NANYANG TECHNOLOGICAL UNIVERSITY

Rock slope failure along non-persistent joints – insights from fracture mechanics approach

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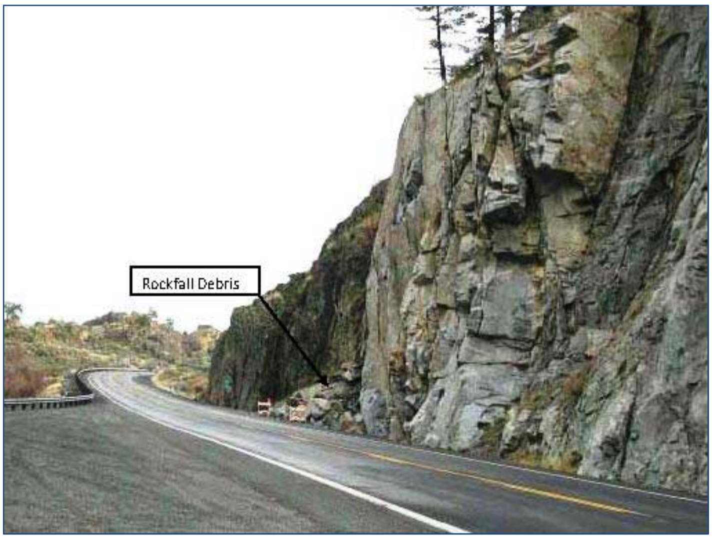
Slope Stability

First Principle of Slope Engineering

All slopes are potentially unstable.



http://www.wsdot.wa.gov/Projects/SR155/ElectricCityRockScaling/Photos.htm

Stability is controlled by

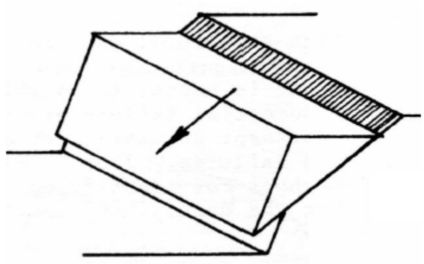
- Material type and properties of rock slope
- Geological structures (faults, joints, etc)
- Geometry of slope
- External factors (weather, water, seismic events, blasting, excavation, etc)
- Rock slopes are predominantly structurally controlled (discontinuities)

http://www.geo-design.co.uk/wp-content/uploads/2010/06/Ting-Kau-Bridge-Approach-Road-Rock-Slopes-Hong-Kong.jpg

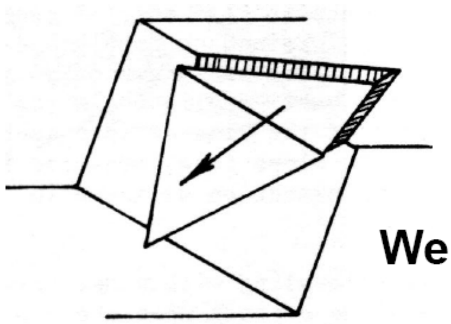
Tennessee Rock Slope Failure

http://www.youtube.com/watch?v=ZVYGJYnJTi0&feature=player_detailpage

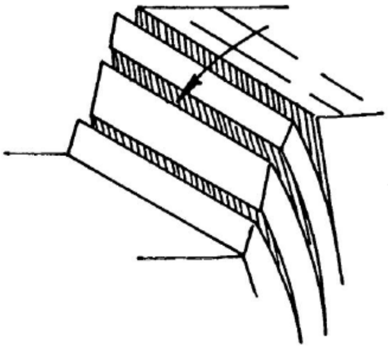
Failure Modes of Rock Slopes



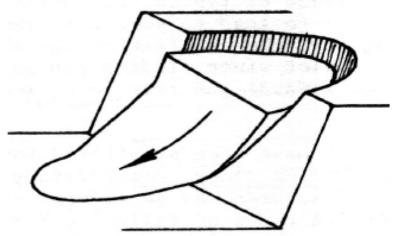
Plane failure



Wedge failure



Toppling failure



Circular failure

Plane (Planar) rock slope failure

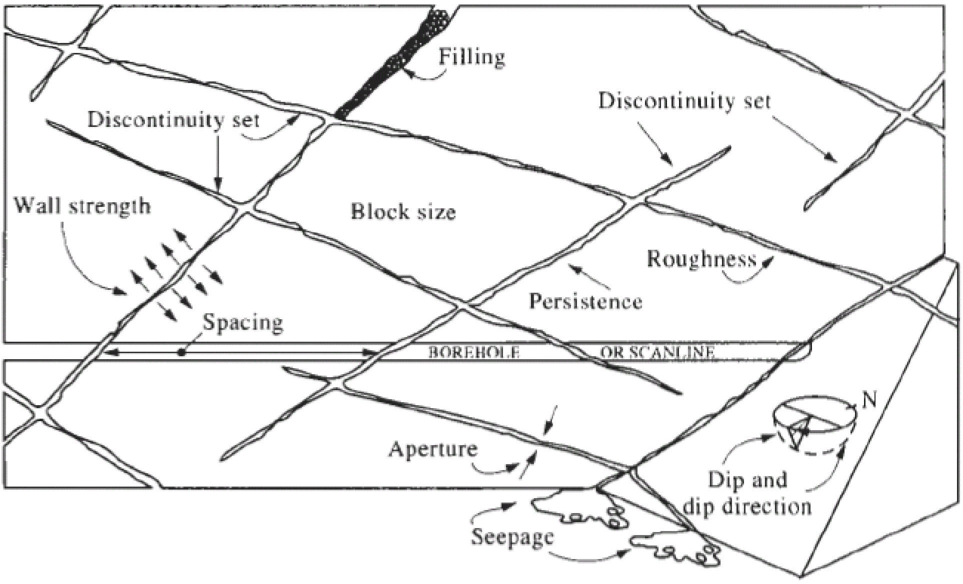
http://www.pacificblasting.com/mining.html

Sliding of a rock mass along a relatively planar failure surface.

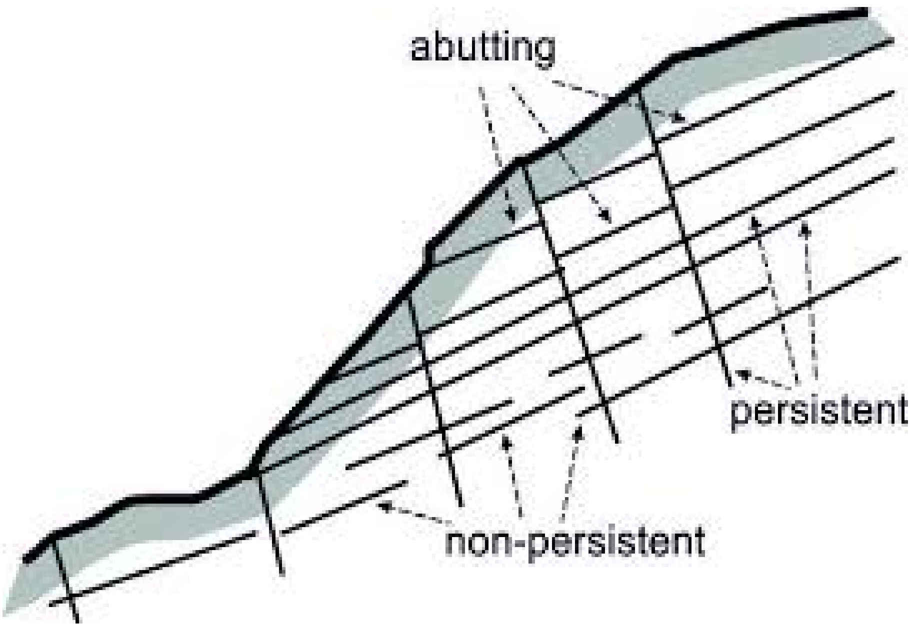
Why meta-stable?
- Shear strength of rock joint
- Rock bridge strength

Rock Joint Survey - Important geomechanical properties of discontinuities

- Orientation
- Spacing
- **Persistence**
- Roughness
- Aperture
- Filling
- Wall strength
- Seepage
- Number of sets
- Block size



Joint Persistence

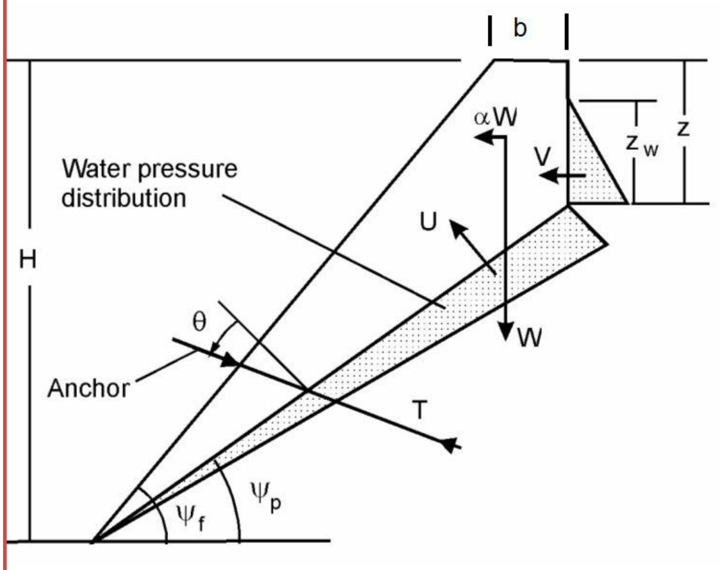


http://www.snipview.com/

Plane Failure Analysis based on water-filled critical tension crack depth

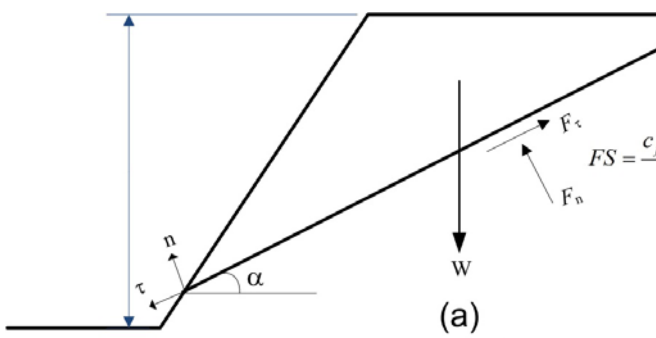
Other forces:

- Surcharge on top of slope
- Ground water (pushing and reduction in normal force)
- Reinforcement (tension, load capacity)
- Earthquakes (horizontal acceleration)

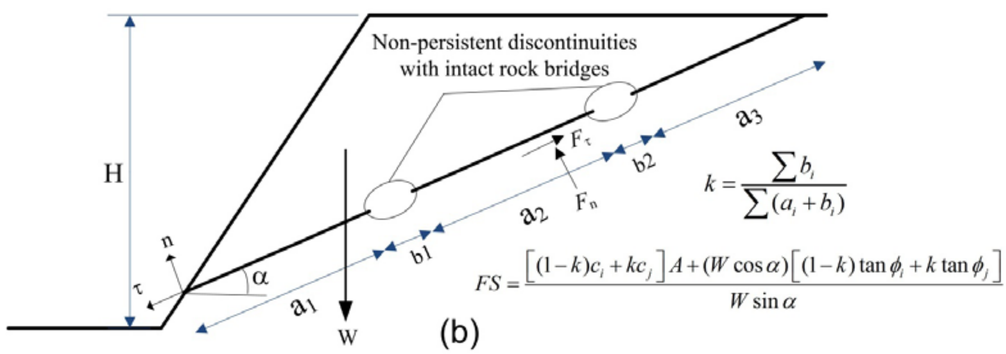


Hoek: Practical Rock Engineering

Analytical approach (a, b)



$$FS = \frac{c_j A + (W\cos\alpha)\tan\phi_j}{W\sin\alpha}$$

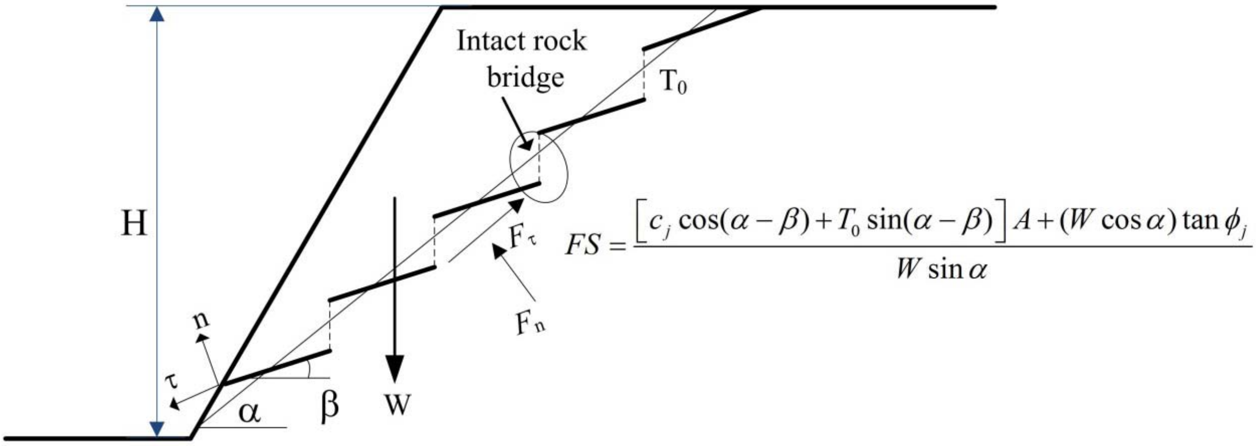


$$k = \frac{\sum b_i}{\sum (a_i + b_i)}$$

$$FS = \frac{\left[(1-k)c_i + kc_j\right]A + (W\cos\alpha)\left[(1-k)\tan\phi_i + k\tan\phi_j\right]}{W\sin\alpha}$$

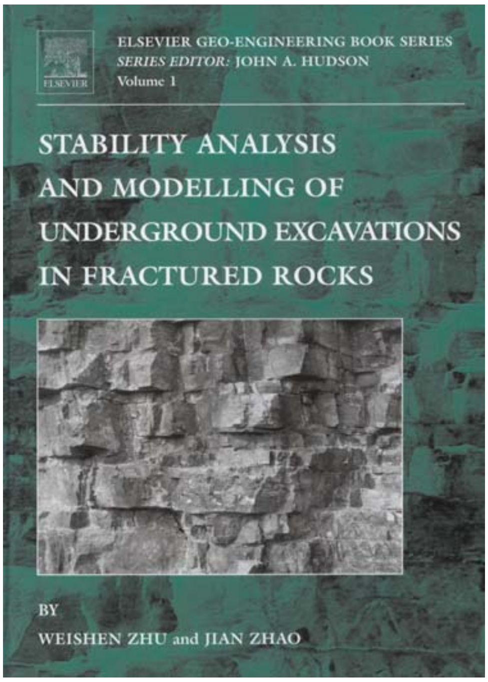
Jennings, J.E. (1970) *A Mathematical theory for the calculation of the stability of slopes in open cast mines.* in *Planning of Open Pit Mines, Proceedings*, Johannesburg; 87-102.

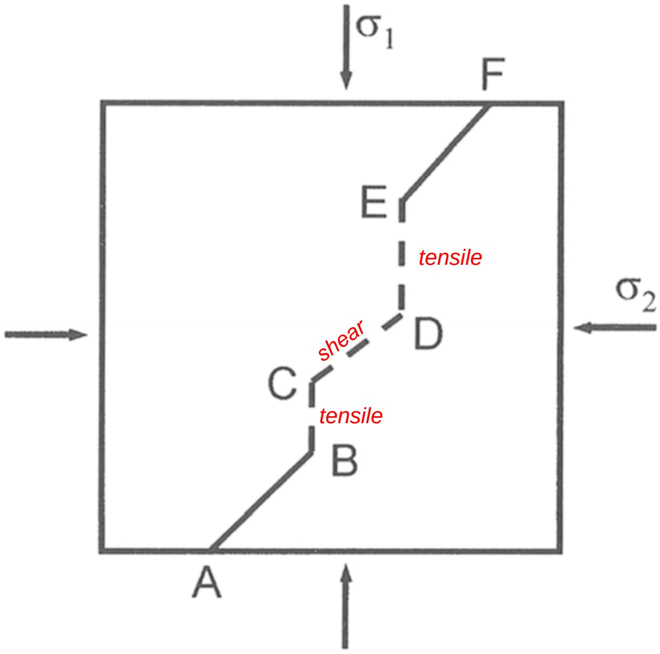
Analytical approach (c)



(c)

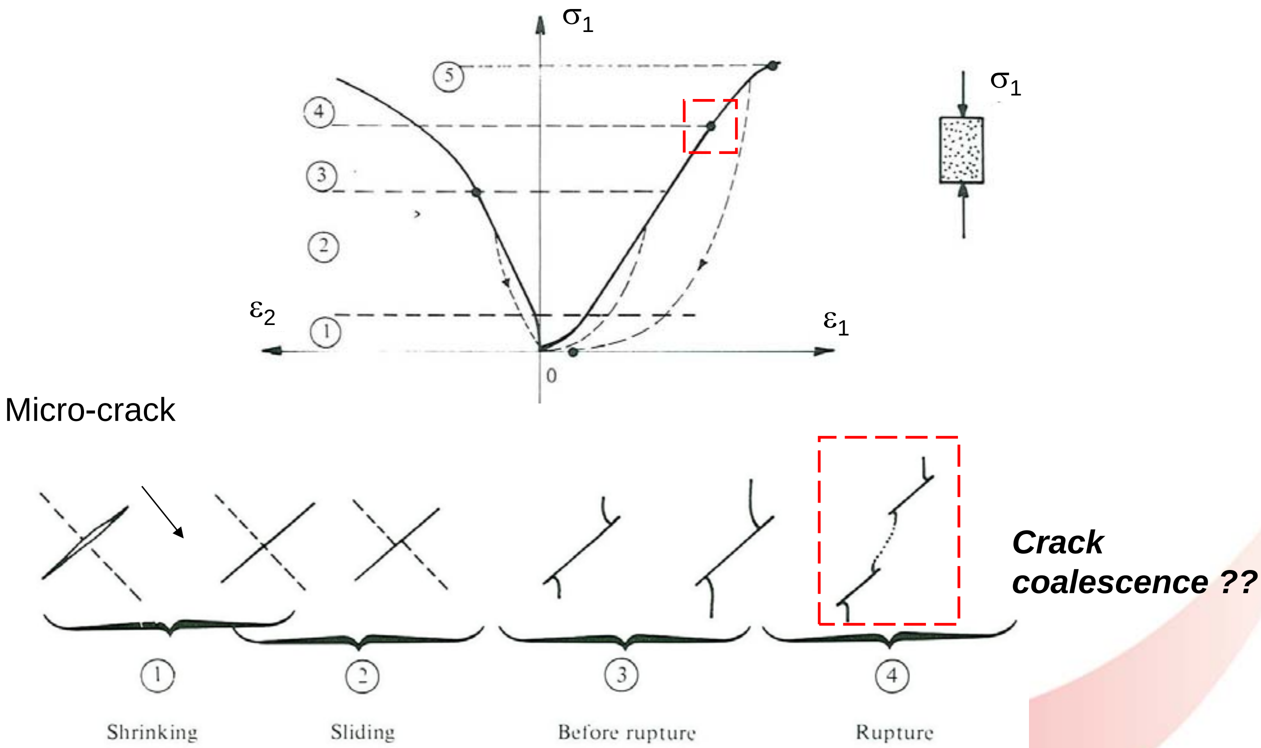
Jaeger, J.C. (1971) *Friction of rocks and stability of rock slopes.* Geotechnique; **21:**97-134.





Enchelon cracking trajectory

Typical Stress-Strain Curve in Rock (lab scale)



Habib, P. (1983) *An outline of soil and rock mechanics*, Cambridge University Press.

Fracture Mechanics Approach

Two scenarios

– Initiation of new cracks in intact material

– Propagation from existing crack tip

Let’s see the mechanics

Fracture Mechanics Approach

new crack initiation in intact material

- For shear crack $\frac{\sigma_1 - \sigma_3}{2} = c_i \cos\phi_i + \frac{\sigma_1 + \sigma_3}{2}\sin\phi_i, \quad \sigma_3 > \sigma_t$

- For tensile crack $\sigma_3 = \sigma_t$

where

- c_i and ϕ_i are the cohesion and friction angle of the intact material
- σ_1 and σ_3 are the maximum principal stress and the minimum principal stress, respectively

Fracture Mechanics Approach

Propagation from existing crack tip

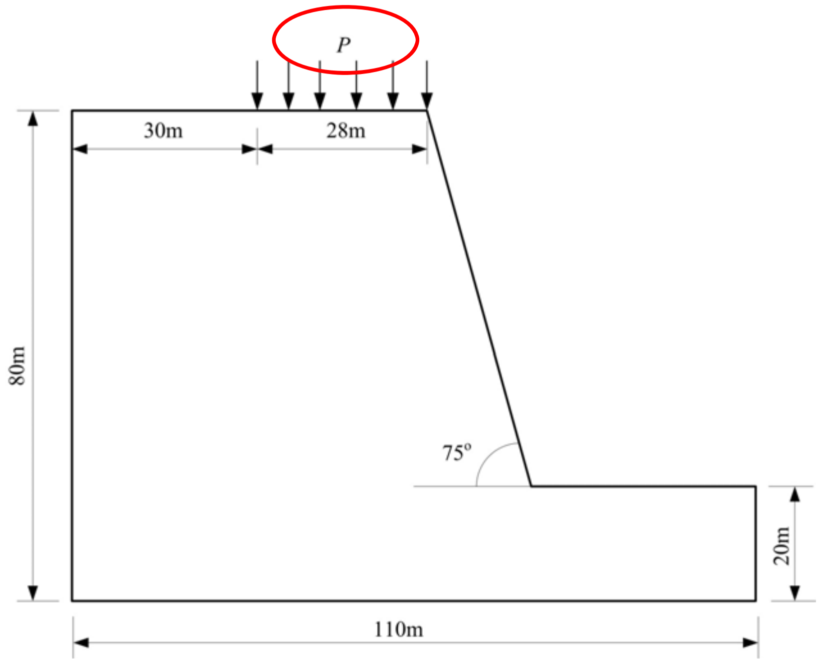
$$\cos\frac{\theta_0}{2}(K_I \cos^2\frac{\theta_0}{2} - \frac{3}{2}K_{II}\sin\theta_0) = K_{IC}$$

where

- K_I and K_II are the mode I and mode II stress intensity factors respectively
- K_{IC} is the mode I fracture roughness and the propagation angle θ_0 can be obtained by the following equation:

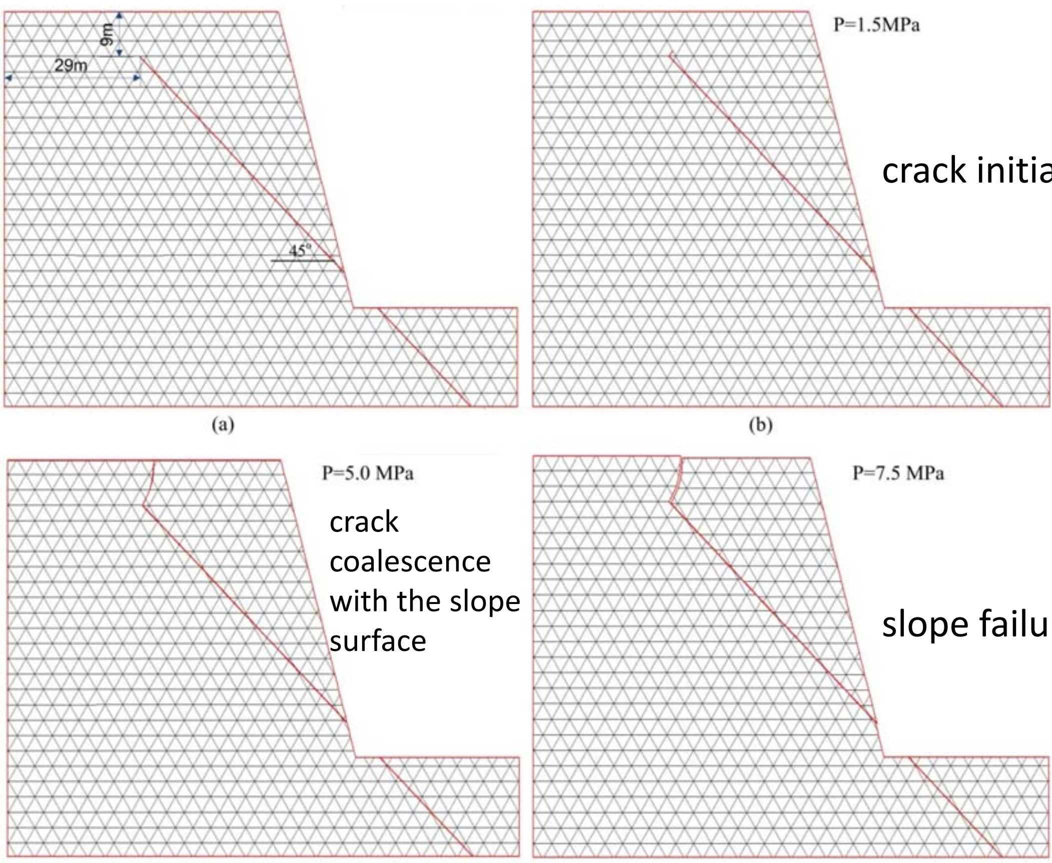
$$\theta_0 = \begin{cases} 2\arctan(\frac{|K_I| - \sqrt{K_I^2 + 8K_{II}^2}}{4K_{II}}) & K_{II} = 0 \\ 0 & K_{II} \neq 0 \end{cases}$$

Slope geometry



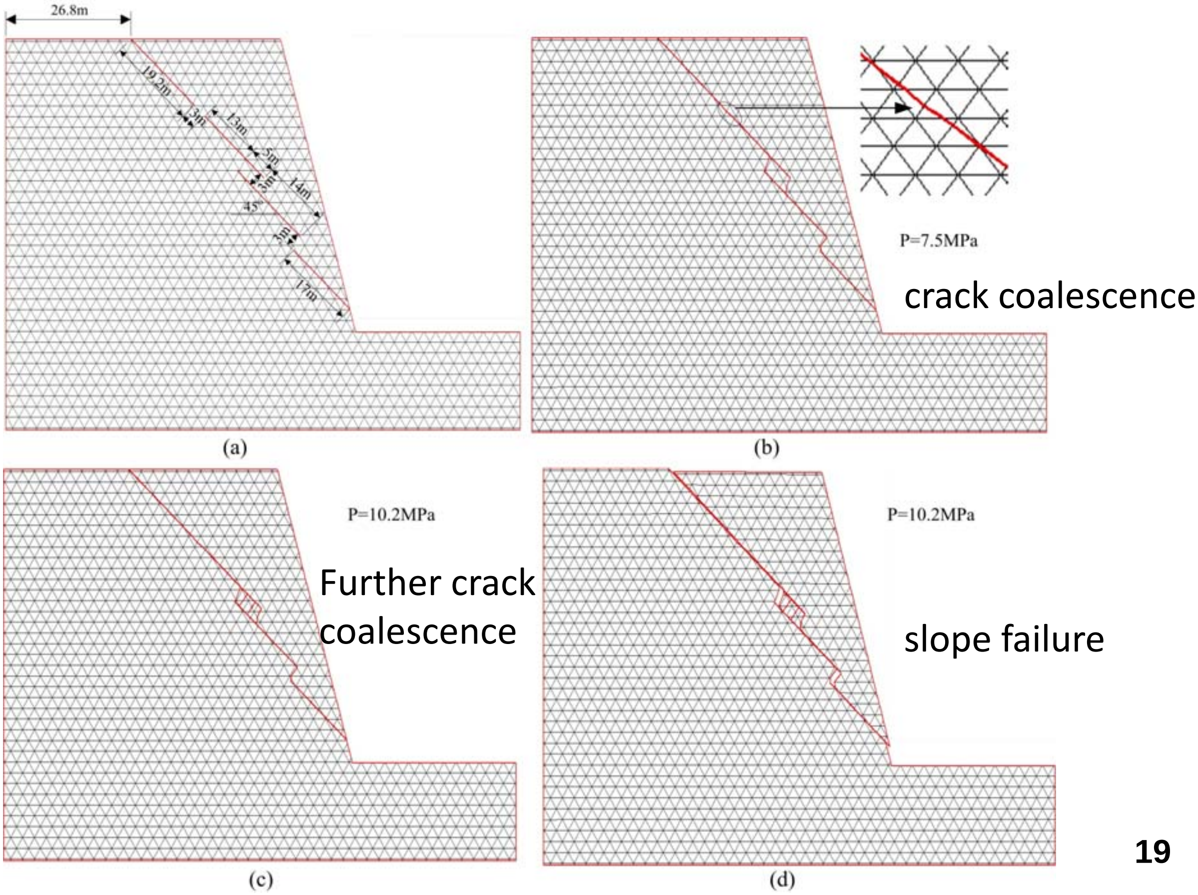
Intact						Discontinuity		
Density ρ (kg/m^3)	Young's modulus E (GPa)	Poisson's ratio v	Tensile strength σ_t (MPa)	Friction angle φ_i (°)	Cohesion c_i (MPa)	Friction Angle φ_j (°)	Cohesion c_j (MPa)	Fracture toughness K_{IC} (MPa·m$^{1/2}$)
3100	33.7	0.15	13.1	23.5	18.1	33	0-0.1	1.0

slope containing one pre-existing discontinuity



(a) (b) (c) (d)

slope containing four pre-existing discontinuities

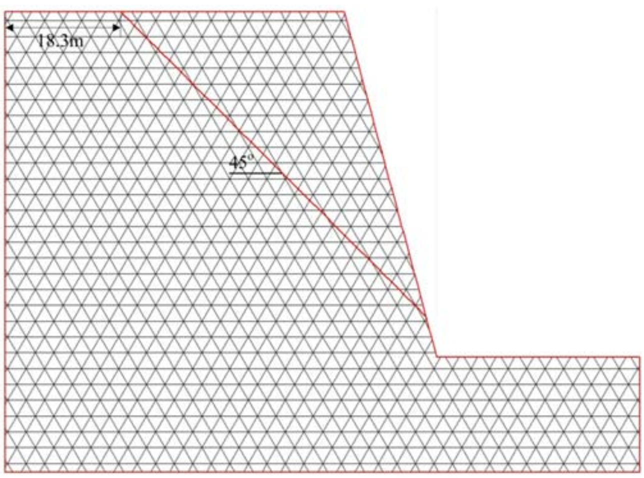


Factor of Safety (SF)

- SF calculation is based on successively increasing the acceleration of gravity until the slope fails.

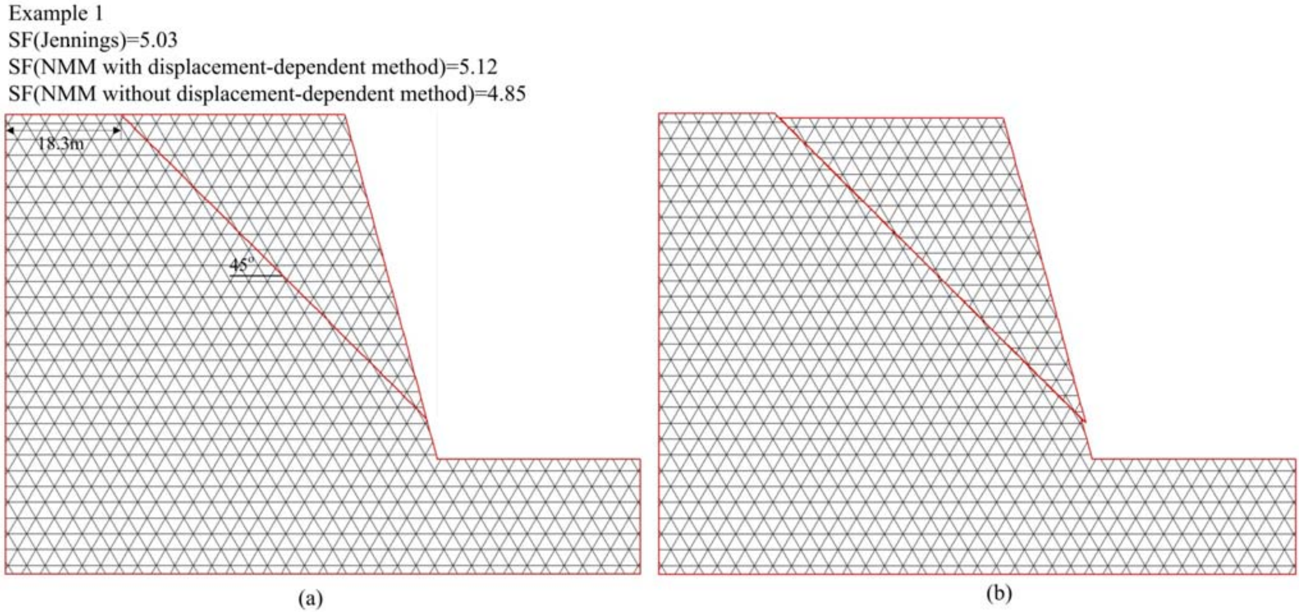
$$SF = \frac{g_{trial}}{g_0}$$

- g_0 = acceleration of gravity in the initial state
- g_{trial} = acceleration of gravity at failure



Li, L.C., C.A. Tang, W.C. Zhu, and Z.Z. Liang (2009) *Numerical analysis of slope stability based on the gravity increase method.* Computers and Geotechnics; **36:**1246-1258.

Factor of Safety (SF) – continuous discontinuity

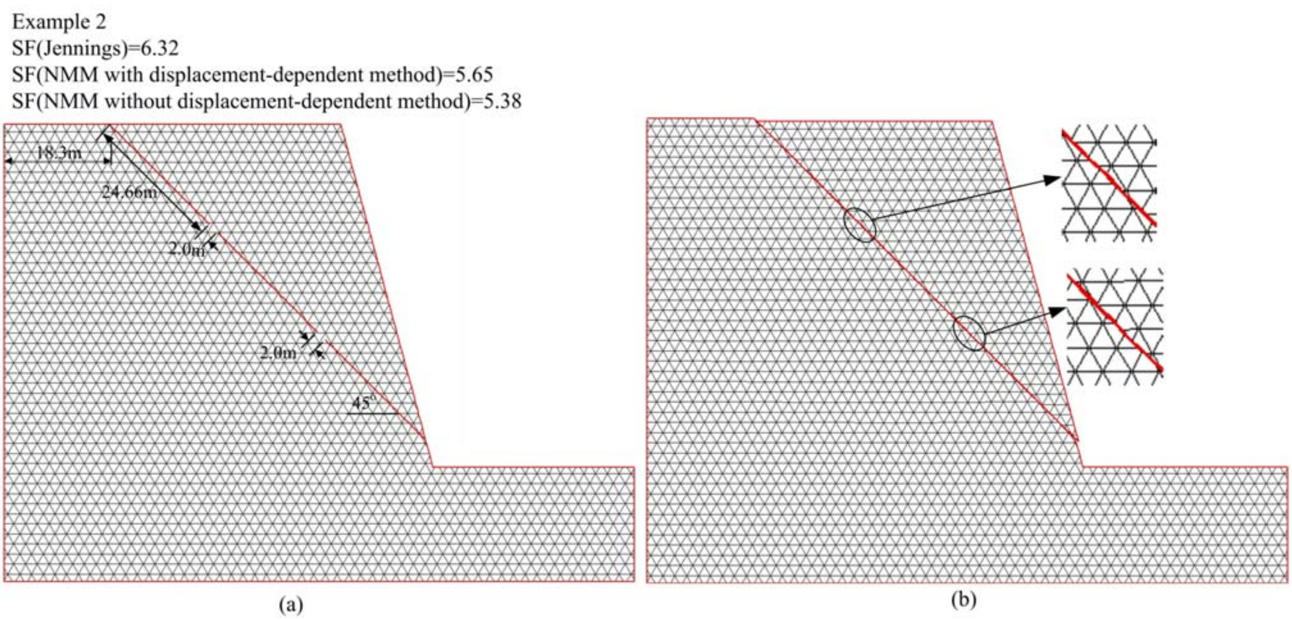


Displacement-dependent cohesion reduction method (Wang et al. 2013)

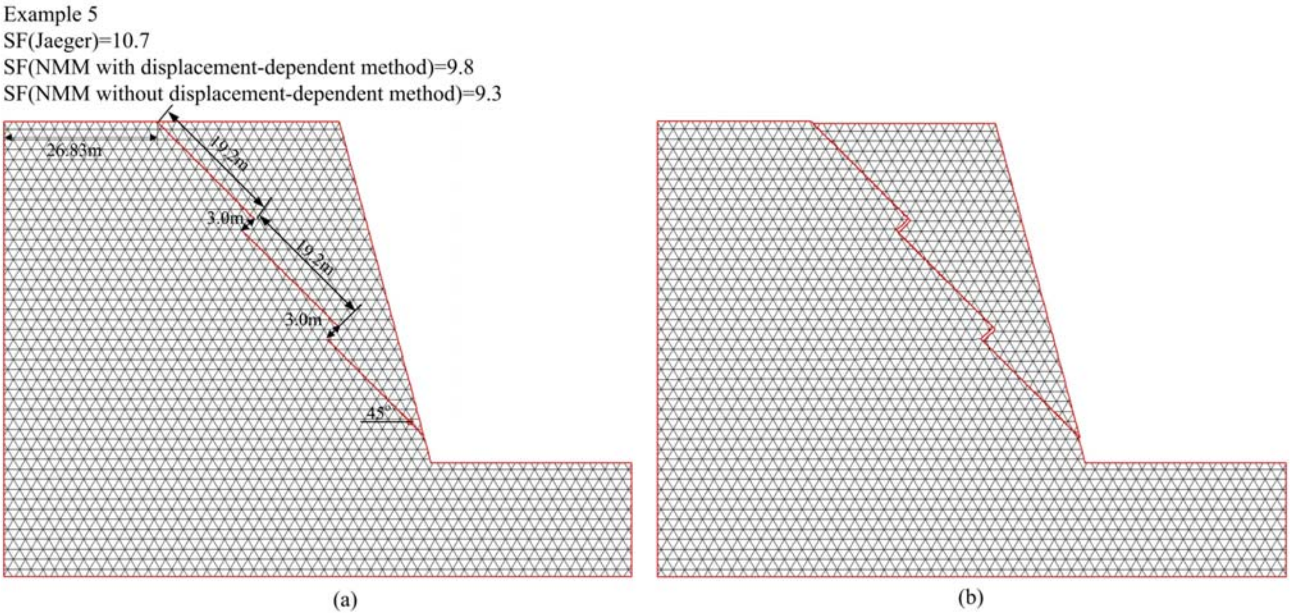
- cohesion between the discontinuity surfaces degrades with increasing movement along the surfaces.
- enables relative movements between contact pairs and the removal of the cohesion based on the accumulated relative sliding

Wang, L.Z., et al. (2013) *Development of discontinuous deformation analysis with displacement-dependent interface shear strength.* Computers and Geotechnics; **47:**91-101.

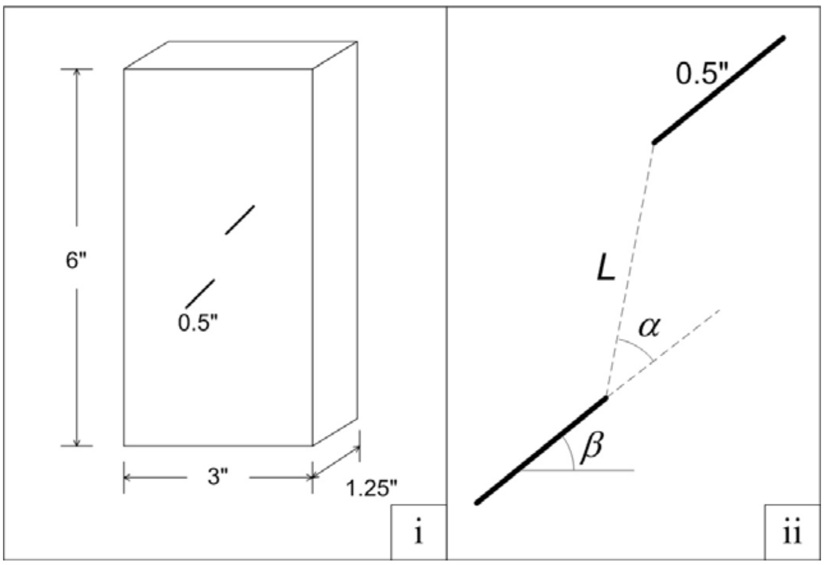
Factor of Safety (SF) – coplanar non-persistent discontinuity



Factor of Safety (SF) – stepped non-persistent discontinuity



Experimental study



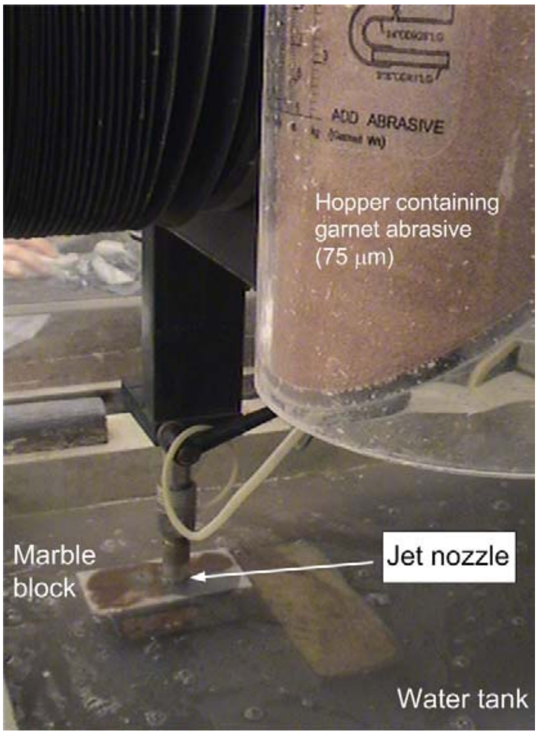
Geometry representation

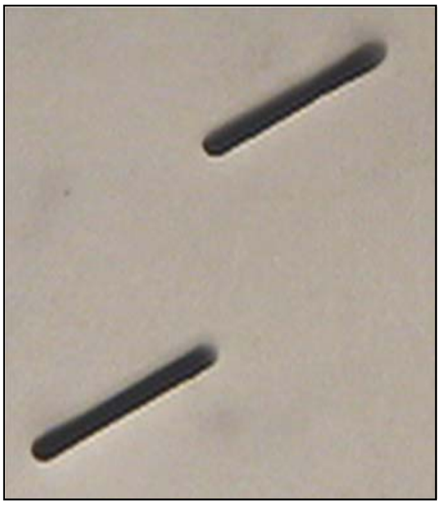
$L - \beta - \alpha$, e.g. 2*a*-30-45

a = half flaw length

Water Abrasive Jet

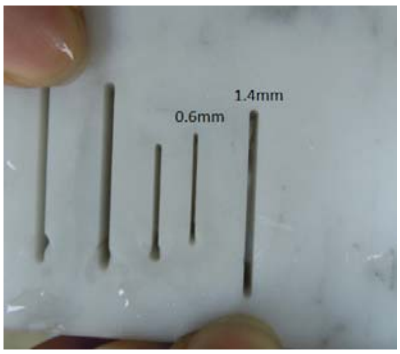
Carrara Marble



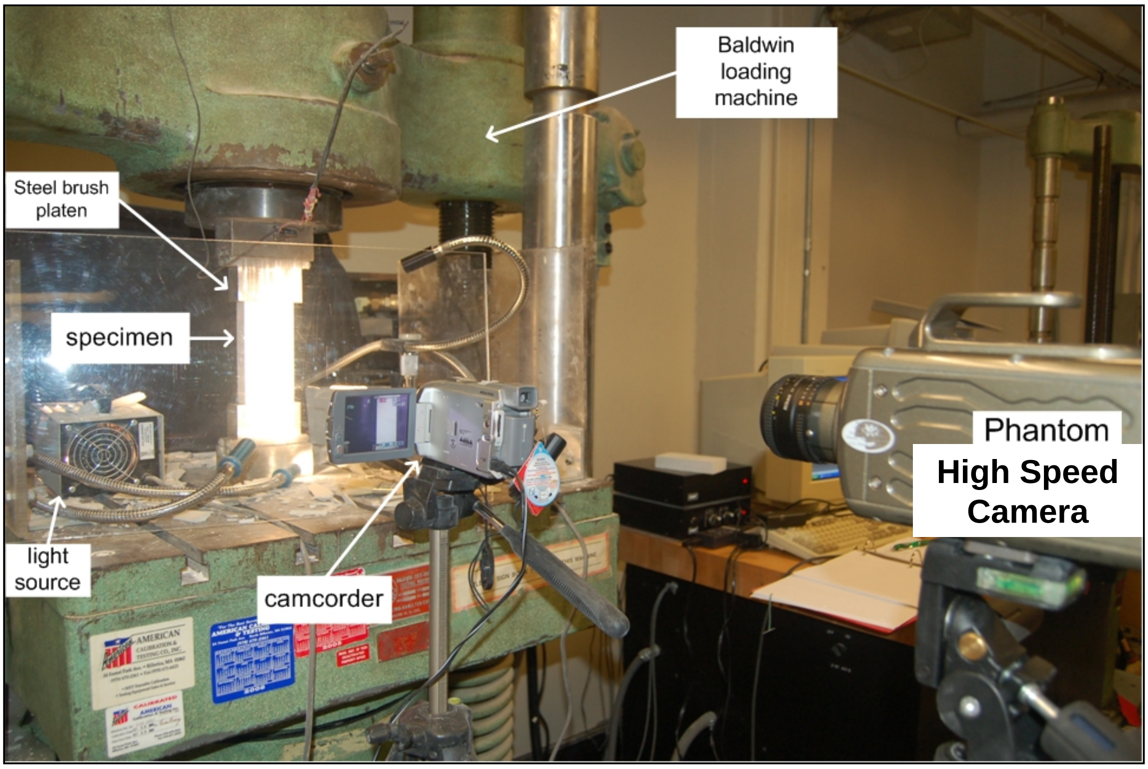


Flaw length	Flaw aperture
13mm (0.5")	1.3mm (0.05")

OMAX water abrasive jet

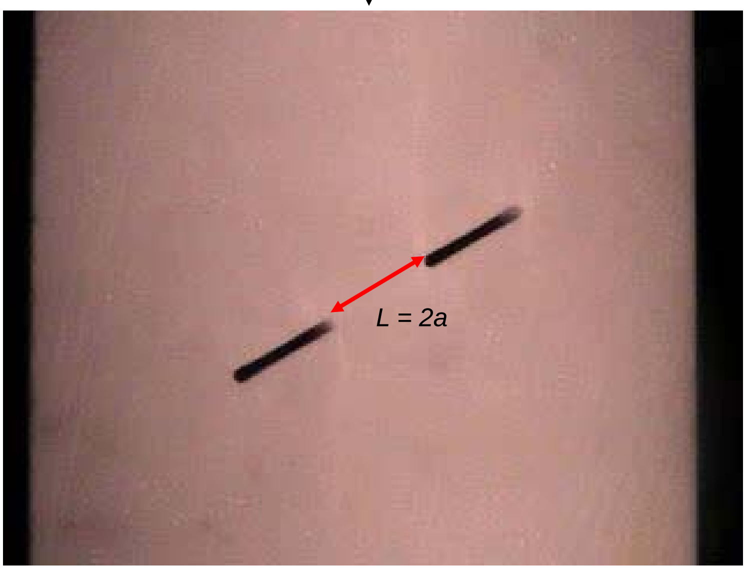


Uniaxial Compression Loading Test

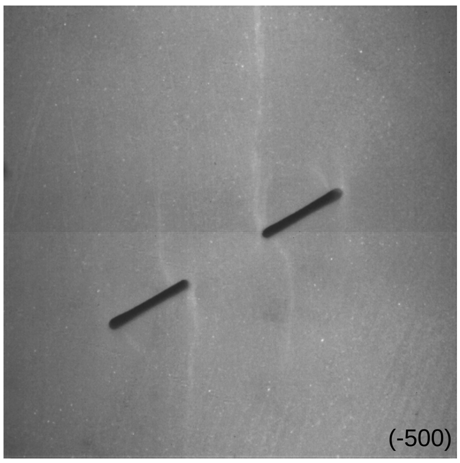


Normal Speed vs High Speed videos

Normal speed video ↓ σ_1

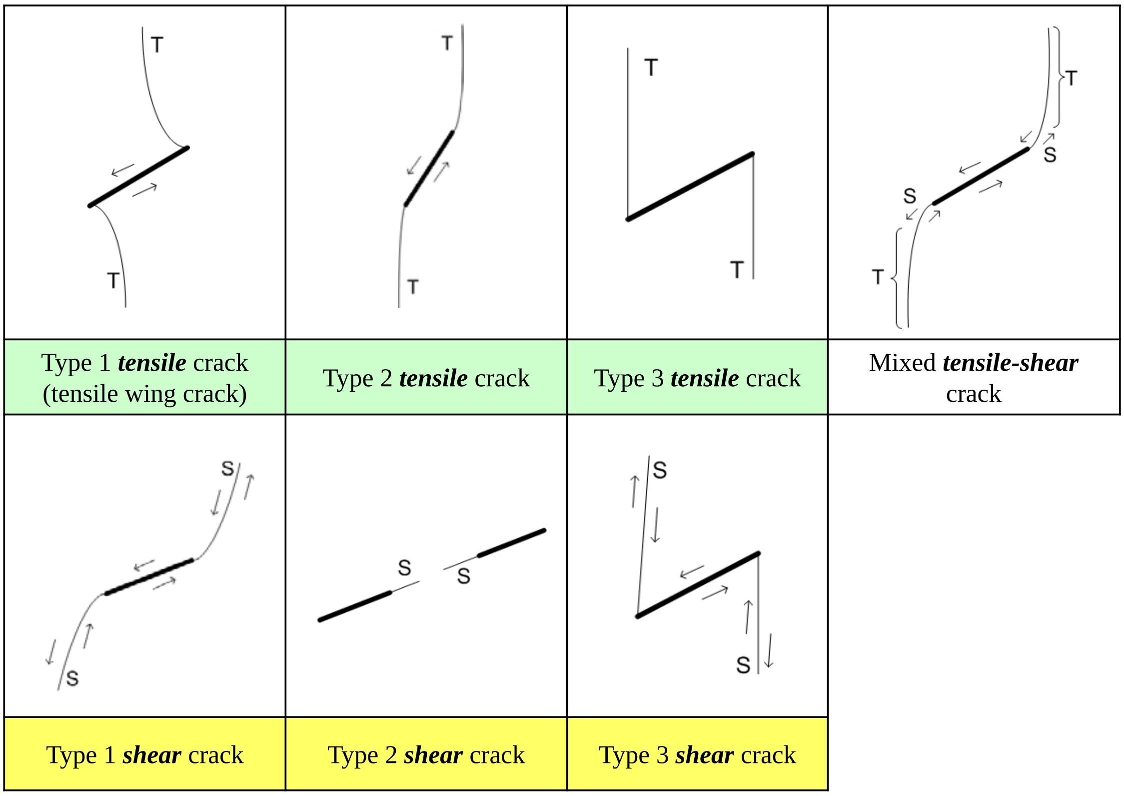


High speed video



- 2000 frames per second
- Video played at 45 times slower

Results - generalized crack types



Type 1 ***tensile*** crack (tensile wing crack)	Type 2 ***tensile*** crack	Type 3 ***tensile*** crack	Mixed ***tensile-shear*** crack
Type 1 ***shear*** crack	Type 2 ***shear*** crack	Type 3 ***shear*** crack	

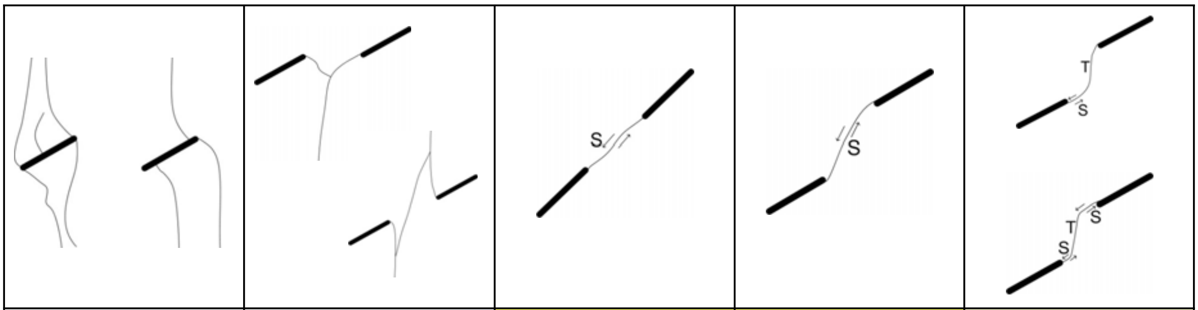
Next Step …

Fundamental Crack Types

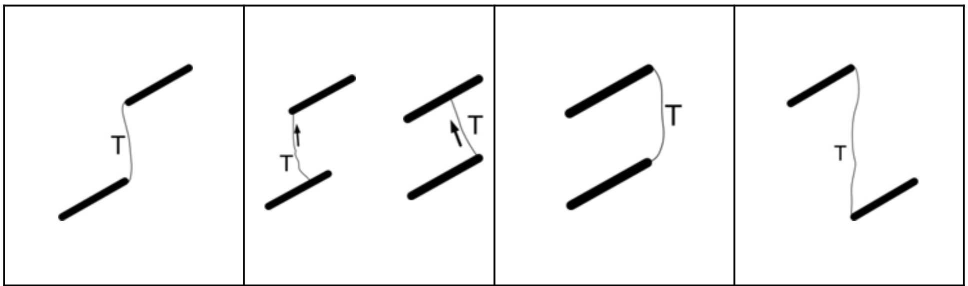
↓

Coalescence Patterns

Results - coalescence categories



(1) **No** coalescence	(2) **Indirect** coalescence	(3) Type 2 shear crack(s)	(4) Type 1 shear crack(s)	(5) Mixed shear-tensile crack(s)



(6) Type 2 tensile crack(s)	(7) Type 1 tensile cracks	(8) Tensile crack (type not assigned)	(9) Type 3 tensile cracks

(3) – (9) **Direct** coalescence

Conclusions

- Progressive rock slope failure requires the consideration of two factors
  - ➢ slide plane development
  - ➢ internal rock mass deformation/degradation

Fracture mechanics approach
- Crack tip
- Intact rock

Conventional approach
- Assumed to be persistent
- Failed when tensile strength or shear strength is overcome

Thank you

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