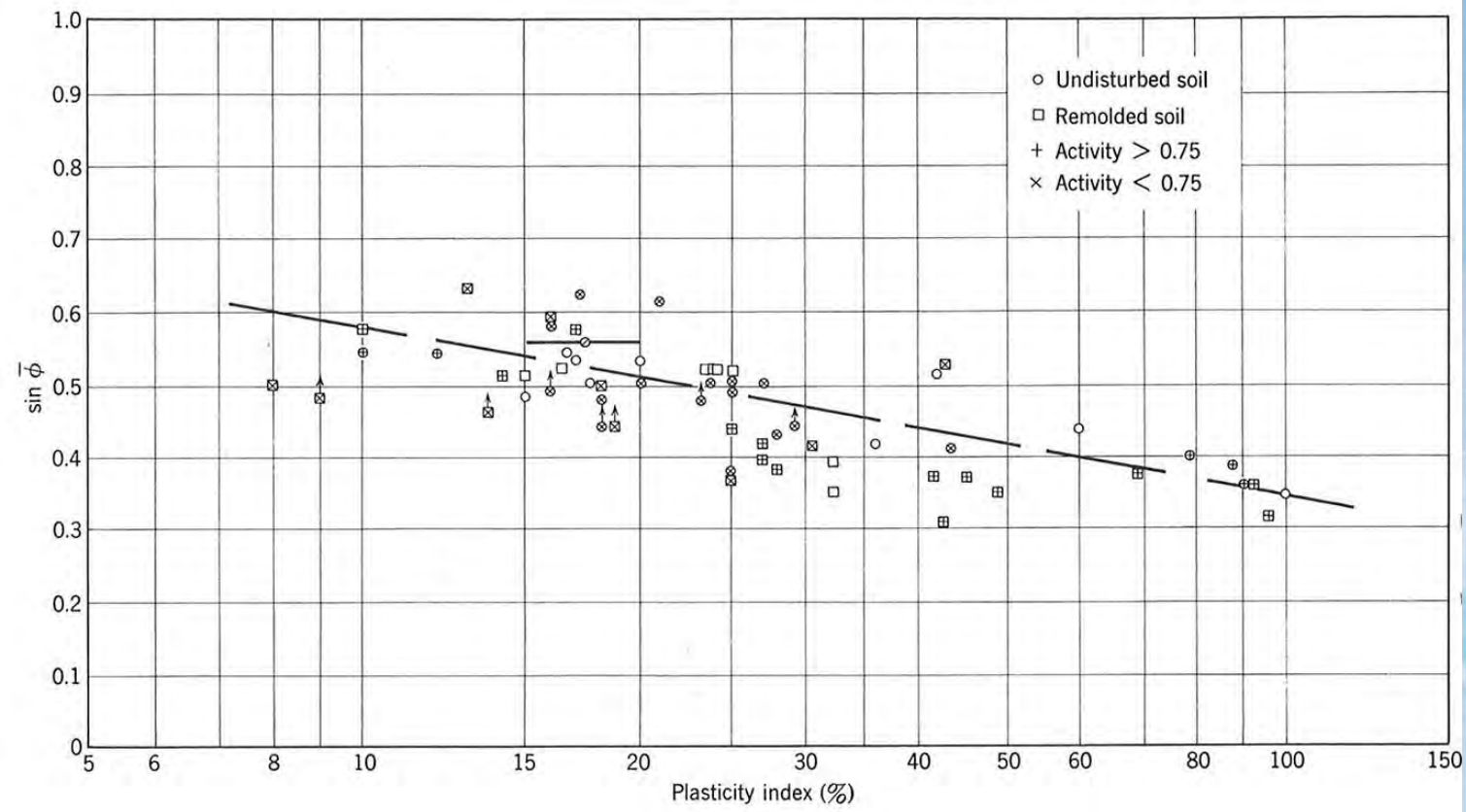


Chart of plasticity versus  $\phi'$   
After Kenney (1953)

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Table from BS8002

Table 3 —  $\varphi'$  for siliceous sands and gravels

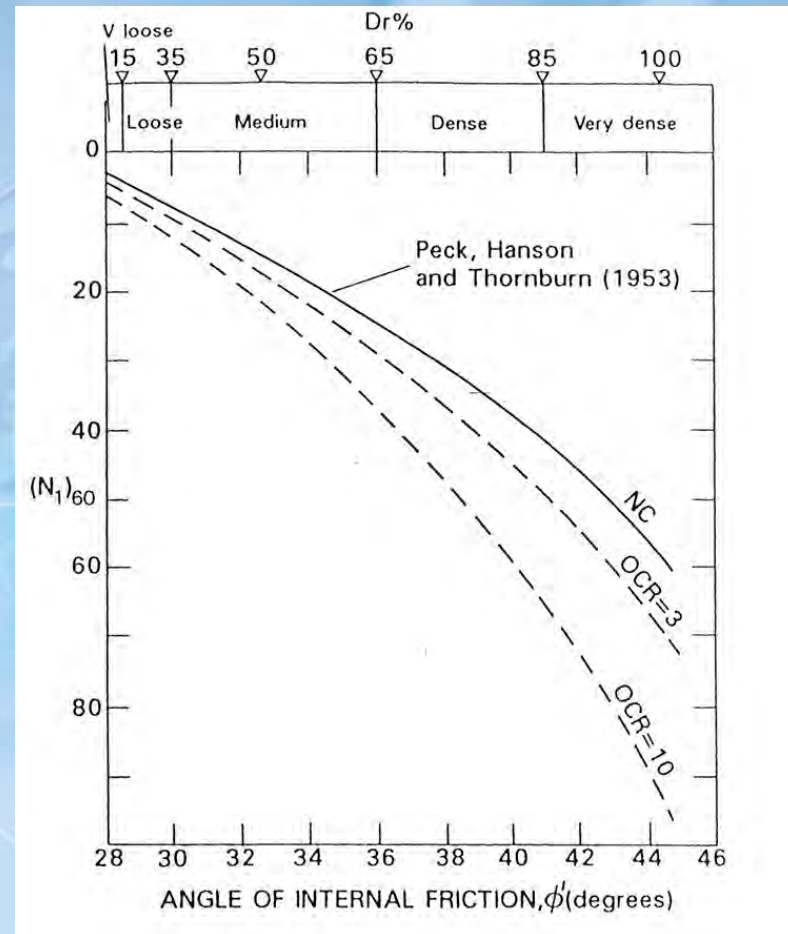
<b>A – Angularity<sup>a</sup></b>	<b>A</b> (degrees)								
Rounded	0								
Sub-angular	2								
Angular	4								
<b>B – Grading of soil<sup>b</sup></b>	<b>B</b> (degrees)								
Uniform	0								
Moderate grading	2								
Well graded	4								
<b>C – N'</b> (blows 300 mm)	<b>C</b> (degrees)								
<10	0								
20	2								
40	6								
60	9								
<p><sup>a</sup> Angularity is estimated from visual description of soil.</p> <p><sup>b</sup> Grading can be determined from grading curve by use of:            Uniformity coefficient = <math>D_{60}/D_{10}</math>            where <math>D_{10}</math> and <math>D_{60}</math> are particle sizes such that in the sample, 10 %, of the material is finer than <math>D_{10}</math> and 60 % is finer than <math>D_{60}</math>.</p> <table> <thead> <tr> <th>Grading</th> <th>Uniformity coefficient</th> </tr> </thead> <tbody> <tr> <td>Uniform</td> <td>&lt;2</td> </tr> <tr> <td>Moderate grading</td> <td>2 to 6</td> </tr> <tr> <td>Well graded</td> <td>&gt;6</td> </tr> </tbody> </table> <p>A step-graded soil should be treated as uniform or moderately graded soil according to the grading of the finer fraction.  <math>N'</math> from results of standard penetration test modified where necessary by Figure 2.            Intermediate values of A, B and C by interpolation.</p>		Grading	Uniformity coefficient	Uniform	<2	Moderate grading	2 to 6	Well graded	>6
Grading	Uniformity coefficient								
Uniform	<2								
Moderate grading	2 to 6								
Well graded	>6								

$$\varphi'_{\text{critical}} = 30^\circ + A + B$$

$$\varphi'_{\text{peak}} = 30^\circ + A + B + C$$

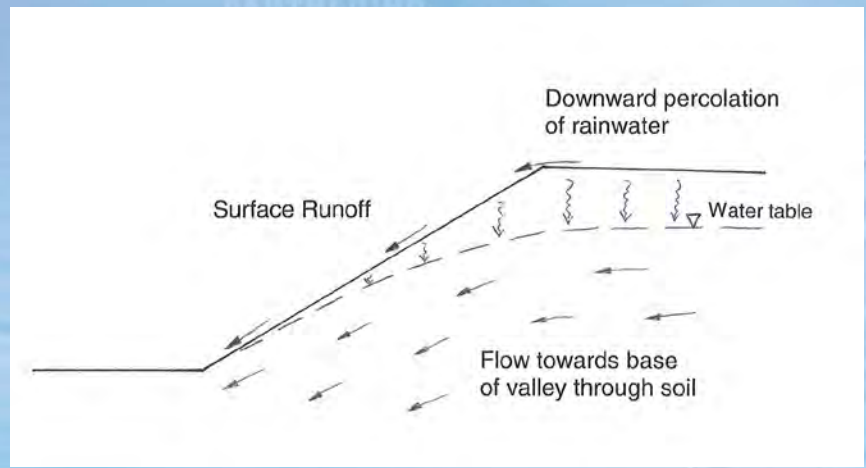
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Correlation between Standard Penetration Test 'N' (blows for 300mm penetration) and friction angle From Stroud (1988)

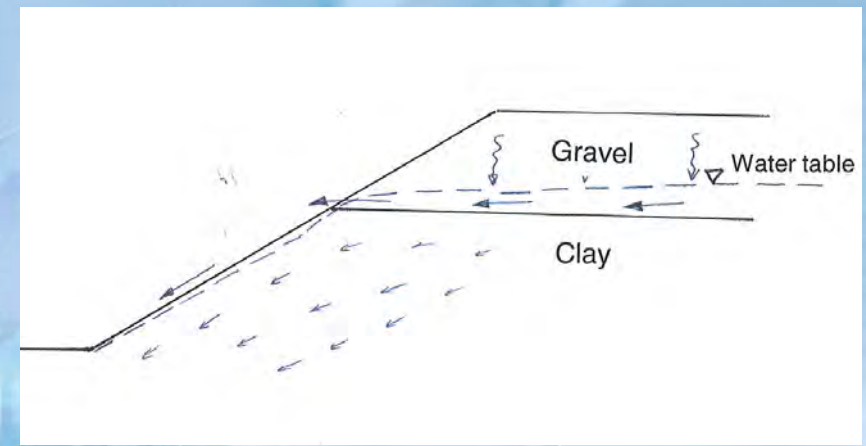


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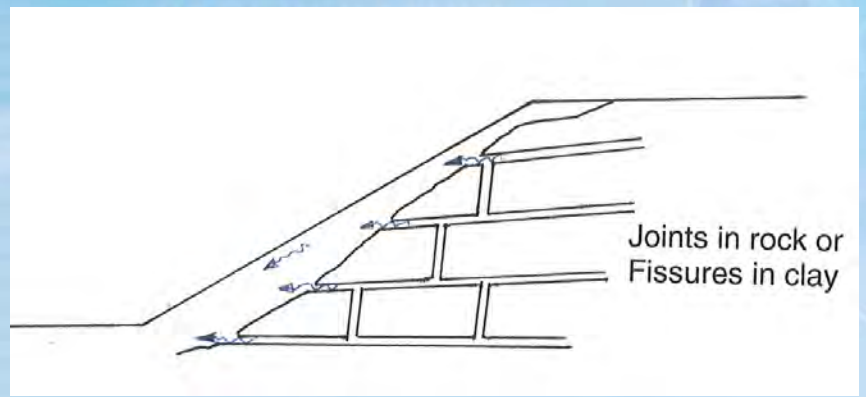
1) Ground water movement through homogenous soils slope



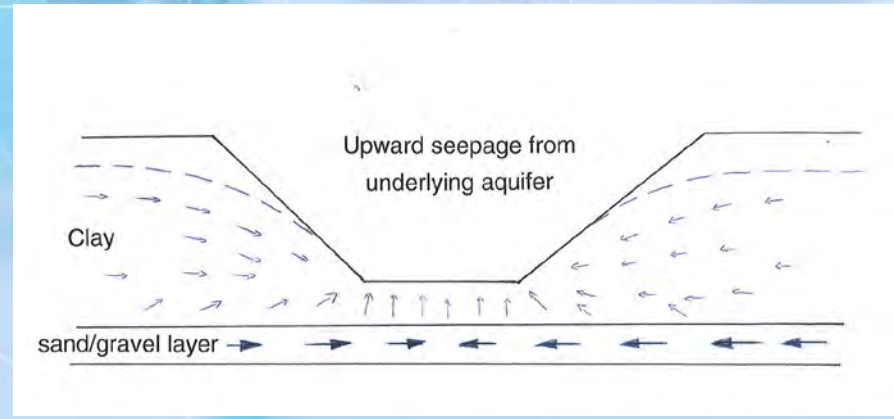
2) Perched water



3) Rapid flow through joints/fissures



4) Upwards seepage from aquifer

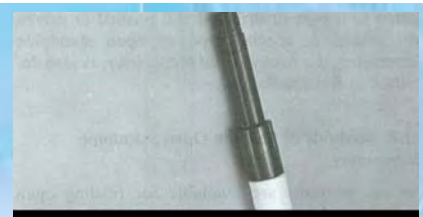
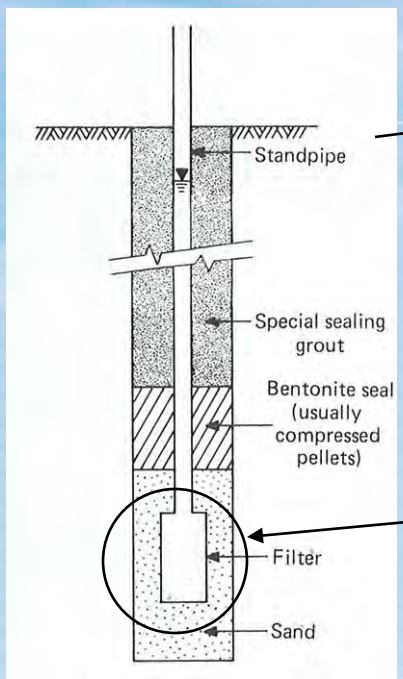
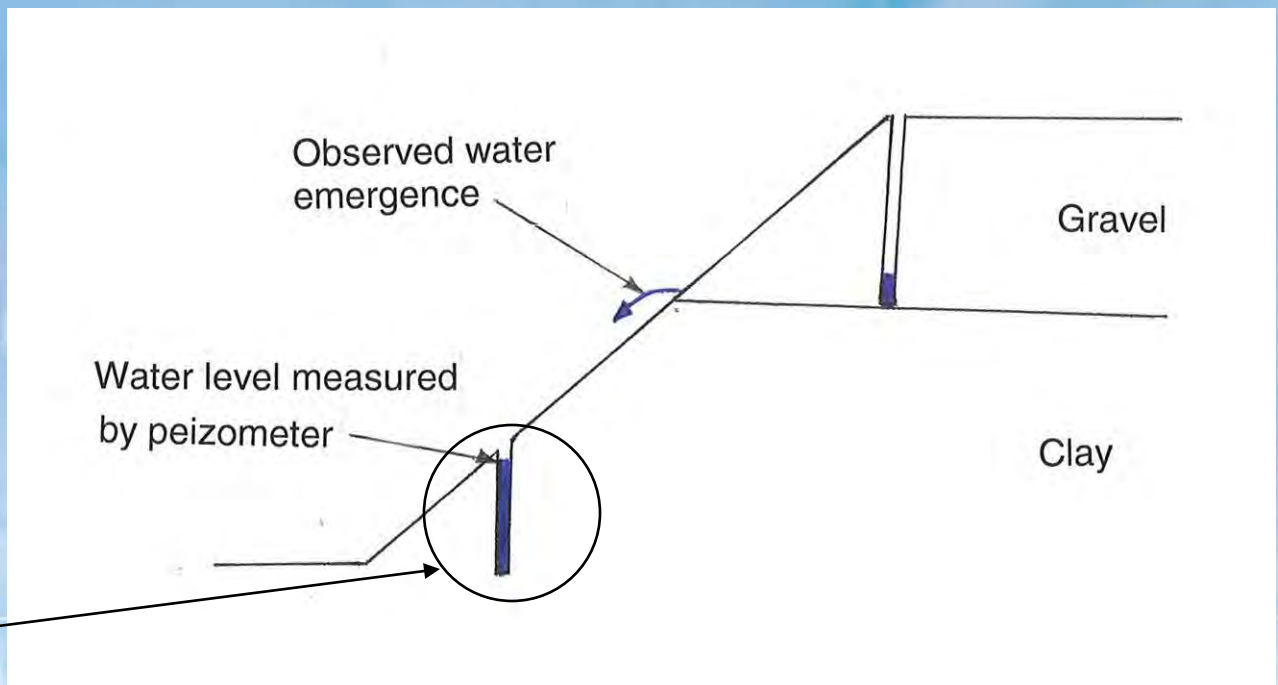


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**How do you characterise the ground water regime?**

- 1) Knowledge of the geology – soil sequence, rock type, jointing.**
- 2) Observation – surface flows, surface ponding, vegetation?**
- 3) Direct measurement - water strikes in trial pits and boreholes, ,piezometers**
- 4) Backanalysis of failures.**

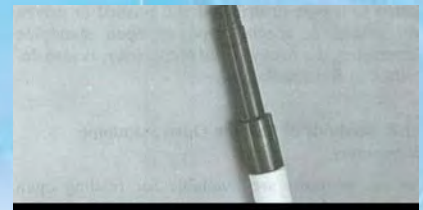
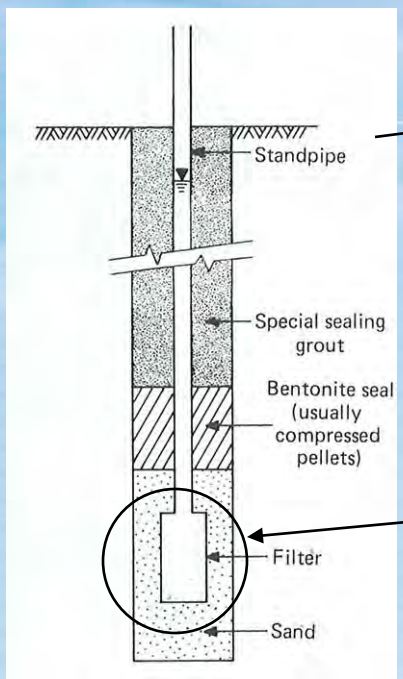
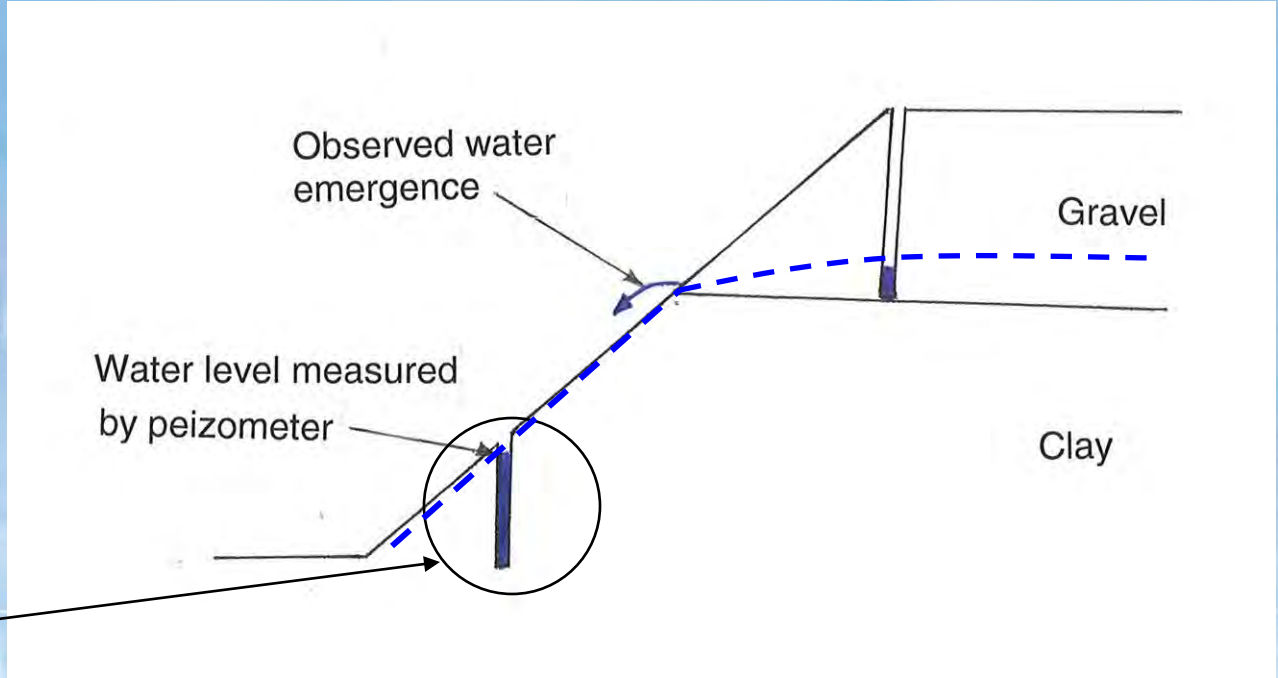
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High density porous hydrophilic polyethylene tip

Figures from "?????????????" by C.J Dunicliff

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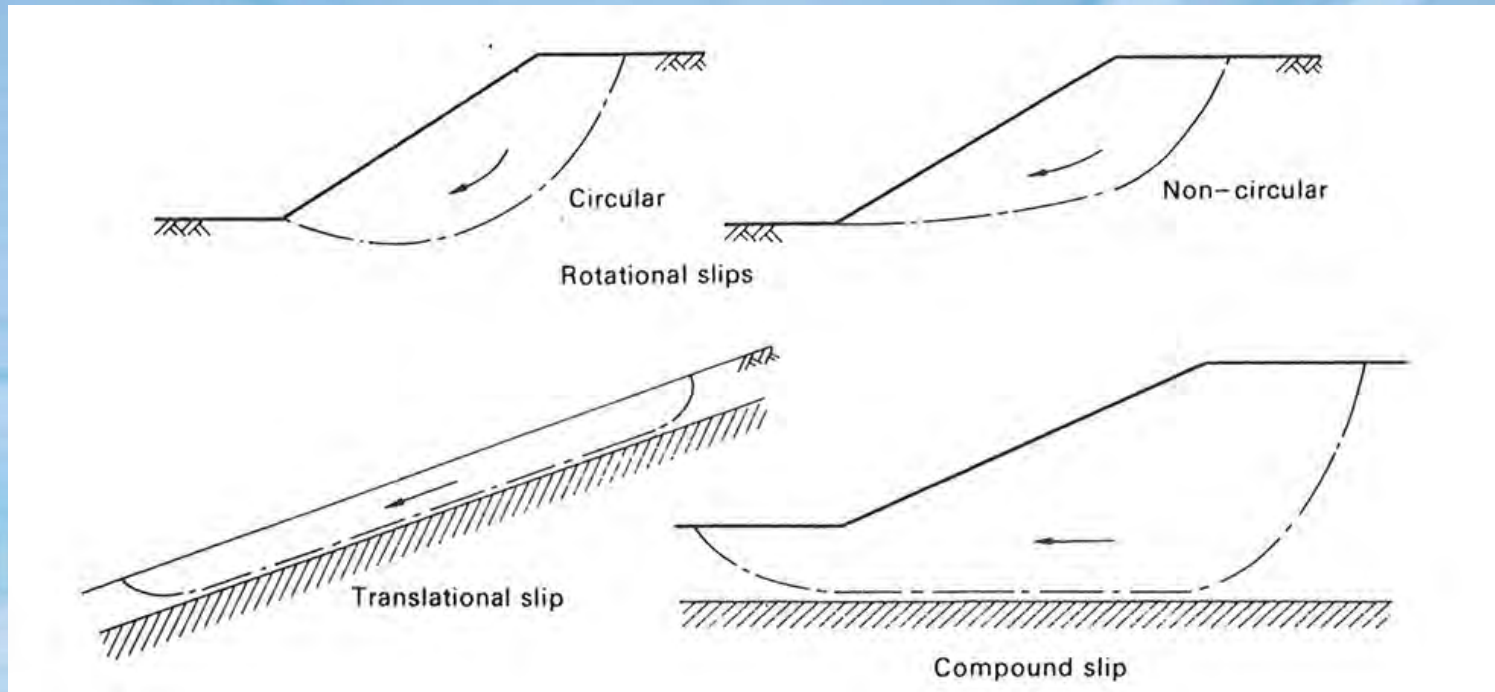
High density porous hydrophilic polyethylene tip

Figures from "?????????????" by C.J Dunicliff

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## Slope stability analysis

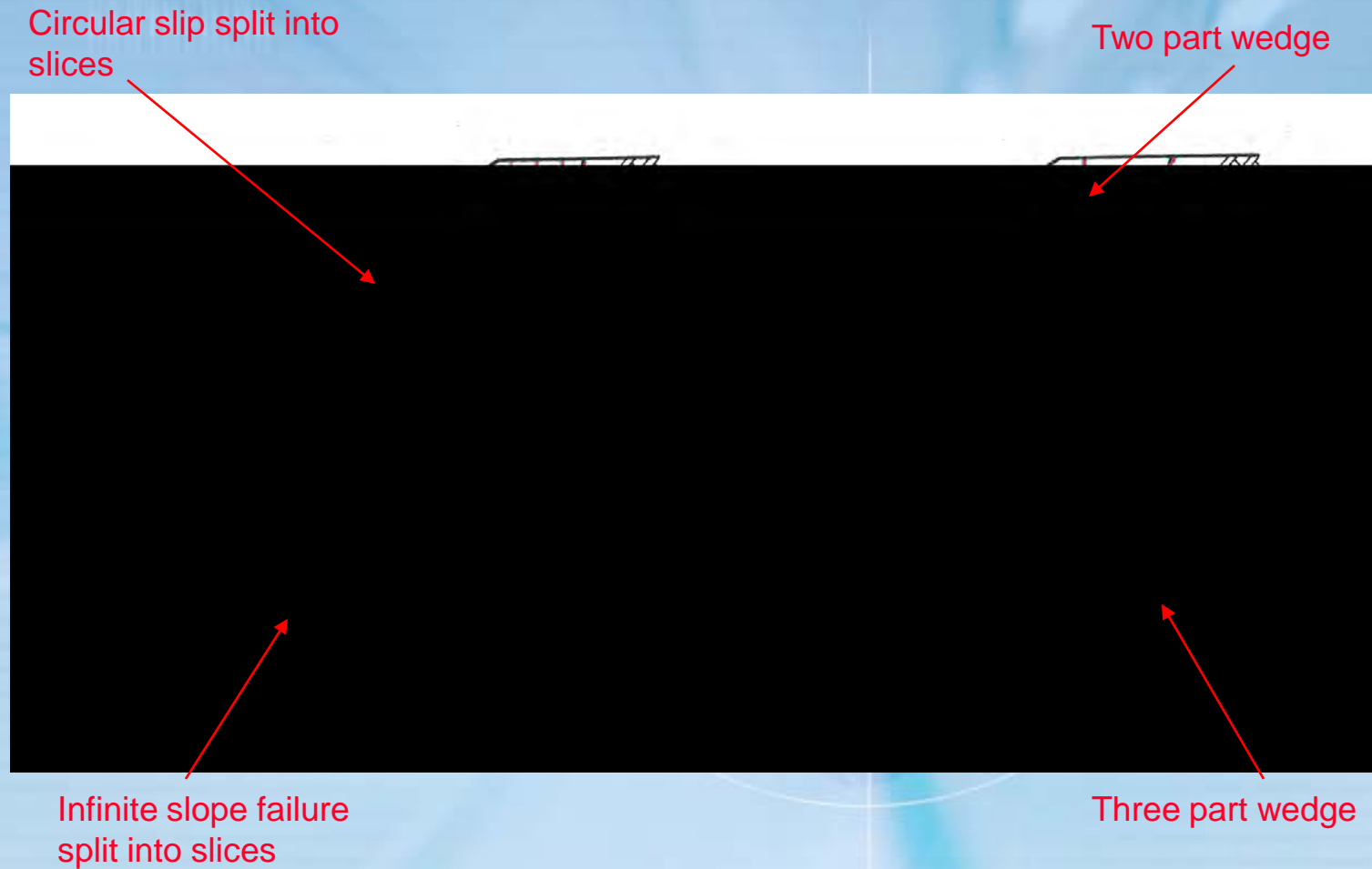
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## Typical failure shapes

Figure from "Soil Mechanics" by R.F Craig

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$$\text{Factor of safety (F)} = \frac{\text{Resisting forces}}{\text{Driving forces}}$$

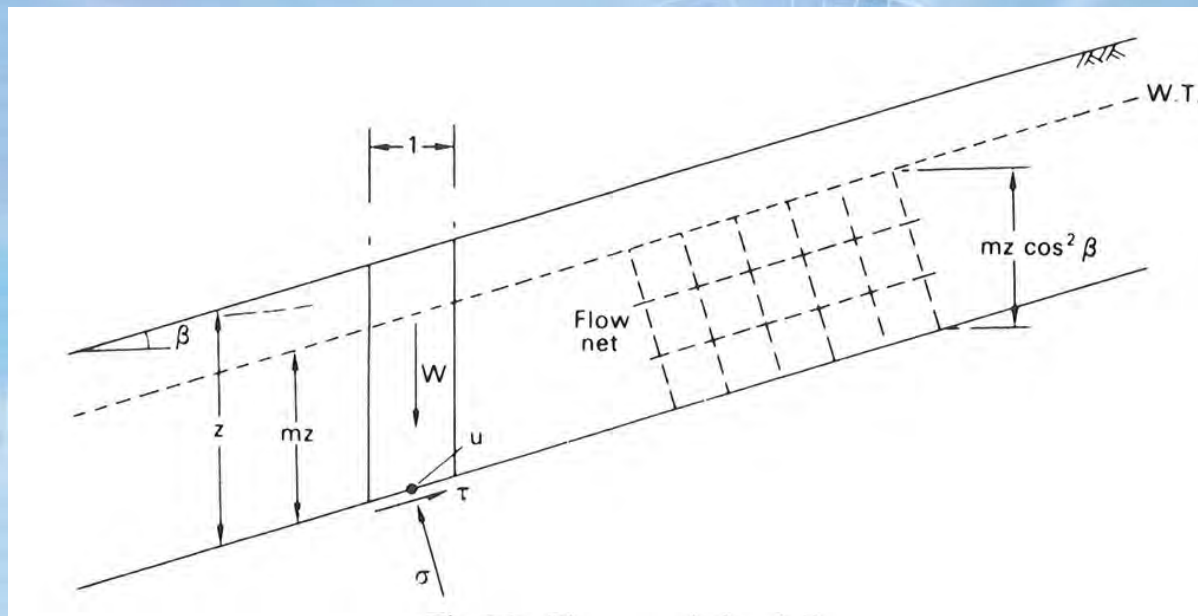
When  $F < 1$  Resisting forces exceed driving forces and slope has failed.  
When  $F > 1$  Resisting forces are less than the driving forces so the slope is stable.

Therefore F is a measure of the degree of stability of the slope.

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## Infinite Slope analysis –

Figure from “Soil Mechanics” by R.F Craig

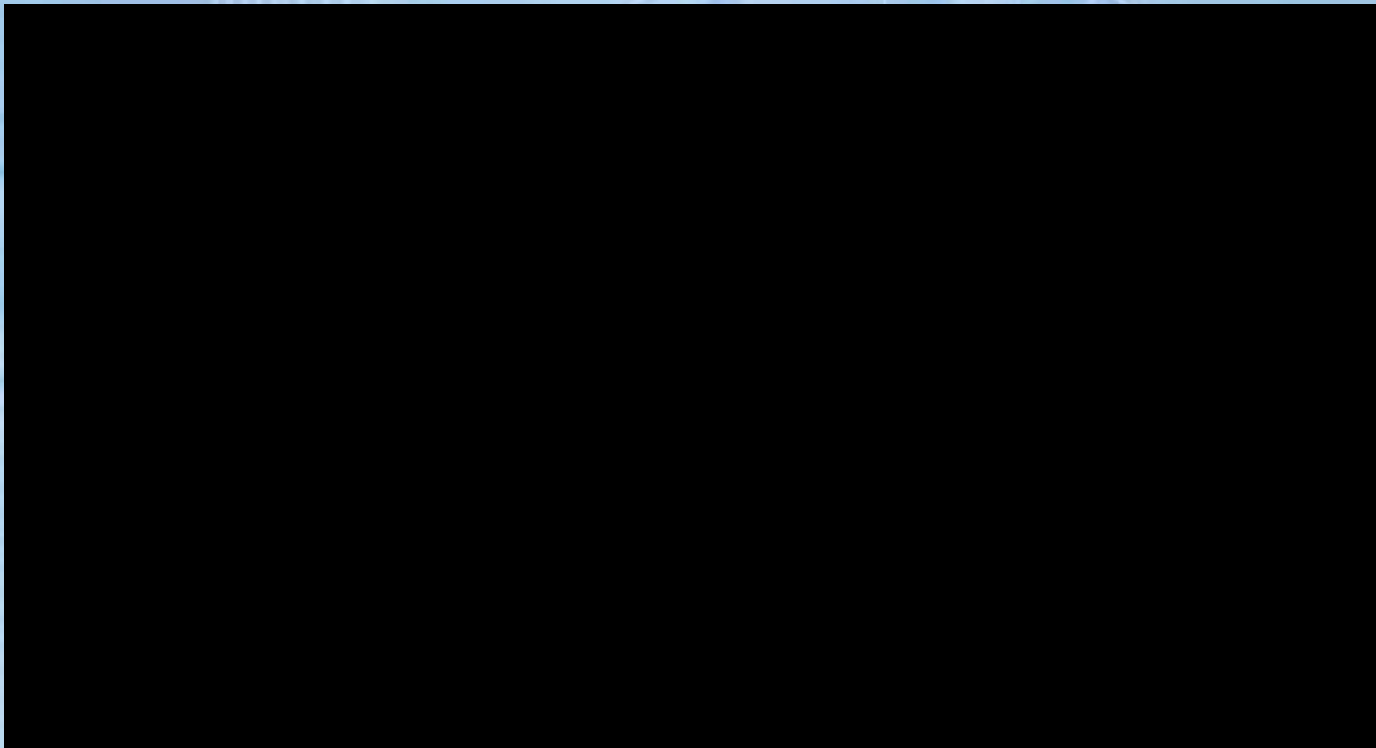


$$F = \tan \phi' / \tan \beta \quad (\text{if } c' = 0 \text{ and } m = 0)$$

$$F = \gamma_{\text{buoy}} \tan \phi' / \gamma_{\text{sat}} \tan \beta \quad (\text{if } c' = 0 \text{ and } m = 1)$$

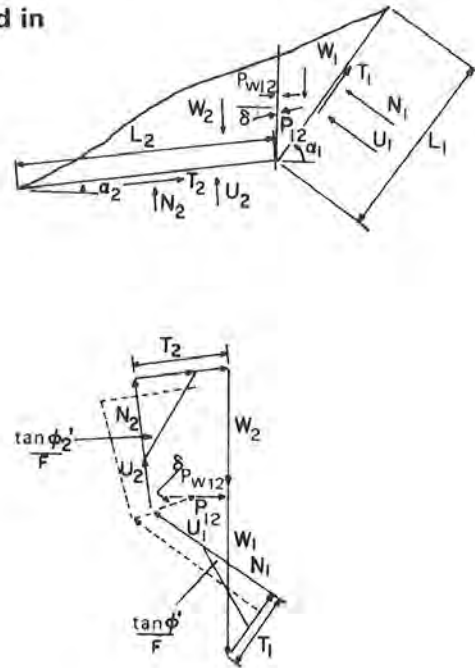
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Circular slip surface – method of slices  
Figure from “Soil Mechanics” by R.F Craig



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Figure 7.17. Forces used in typical wedge analysis.



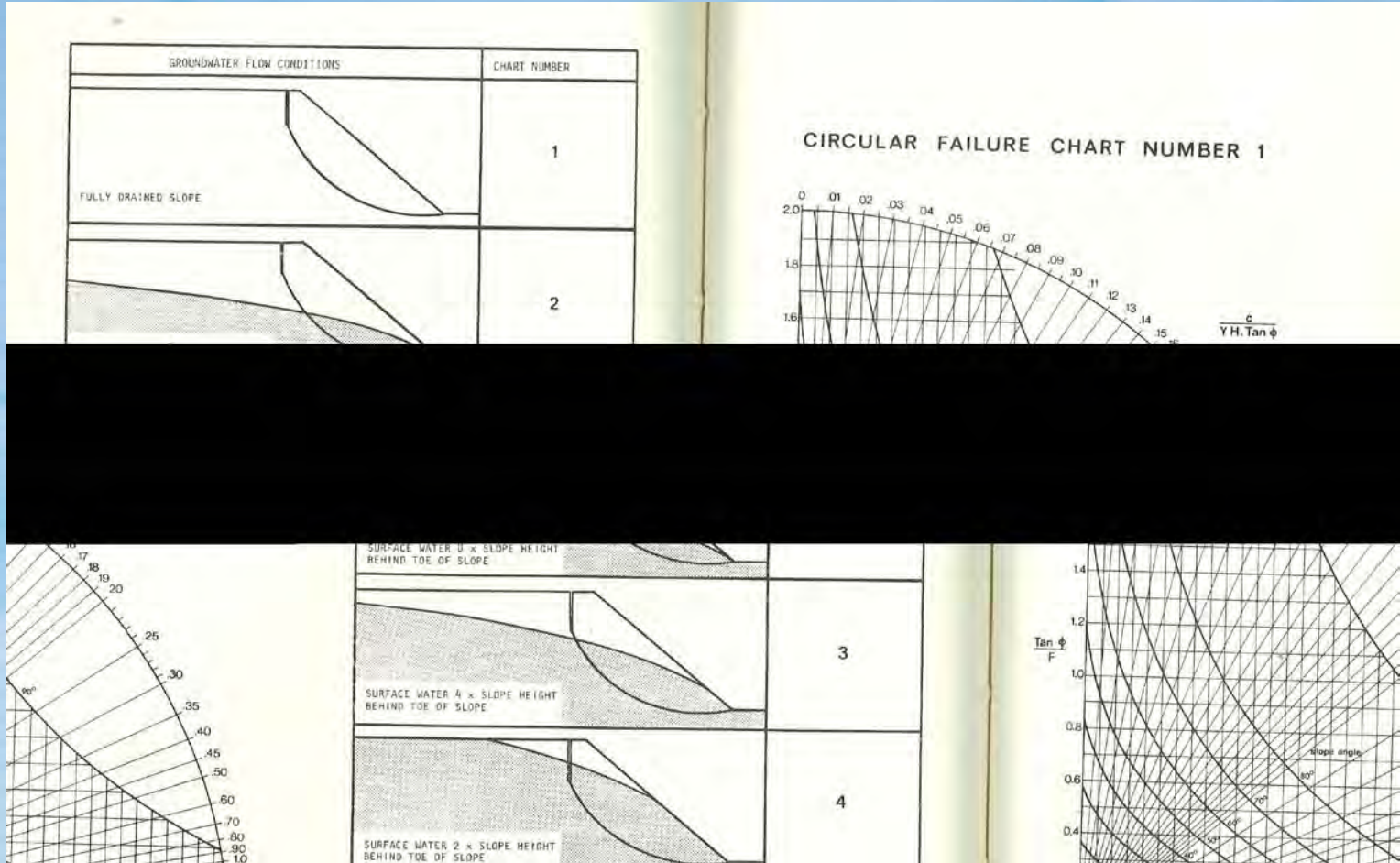
## Two part wedge analysis

Figure from "Landslides – Analysis and Control" Special Report 176 by Transportation Research Board National Academy of Sciences.

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- Undertaking a single slope stability analysis is quite complicated
- In most cases you won't know the shape or depth of the most critical (worst) failure surface. Need to undertake many calculations to determine which has the lowest factor of safety.
- There are a couple of ways to speed up the process:
  - 1) using slope stability charts
  - 2) slope stability computer programs

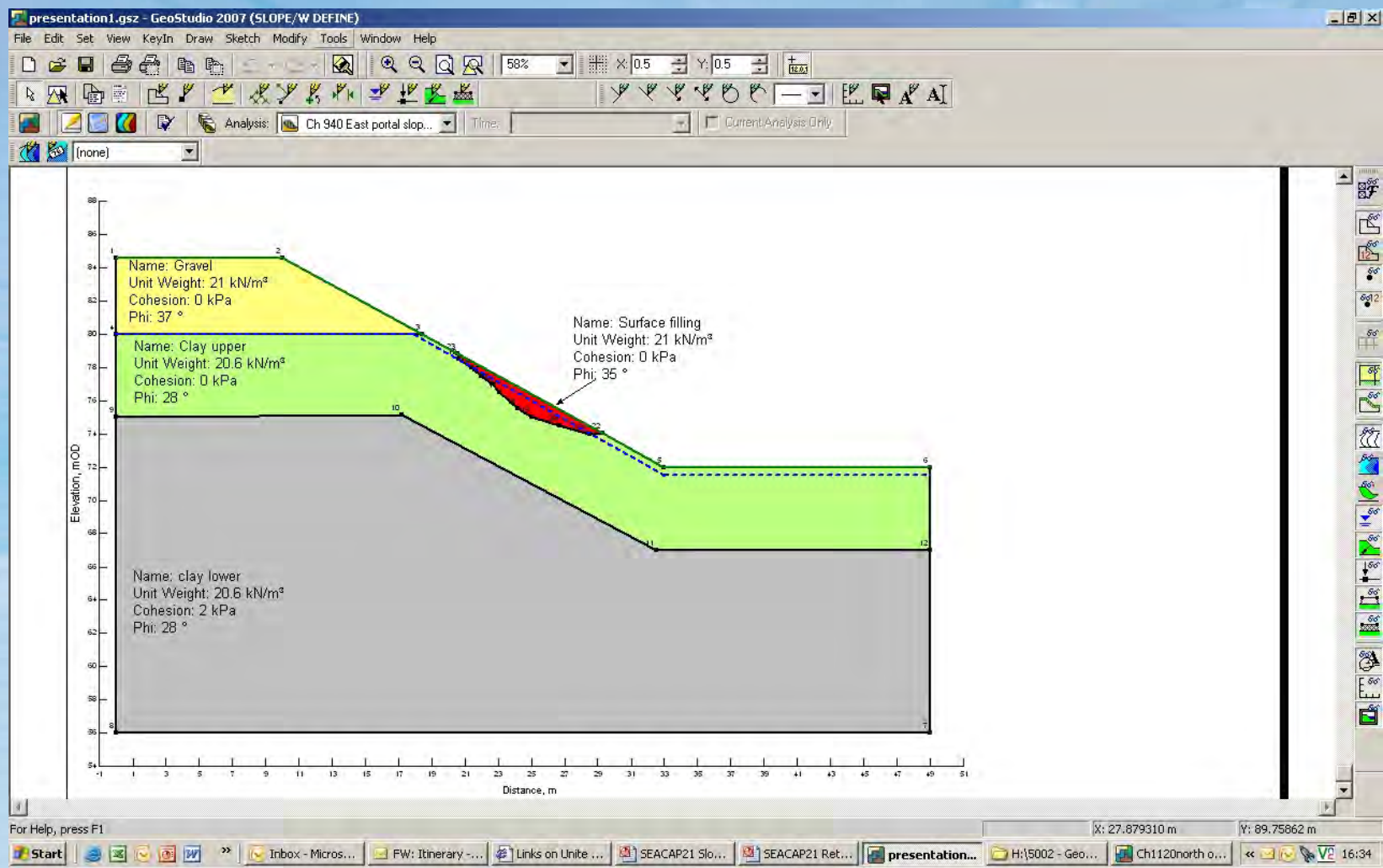
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**Example slope stability charts**  
from "Rock Slope Engineering" by Hoek and Bray

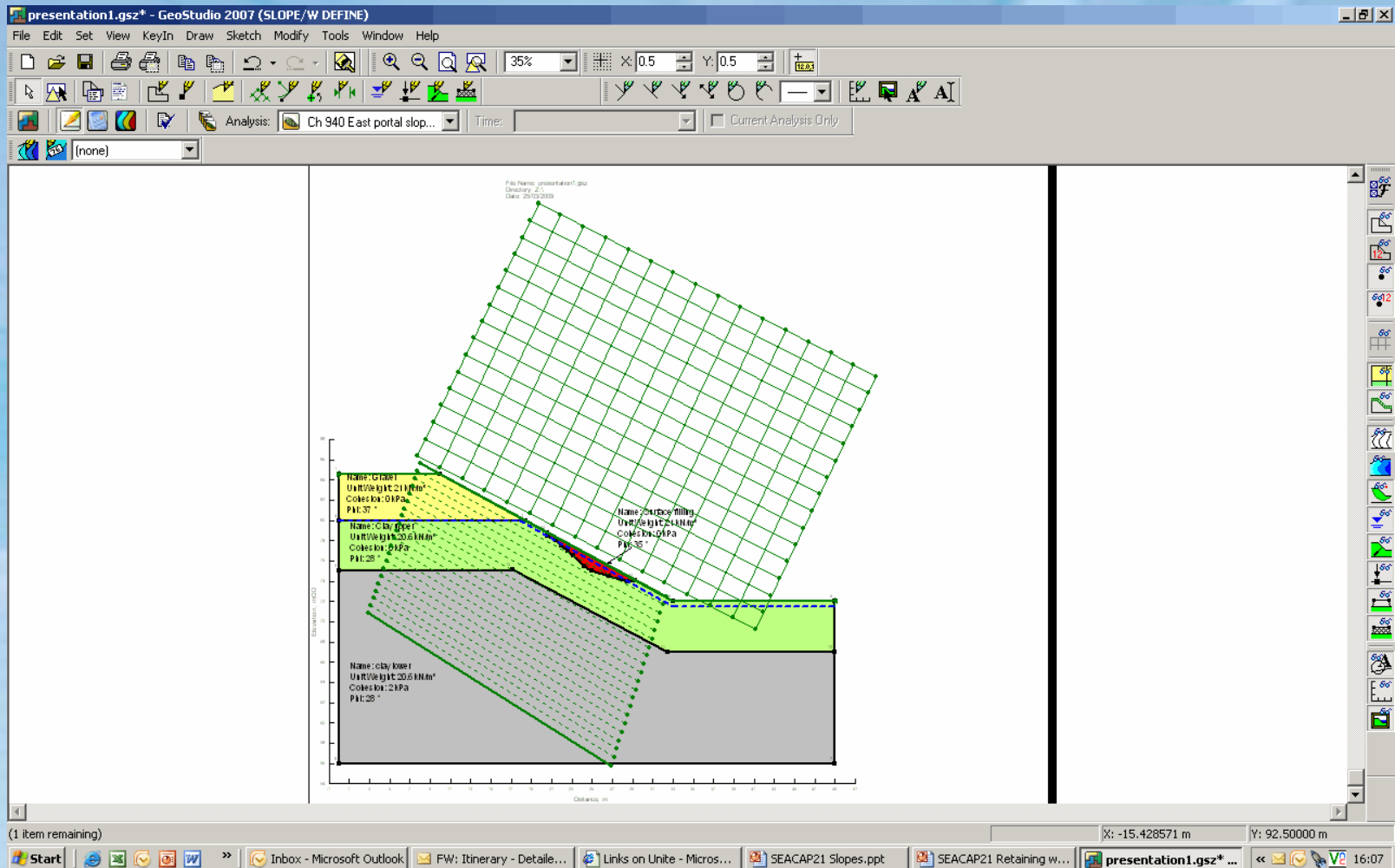
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Screen from SLOPE/W software



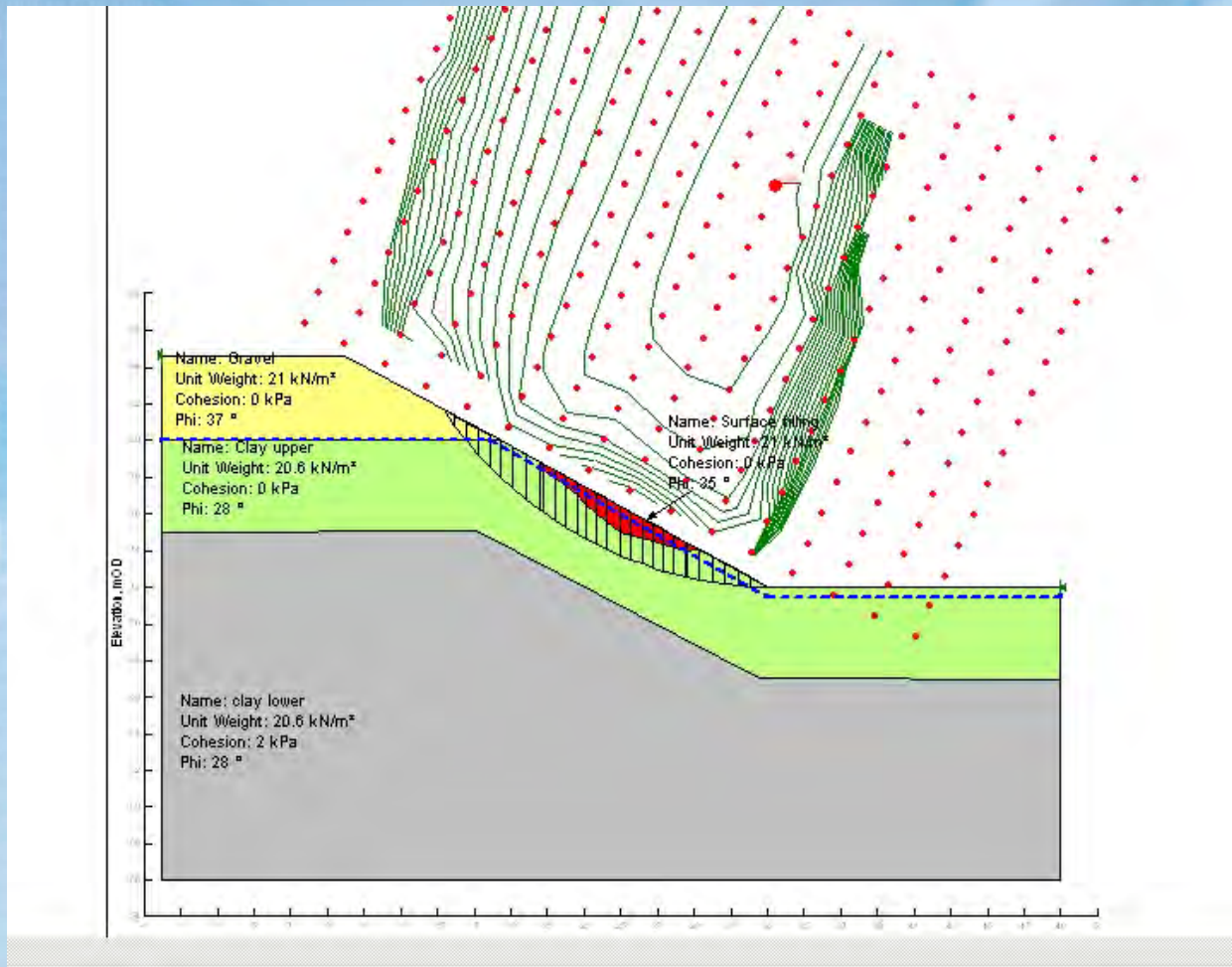
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Screen from SLOPE/W software



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Partial screen from SLOPE/W software



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Partial screen from SLOPE/W software

The screenshot displays the SLOPE/W software interface. The main window shows a cross-section of a slope with a failure surface. The soil is divided into layers with different properties. A red shaded area represents the failure surface. The software is using the Morgenstern-Price method for the analysis.

**Free Body Diagram & Force Polygon**

Slice 11 - Morgenstern-Price Method

Factor of Safety	0.60535
Phi Angle	28°
C (Strength)	0 kPa
C (Force)	0 kN
Pore Water Pressure	23.147 kPa
Pore Water Force	17.637 kN
Pore Air Pressure	0 kPa
Pore Air Force	0 kN
Phi B Angle	0°
Slice Width	0.62703 m
Mid-Height	2.682 m
Base Length	0.76195 m
Base Angle	-34.622°
Anisotropic Strength Mod.	1
Applied Lambda	0.6182
Weight (incl. Vert. Seismic)	34.728 kN
Base Normal Force	27.898 kN
Base Normal Stress	36.614 kPa
Base Shear Res. Force	-5.4558 kN
Base Shear Res. Stress	-7.1603 kPa
Base Shear Mob. Force	-9.0127 kN
Base Shear Mob. Stress	-11.828 kPa
Left Side Normal Force	60.254 kN
Right Side Normal Force	68.734 kN
Left Side Shear Force	27.898 kN
Right Side Shear Force	35.634 kN

View Slice Information: Click on any slice to view computed information about it

Step: 1 | X: 28,285714 m | Y: 82,12605 m

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# Backanalysis

A method of diagnosis

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## Slope stability analysis – Use in design

There are two main ways that slope stability analysis is used in design.

### 1) Forward analysis

- Determine ground topography,
- do ground investigation to find soil and rock geometry and engineering properties and ground water regime.
- Set up slope stability analysis to examine the most likely failure shapes and the minimum factor of safety.

2) **Backanalysis** – Where the shape and depth of an existing slip is known then this information can be used to check that the soil parameters and ground water regime are reasonable.

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### “Back” Analysis

Immediately prior to failure we know the the Factor of Safety was = 1  
(UNITY)

From the mapping we can determine:

- Original ground level.
- Position of failure plane.
- Type of failure i.e. planar, rotational etc

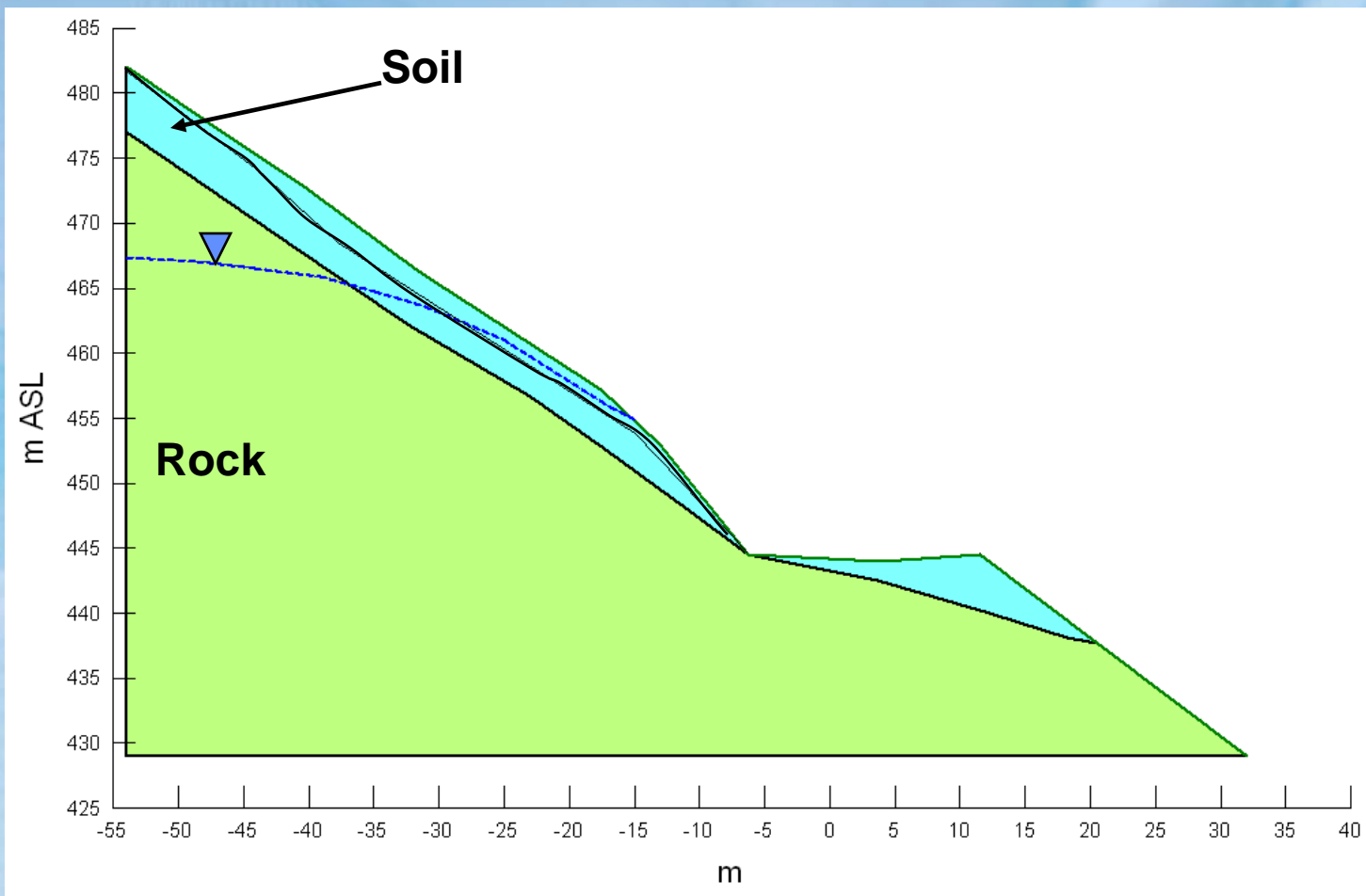
From the ground investigation we can determine:

- The level of the strata
- Soil parameters
- Ground water regime

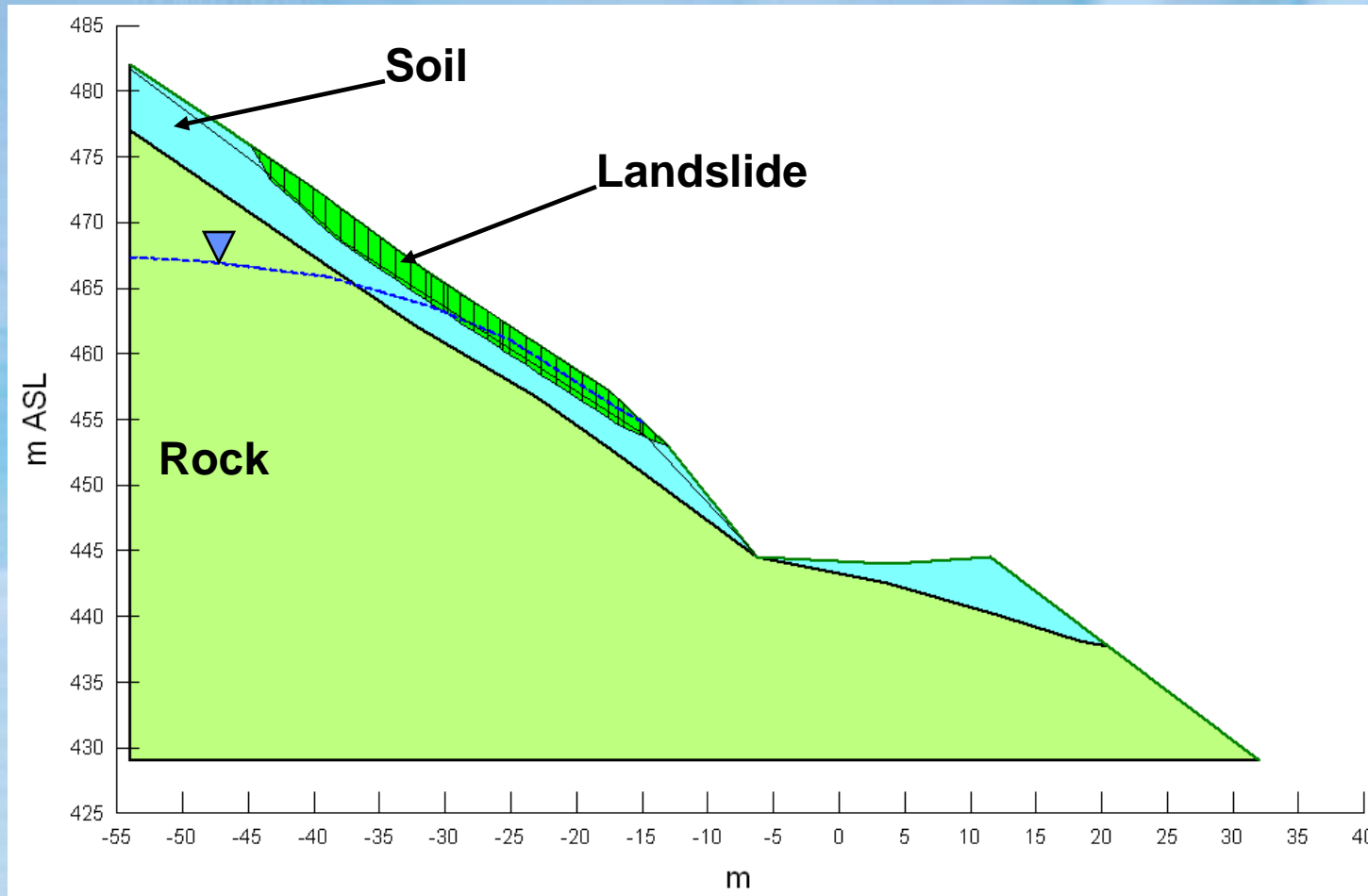
However there are often areas of the ground investigation where there is still uncertainty.

Back analysis can enable us to check the areas of uncertainty.

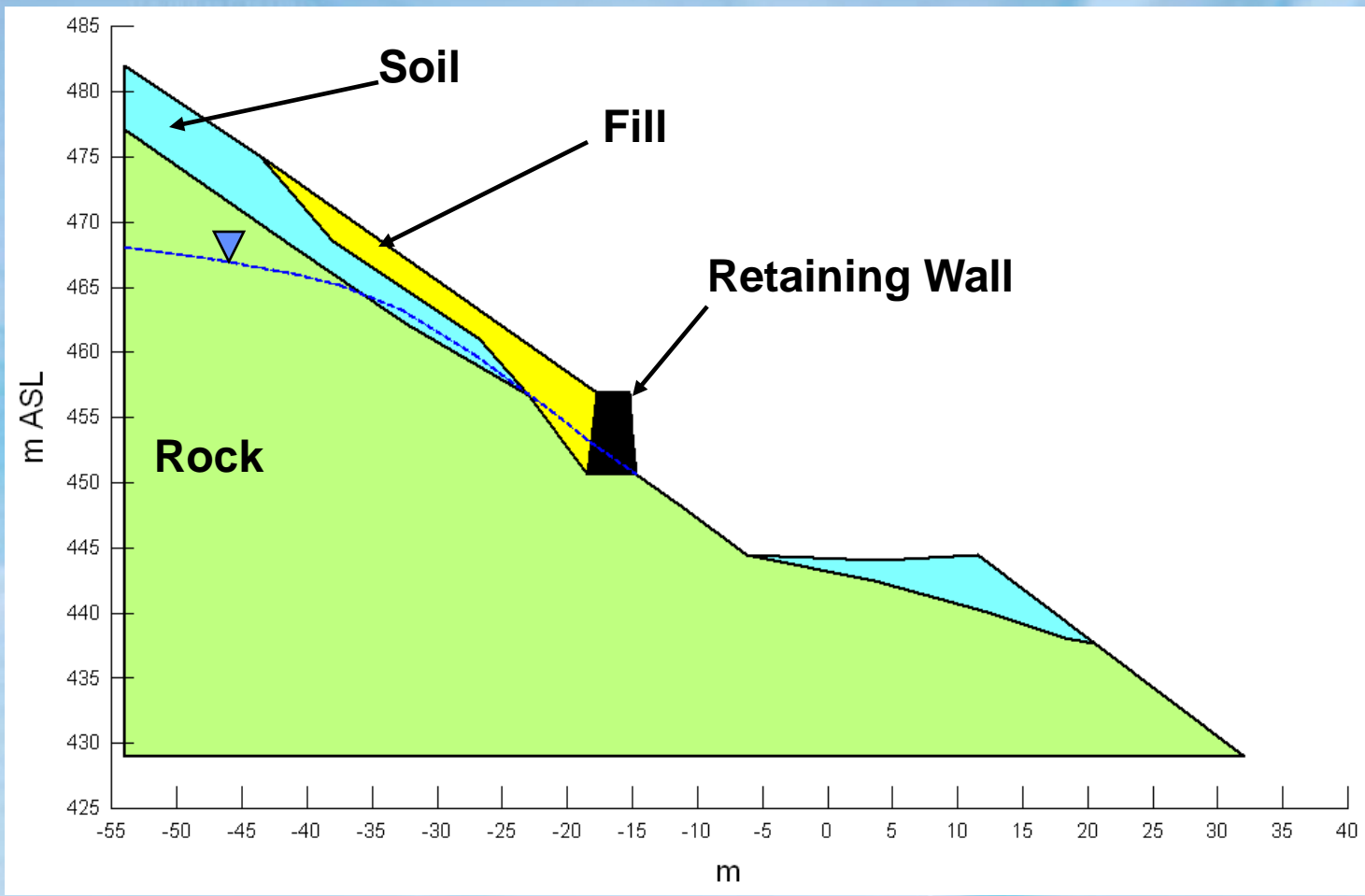
# SEACAP 21/004 Landslide Management Back Analysis Example



# Back Analysis Example



# Back Analysis Example



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## In conclusion

Why do slopes fail?

Either the:

Driving loads increased by adding weight near head of slip.

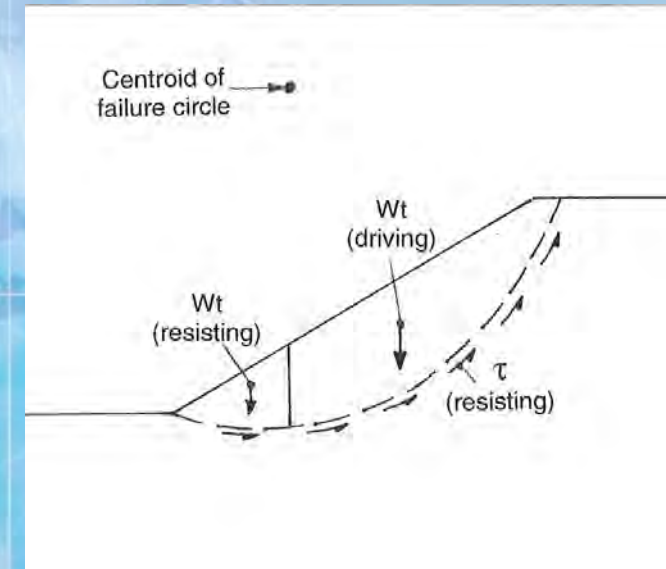
Or the:

Resisting loads reduced by either:-

Reduction in weight near toe of slip (by erosion or excavation).

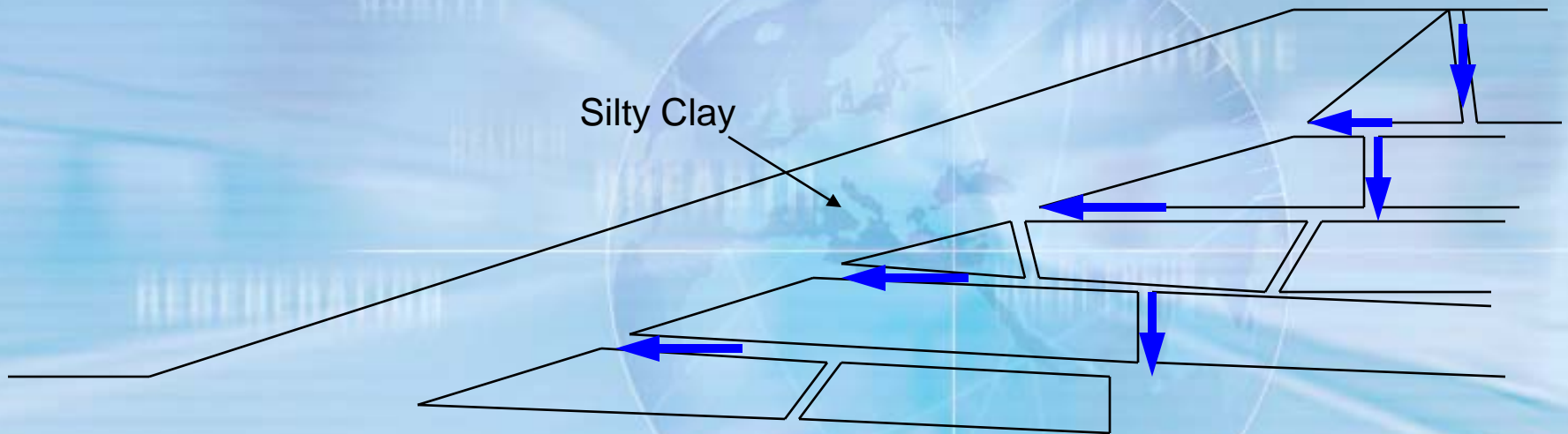
or:

Reduction in shear strength – rarely by reducing  $\phi$  or  $c'$  but often by increasing  $u$ .



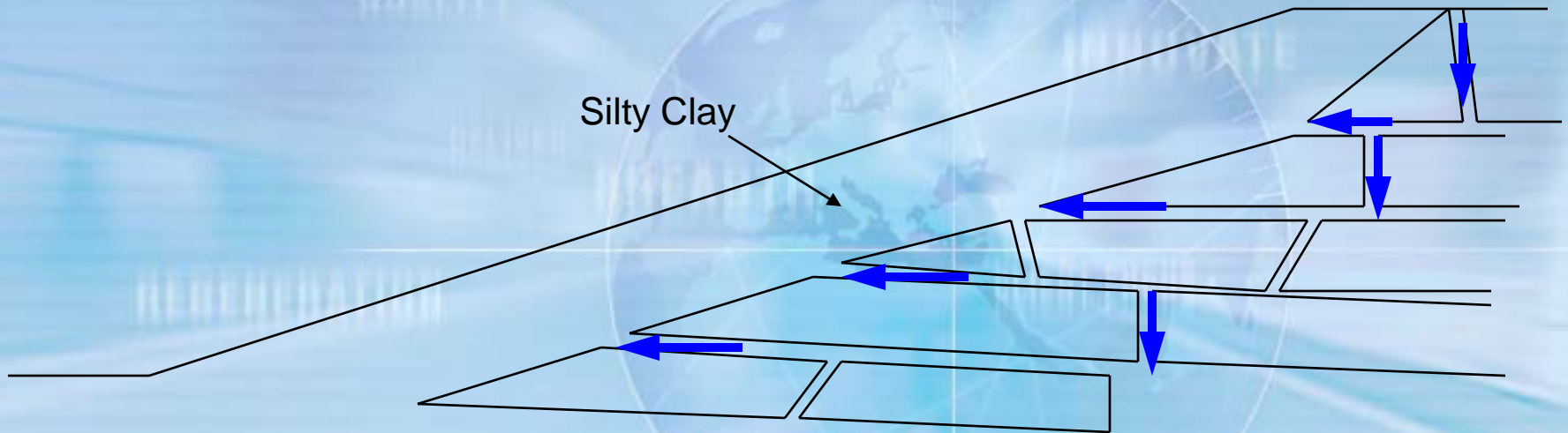
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1) How is this slope most likely to fail?



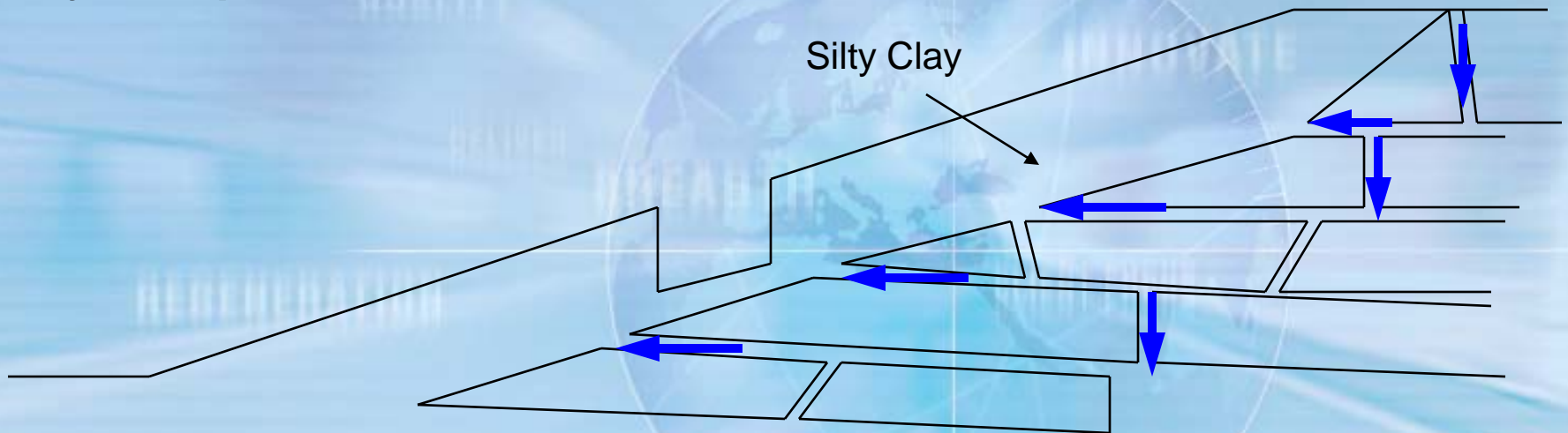
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2) What method would you use to analyse this failure?



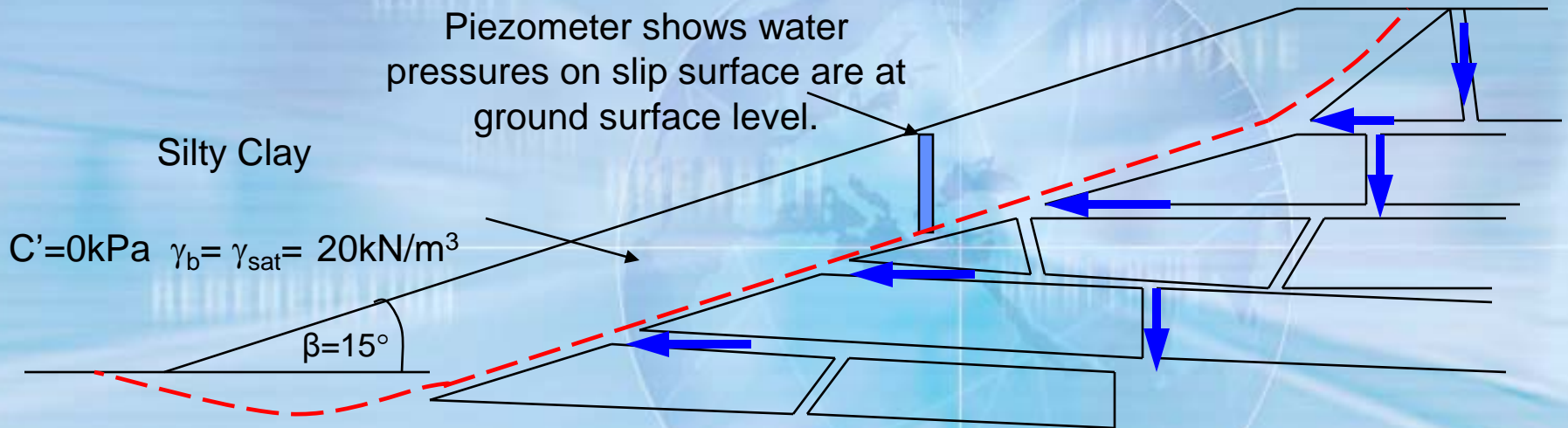
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3) If you dug a trial pit or a borehole would you expect water to flow in?



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4) The slope has just failed (as you thought it might)! What was the friction angle of the clay?



For infinite slope failure where water table is at ground surface and  $c'=0$ .

$$F = \gamma_{\text{buoy}} \tan \phi' / \gamma_{\text{sat}} \tan \beta$$

Where  $\gamma_{\text{sat}}$  is the saturated bulk unit weight (for clays =  $20\text{kN/m}^3$ )

$$\gamma_{\text{buoy}} = \gamma_{\text{sat}} - \gamma_w = 20 - 10 = 10\text{kN/m}^3$$

$$\beta = 15^\circ$$

At time of failure  $F=1$

Substitute numbers into equation above:  $1 = 10 \tan \phi' / 20 \tan 15^\circ$

Rearrange to find  $\phi'$ :  $\phi' = \tan^{-1} \left( \frac{20 \tan 15^\circ}{10} \right)$

$$\phi' = 28^\circ$$

In reality there may be a small cohesion and if this were the case then  $\phi$  at failure would be slightly lower.