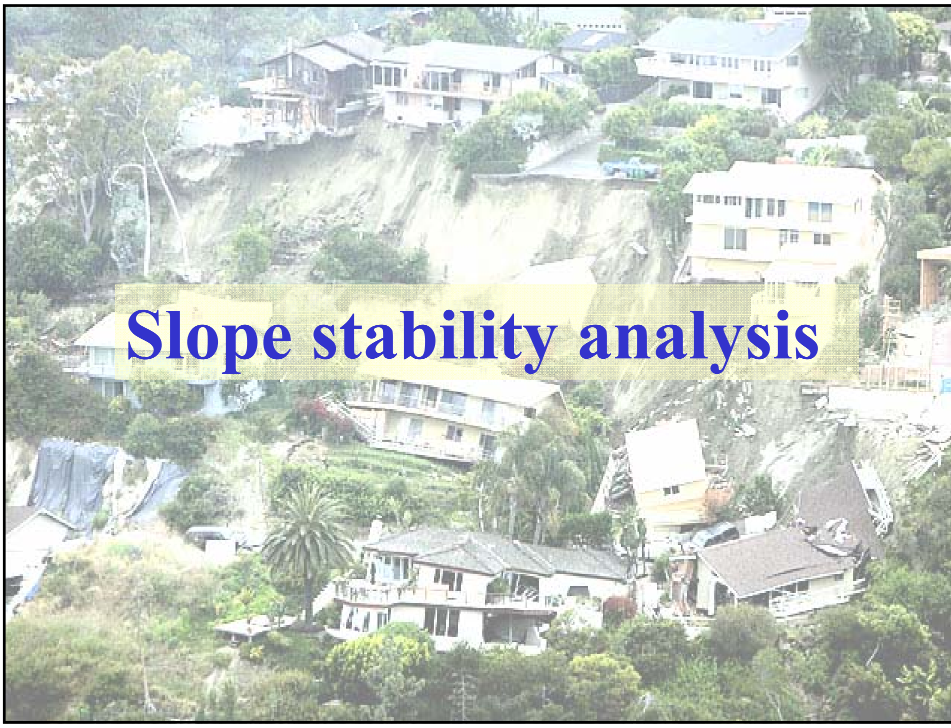
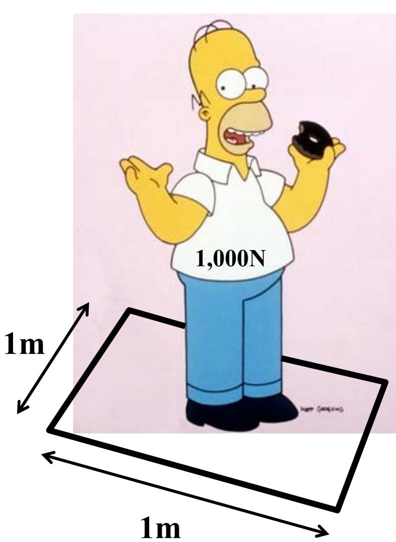


Slope stability analysis



Unit of stress:

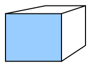
1 kilopascal kPa

= 1 kN/m^2

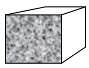
(Kilo Newtons per square meter)

Slightly above-average American male

Unit weights of materials (per m^3)

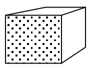


Water, $\gamma_w = g\rho_w = 9.81$ kN/m^3

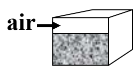


Solid rock, $\gamma_s = 26.0$ kN/m^3

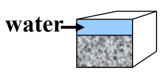
V_s= volume solids
V_v= volume voids
Porosity:
$n=V_v/(V_v+V_s)$



Soil-made up of solid grains and pores



Dry soil, idealized:
$\gamma_d = \gamma_s V_s/(V_s+V_v) = \gamma_s(1\text{-}n) = 15\text{-}20$ kN/m^3



Saturated soil:
$\gamma_{sat} = (\gamma_s V_{s+} \gamma_s V_s)/(V_s+V_v) = 20\text{-}23$ kN/m^3

Infinite slope equation

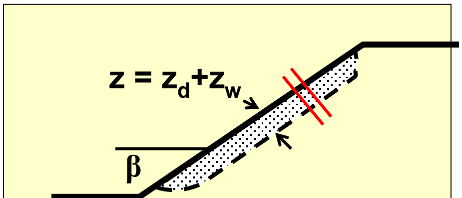


Fig. 1
Slope cross-section

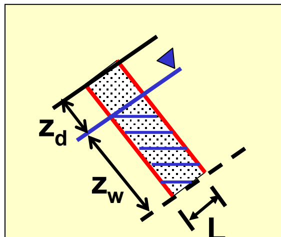


Fig. 2
Isolate a column

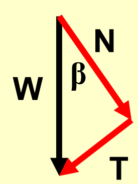


Fig. 3
Force polygon

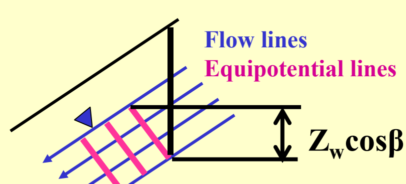


Fig. 4
Groundwater pressure

$$F = \frac{c' + (\gamma_d z_d + \gamma_{sat} z_w - \gamma_w z_w)\cos\beta \tan\phi}{(\gamma_d z_d + \gamma_{sat} z_w)\sin\beta}$$

γ_w = unit weight of water (9.81 kN/m^3)

γ_d = dry unit weight of soil (15-20 kN/m^3)

γ_{sat} = saturated unit weight of soil (20-23 kN/m^3)

Note: the soil column is assumed to be 1m wide perpendicular to paper

Assume no cohesion (c=0) and full saturation, $z_d = 0$:

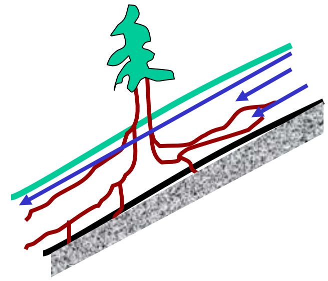
$$F = \frac{z_w(\gamma_{sat} - \gamma_w)\cos\beta \tan\phi}{\gamma_{sat} z_w \sin\beta} = (1 - \frac{\gamma_w}{\gamma_{sat}})\frac{\tan\phi}{\tan\beta} \approx 0.5\frac{\tan\phi}{\tan\beta}$$

Assume no cohesion (c=0) and a dry slope, $z_w = 0$:

$$F = \frac{\tan\phi}{\tan\beta}$$

Conclusion: a dry cohesionless slope will be at the point of failure when $\beta = \phi$ ("angle of repose"). However, a saturated slope with parallel seepage will be about half as steep.

Role of cohesion:

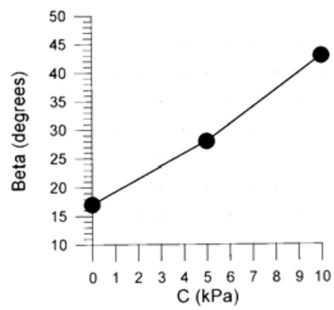


Assume fully saturated slope, parallel seepage
$z = z_w = 1.5$ m
$\varphi = 32^o$

$$F = \frac{c' + (\gamma_d z_d + \gamma_{sat} z_w - \gamma_w z_w)\cos\beta\tan\phi}{(\gamma_d z_d + \gamma_{sat} z_w)\sin\beta}$$

Solve equation to find c' when F=1.0 (at failure)

Conclusion:
Slopes in mountainous regions require cohesion



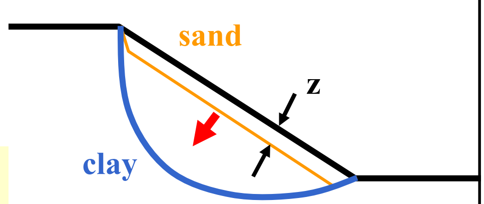
Undrained (short term) slope failure in clay

$$F = \frac{c' + (\gamma_d z_d + \gamma_{sat} z_w - \gamma_w z_w)\cos\beta\tan\phi}{(\gamma_d z_d + \gamma_{sat} z_w)\sin\beta}$$

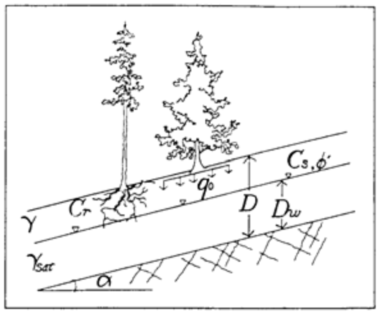
- **$\varphi' = 0$**
- **S_u instead of c'**
- **Slope fully saturated** (by capillary action) **, $z = z_w$**

$$F = \frac{S_u}{(\gamma_{sat} z)\sin\beta}$$

Undrained failures in clay tend to be rotational



Shallow landslide susceptibility

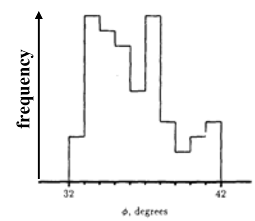


(Hammond et al., 1992)

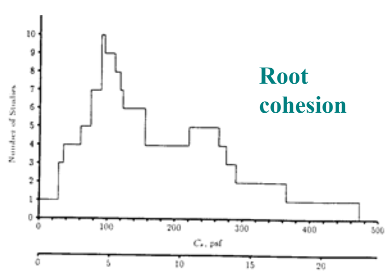
$$FS = \frac{C_r + C_s' + \cos^2\alpha[q_0 + \gamma(D - D_w) + (\gamma_{sat} - \gamma_w)D_w]\tan\phi'}{\sin\alpha\cos\alpha[q_0 + \gamma(D - D_w) + \gamma_{sat}D_w]}$$

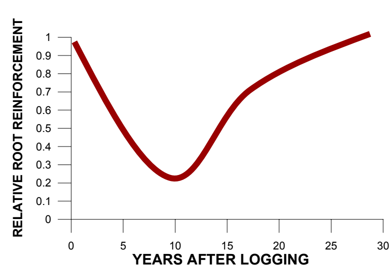
where FS = factor of safety
α = slope of the ground surface, degrees
D = total soil thickness, ft
D_w = saturated soil thickness, ft
C_r = tree root strength expressed as cohesion, psf
q_0 = tree surcharge, psf
C_s' = soil cohesion, psf
ϕ' = effective internal angle of friction, degrees
γ_d = dry soil unit weight, pcf
γ = moist soil unit weight, pcf
γ_{sat} = saturated soil unit weight, pcf
γ_w = water unit weight, pcf

Program LISA (US Forest Service): apply Infinite Slope Equation on an areal basis, in a probabilistic manner, map "probability of failure" (or Factor of Safety)



Influence of logging on slope stability





Debris slides/avalanches from forest slopes

(selected from NCASI Technical Bulletin No. 456, New York, 1985)

Location	*Forested*		*Clearcut*		*Road right-of-way*	
	Events per km^2/y	*Volume m^3/km^2/y*	*Events per km^2/y*	*Volume m^3/km^2/y*	*Events per km^2/y*	*Volume m^3/km^2/y*
Southern Coast, B.C.	0.004	11	0.02	24	0.08	282
Mapleton District, Oregon	0.53	32	0.55	62	3.7	1430
H.J.Andrews Ex. Forest, Oregon*	0.1	2134	1	11000	31	128000
Alder Ck. Oregon	0.02	46	0.27	118	8.3	15764
Amplification ratios	**1x**	**1x**	**1x-13x**	**2x-5x**	**7x-415x**	**26x-343x**

* December 1964, 50 year storm

Subjective slope stability mapping

SOIL DRAINAGE CLASSES

r	rapidly drained	i	imperfectly drained
w	well drained	p	poorly drained
m	moderately well drained	v	very poorly drained

Where two drainage classes are shown: if the symbols are separated by a comma, e.g., "w,i", then no intermediate classes are present; if the symbols are separated by a dash, e.g., "w-i", then all intermediate classes are present.

SLOPE CLASSES

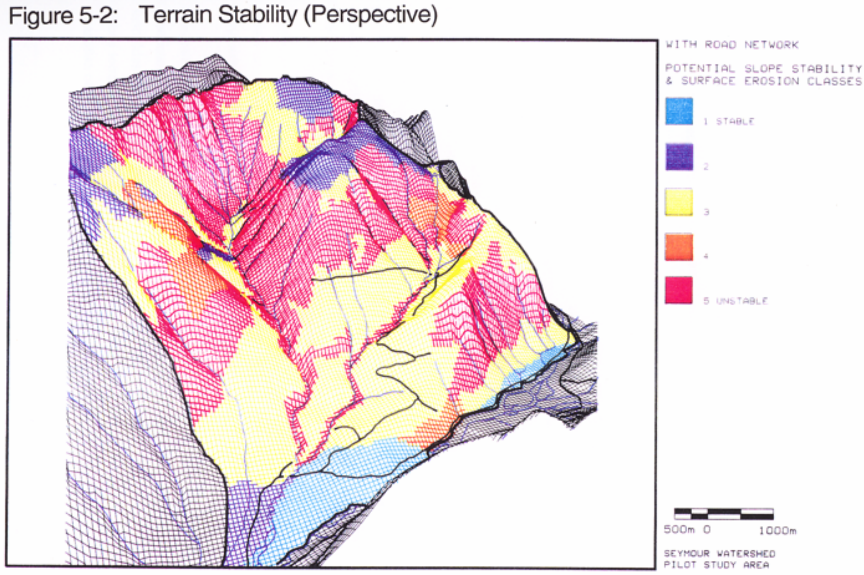
Class	%	degrees
1	0-5	0-3
2	6-27	4-15
3	28-49	16-26
4	50-70	27-35
5	>70	>35

CRITERIA FOR SLOPE STABILITY INTERPRETATIONS

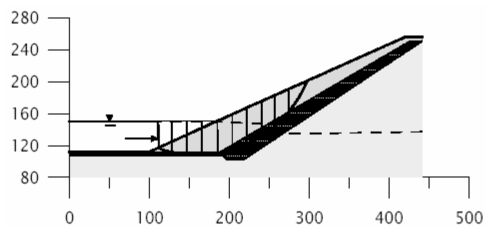
Potential Slope Stability and Surface Erosion Classes	Dominant Slope Class*	Material and Landforms	Dominant Texture	Active Processes	Soil Drainage	Slope Morphology
I	1 and 2 .... 1&2 mixed	F^Gt, F^Gu; Cf; Ff .... Mv, Mb; Cv; R	g; sr, g .... $s, s; sr	none none	poorly drained and wet soils are relatively susceptible; units with slopes within 3 or 4° of an upper class boundary may be assigned to the next highest class	slopes with irregular or benched topography controlled by bedrock are relatively stable; units with slopes close to a lower class boundary may be assigned to the next lowest class.
II	2 .... 2 and 3	Mv, Mb .... Cf; F^G; R	, s$ .... sr; g;	none none		
III	3 4	Mv, Mb; Cv .... Ca, Ck, R, F^G	$s; sr .... sr, x; g	none none		
IV	4 and 5 .... 4 and 5	Mv, Mb, Cv, Cb .... Rk, Rs	all	-V, -Rb*		
V	any gradient	M, C, R	all	-F, -Rd*, -Rs* **		

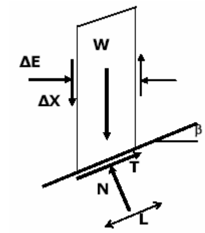
(J. Ryder, Vancouver, 1998)

Figure 5-2: Terrain Stability (Perspective)



Deep-seated landslides: Method of Slices

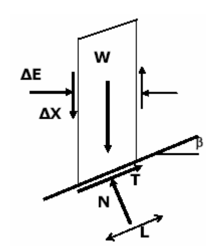




General method:

1) Work out the equilibrium of each slice
2) Calculate the equilibrium of the slice assembly
3) Results depend on assumptions regarding the **interslice forces E and X**

Available equations



1) Vertical equilibrium of a single slice (n equations)

$$W = N\cos\beta + T\sin\beta + \nabla X$$

2) Mohr-Coulomb strength (n equations)

$$T = \frac{c'L}{F} + (N - uL)\frac{\tan\phi'}{F}$$

"Mobilized strength"

3) Horizontal force equilibrium for the slice assembly (1 equation)

$$\sum N\sin\beta - \sum T\cos\beta = 0$$

4) Moment equilibrium for the slice assembly (1 equation)

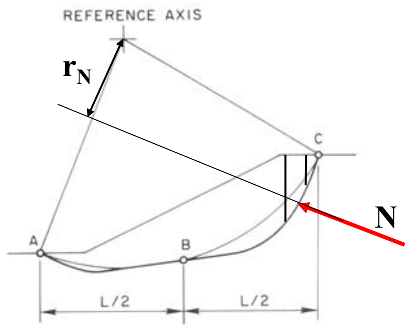
$$\sum W r_w - \sum N r_N - \sum T r_T = 0$$

Interslice forces cancel out in these equations

r's are radii of rotation

Bishop's Simplified Method:

Fredlund Krahn (1978) Modification for Non-circular surfaces



Add moment of the normal forces

Possible solutions

For n slices, we have the following unknowns:

n N forces + n T forces + n ΔX + n ΔE +1F =4n+1 unknowns

Bishop's simplified method:

1) assume $\Delta X = 0$ (no shear between slices)
2) use only Equations 1,2 and 4 (neglect horizontal force equilibrium)→ ΔE not needed, problem determinate
3) Good for circular sliding surfaces, conservative for others
4) Not good if large horizontal external forces involved

More solutions

Janbu simplified method:

1) assume $\Delta X = 0$ **(no shear between slices)**
2) use only Equations 1,2 and 3 (neglect moment equilibrium)
3) Good for shallow sliding surfaces, tends to be more conservative than Bishop (correction needed)

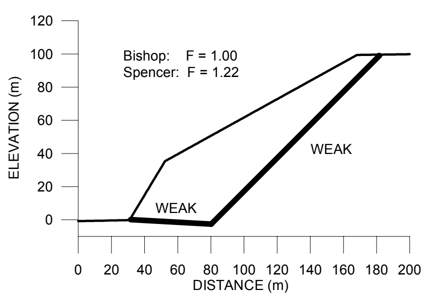
Spencer's method:

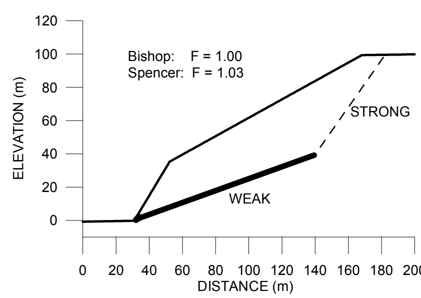
1) assume $\Delta X/\Delta E$ = constant **(constant interslice friction)**
2) Must add another equation (horizontal force equilibrium on each slice). Use all five equations ("rigorous solution")
3) Requires iterative solution, may not converge

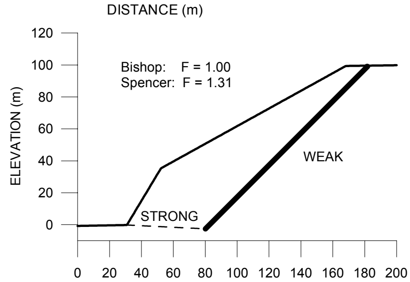
Morgenstern-Price method:

1) assume $\Delta X/\Delta E$ varies according to a prescribed function ("rigorous solution")
2) Requires iterative solution, may not converge

Simplified and rigorous method comparison

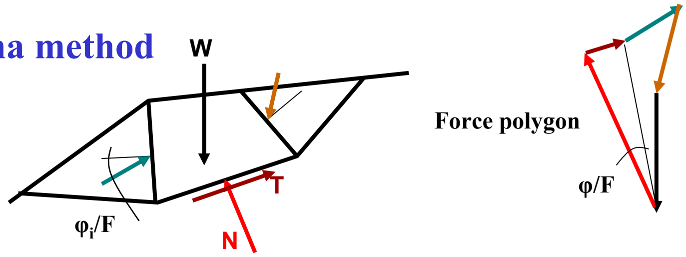






→ Simplified method OK, if slide head stronger than toe (classic compound slide) not good if the opposite

Sarma method



1) Divide sliding body into blocks
2) Assume that a constant friction angle, φ_i/F will be mobilized on all block interfaces
3) Solve graphically from first block to last. Will only work out for one specific value of F (iterations)
4) Problem: can we justify the given value of internal friction? Danger of non-conservative error! Good for structurally-controlled slides in rock

Limit Equilibrium Methods, Summary 1

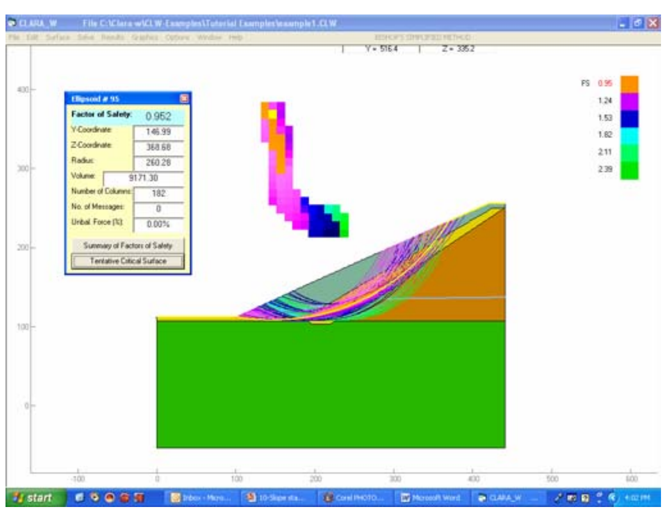
Method	*Type*	*Vertical Force Equilibrium*	*Horizontal Force Equilibrium*	*Moment Equilibrium*	*Slices*
Bishop	Simplified	Yes	No	Yes	Vertical
Janbu	Simplified	Yes	Yes	No	Vertical
Spencer	Rigorous	Yes	Yes	Yes	Vertical
Morgenstern-Price	Rigorous	Yes	Yes	Yes	Vertical
Sarma	Rigorous	Yes	Yes	Yes	Vertical or Inclined

Limit Equilibrium Methods, Summary 2

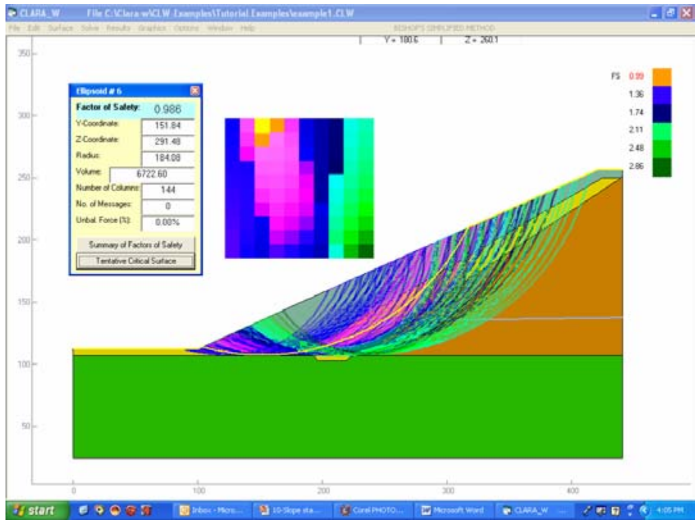
Method	Type	Advantages	Disadvantages
Bishop	Simplified	-very efficient -accurate for circular surfaces and some non-circular (with Fredlund-Krahn modification)	-conservative with cases involving internal distortion -can be incorrect with external horizontal loads (including earthquake loads)
Janbu	Simplified	-very efficient -good for shallow slides -horizontal external loads are OK (includes horizontal force equilibrium)	-usually more conservative than other methods -requires correction factor
Spencer	Rigorous	-any geometry and loads	-less efficient, may not converge -often more conservative than MP
Morgenstern -Price	Rigorous	-any geometry and loads -can simulate internal shearing -often cited as a benchmark	-less efficient, may not converge -choice of interslice function required
Sarma	Rigorous	- good for structured slides (esp. rock)	-less efficient, may not converge -the assumption of fully mobilized internal friction could lead to incorrect (non-conservative) results, if not justified (e.g. in rotational slides)

Search for the critical sliding surface

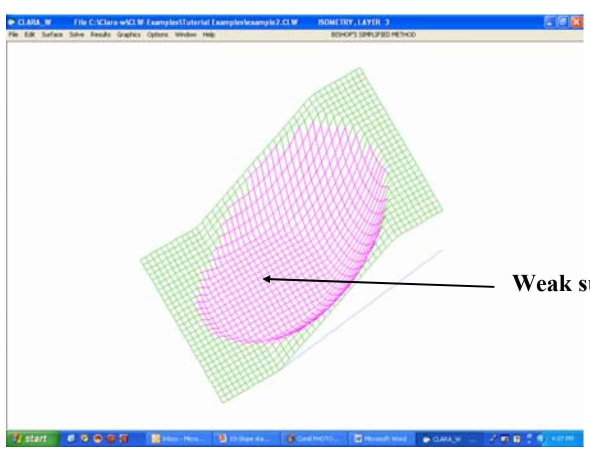
Automatic "Simplex" search



Grid search

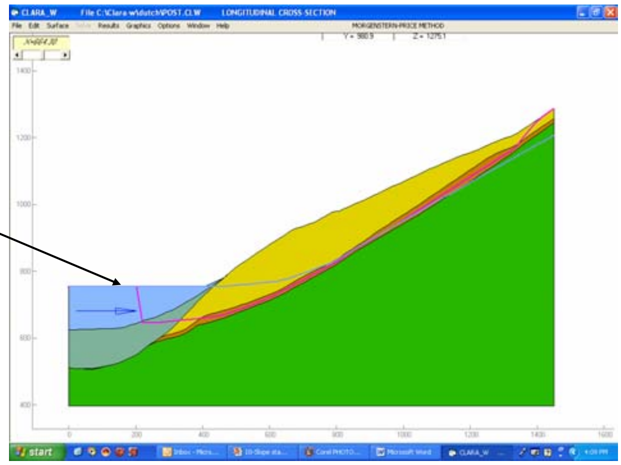


Compound sliding surface (3D)

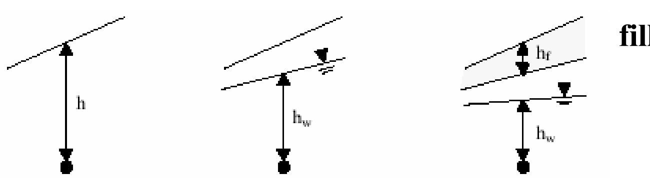


Specified non-circular sliding surface

Toe
submergence



Pore pressure conditions



$$u = h\gamma r_u$$

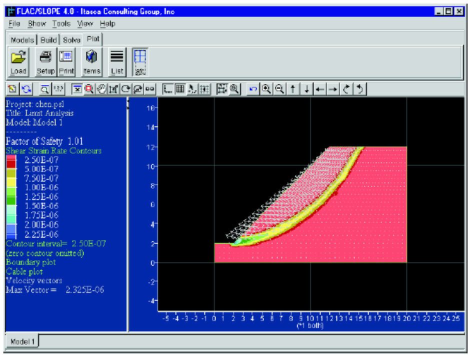
$$u = h_w \gamma_w$$

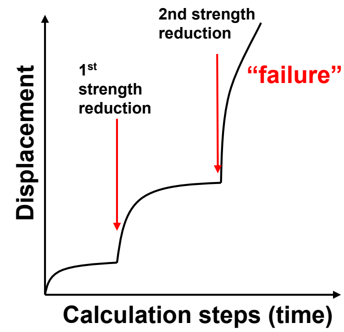
$$u = h_w \gamma_w + \overline{B} h_f \gamma_f$$

r_u= pore pressure ratio

Strength reduction method

FLAC: “Fast Lagrangian Analysis of Continua”





Strength reduction:

$c_{mob}=c/F \quad \varphi_{mob} = \varphi/F$

Every strength reduction increases displacements. Start with F=1, apply successively higher reduction in cycles, until “failure” occurs.