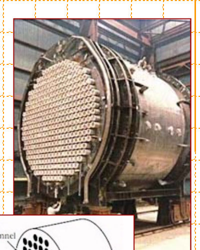
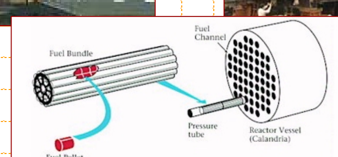
EOSC433:

Geotechnical Engineering Practice & Design

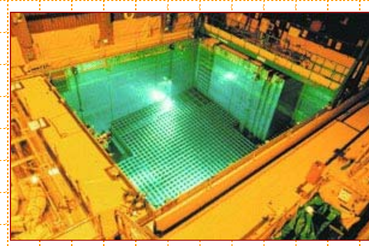
Lecture 12: Stress-Induced Brittle Failure (Spalling & Rockbursting)

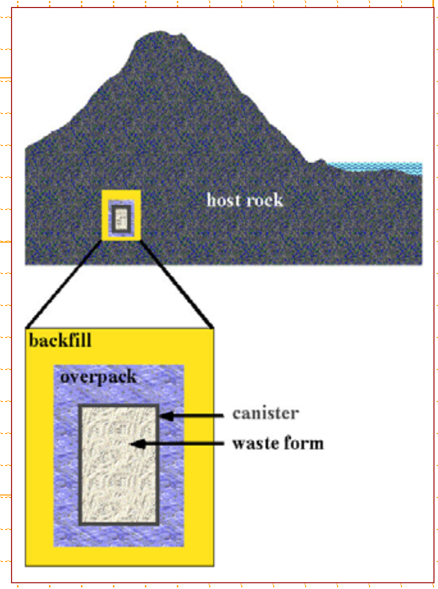
Canada's Nuclear Waste Disposal Concept





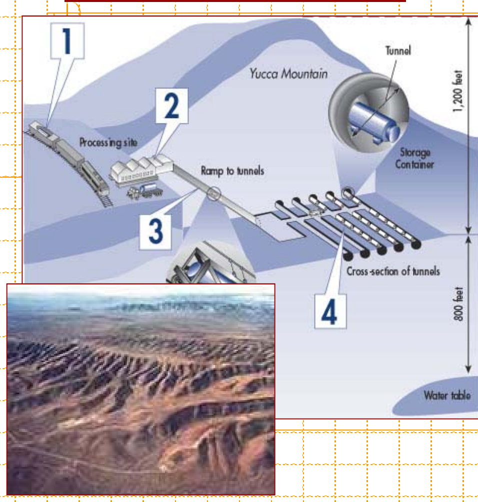
Nuclear Waste Disposal





Nuclear Waste – Geologic Disposal

USA Yucca Mountain - Tuffs



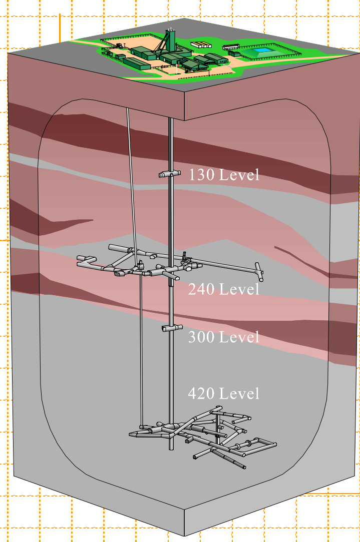
Swiss – Opalinus Clay

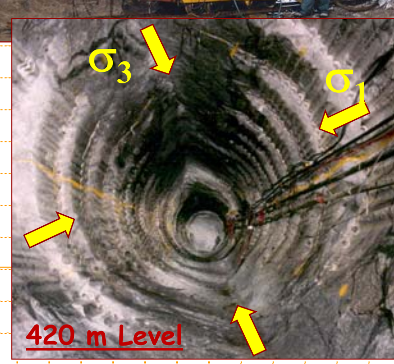
Germans – Salt

Canada's Nuclear Waste Disposal Concept

AECL's URL = Atomic Energy of Canada Limited's Underground Research Laboratory

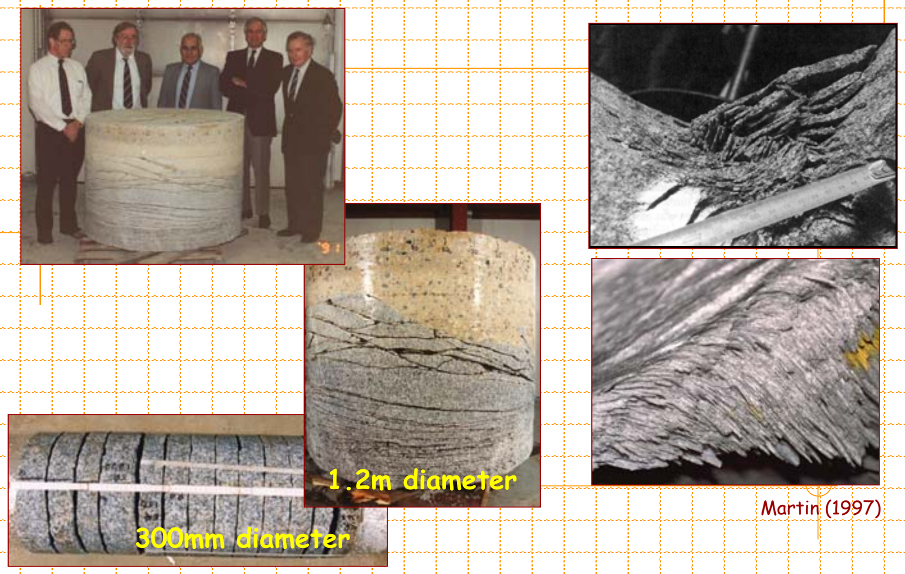
AECL's Underground Research Laboratory





Martin (1997)

AECL's URL – Brittle Failure

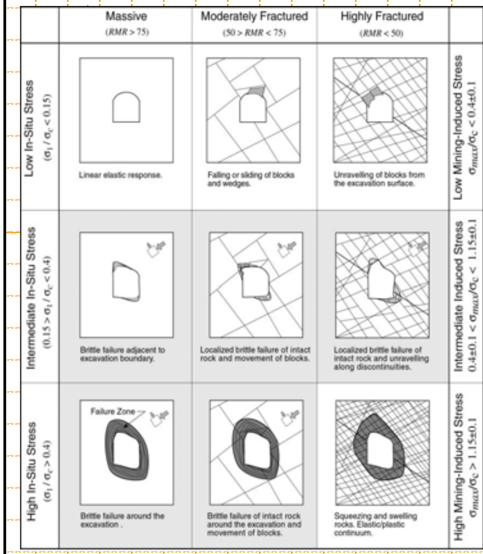


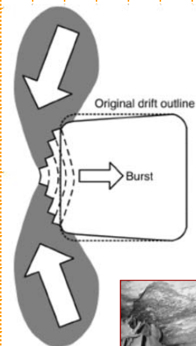
Martin (1997)

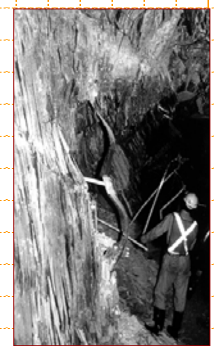
Brittle –vs– Plastic Failure Mechanisms

Failure Mechanisms	Characteristics	Support Requirements
• Brittle	• Sudden • Unexpected • Danger potential	• Immediate setting • Immediate bearing capacity
• Plastic	• Time dependent • High forces • Large deformations • Damage potential	• High bearing capacity • Flexible • Sustain deformations

Spalling and Rockbursting

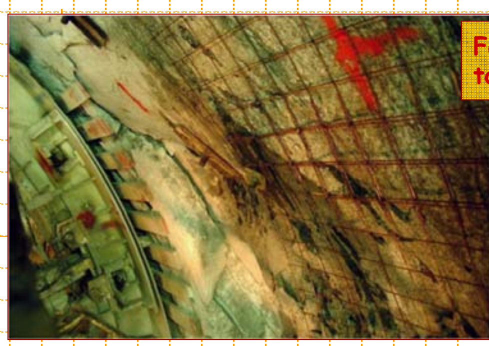




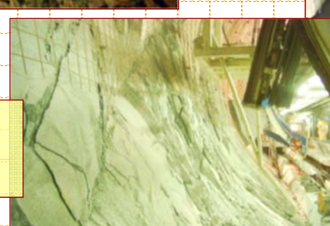


Kaiser *et al.* (2000)

Stress-Driven Spalling in Tunnelling



Falling slabs of rock a hazard to workers.

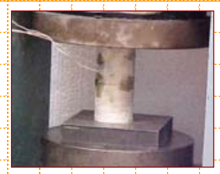


Problem for TBM as gripper pads cannot be seated on the side wall.

Failure Criterion in Solid Mechanics

To understand the mechanisms that contribute to stress-induced brittle failure (spalling, bursting, etc.), we need to understand the basic principals of rock strength and the initiation and propagation of brittle fractures.

Traditionally, there have been two approaches to analyzing rock strength:



⇨ *experimental approach* (i.e. phenomenological)
- stress based
- strain based
- energy based

⇨ *mechanistic approach*

Analysis of Rock Strength

Phenomenological Approach

Relies on generalization of large scale observations.

Theories include:

- Maximum Stress theory
- Tresca theory
- Coulomb theory
- Mohr-Coulomb failure criterion
- Hoek-Brown failure criterion

Mechanistic Approach

Derives its theories from elements of fracture at the microscopic scale.

Theories include:

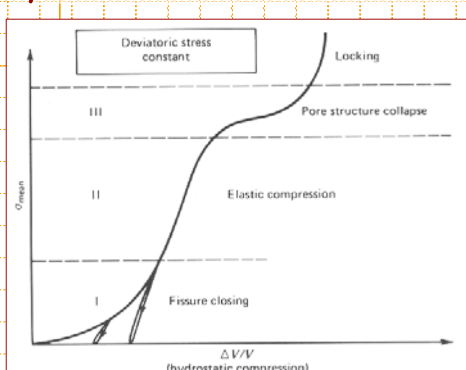
- Griffith Crack theory
- Linear Elastic Fracture Mechanics (LEFM)

Deviatoric Stress and Failure in Shear

Lab testing and field observations suggest that a shear failure criterion may be more applicable than a maximum stress criterion. The maximum shear stress is related to the difference in the major and minor principal stresses (i.e. deviatoric stress).

Hydrostatic Compression

Applying uniform stresses produces a *volume decrease* which eventually changes the rock fabric permanently as pores are crushed. Although such collapse produces an inflection in the stress -vs- strain response the rock will always accept additional hydrostatic load.

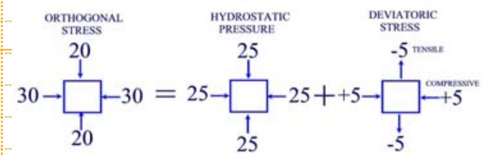


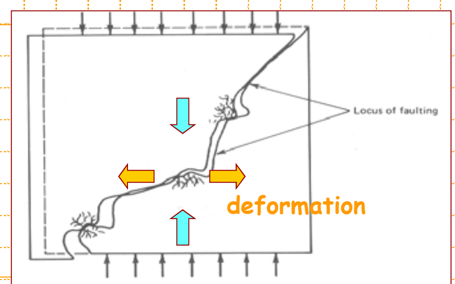
Goodman (1989)

- *I* existing cracks close and minerals are compressed;
- *II* elastic rock compression, consisting of pore deformation and grain compression at an approximately linear rate;
- *III* pore collapse;
- *IV* intergrain locking and infinite compression as the only compressible elements remaining are the grains themselves.

Deviatoric Compression

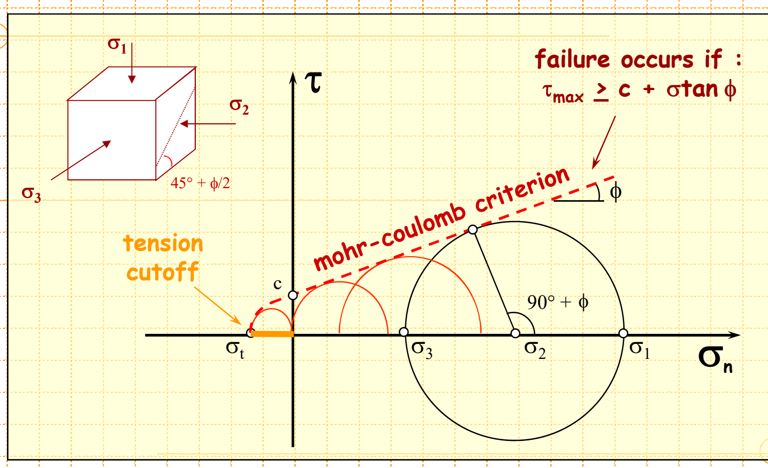
Deviatoric stresses are obtained by subtracting the mean (or hydrostatic) stress from each principal stress (i.e. $\sigma_1-\sigma_m$, etc.). Deviatoric stresses control the degree of distortion, allowing for a material to deform in one direction more than the others (i.e. in the direction of the smaller stress). In effect, this allows fracturing, rupture and shearing of the rock to occur.





Goodman (1989)

Mohr-Coulomb Failure Criterion



Analysis of Brittle Rock Strength

Phenomenological Approach

Relies on generalization of large scale observations.

Theories include:

- Maximum Stress theory
- Tresca theory
- Coulomb theory
- Mohr-Coulomb failure criterion
- Hoek-Brown failure criterion

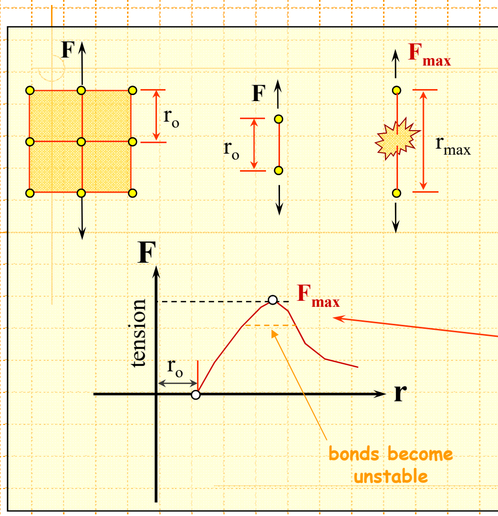
Mechanistic Approach

Derives its theories from elements of fracture at the microscopic scale.

Theories include:

- Griffith Crack theory
- Linear Elastic Fracture Mechanics (LEFM)

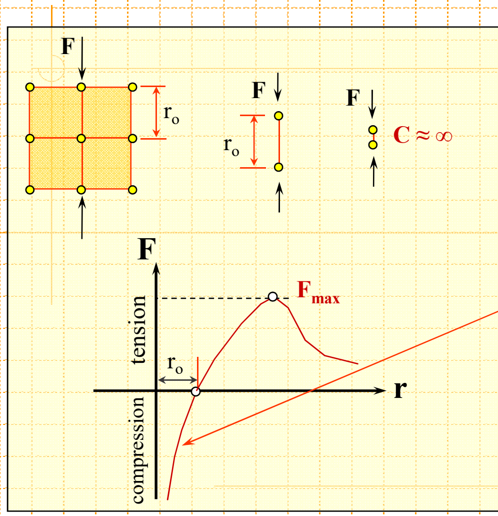
Mechanistic Brittle Fracture Theories



At the atomic level, the development of interatomic forces is controlled by the atomic spacing which can be altered by means of external loading …

… on extension, the structure fractures where the interatomic force is exhausted (i.e. the theoretical tensile strength)

Mechanistic Brittle Fracture Theories

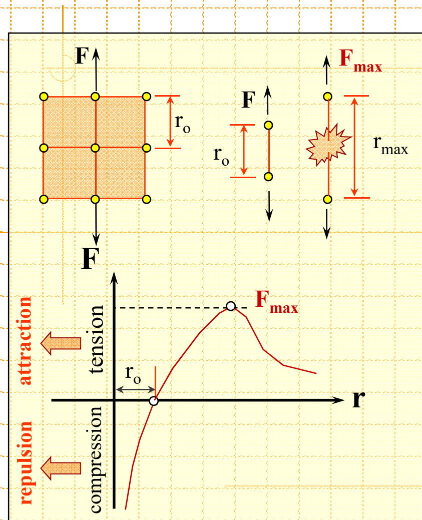


In compression …

… displacement is countered by an inexhaustible repulsive force

Thus, interatomic bonds will only break when pulled apart (i.e. in tension).

Theoretical Strength



Strength is therefore a function of the cohesive forces between atoms, where if $F > F_{max}$, then the interatomic bonds will break. As such, we can derive the following:

$$F_{max} = \left(\frac{1}{3} \div \frac{1}{2}\right) C(r - r_0) \approx \left(\frac{1}{5} - \frac{1}{10}\right) Ca$$

$N \approx a^{-2}$ *number of atoms per unit area*

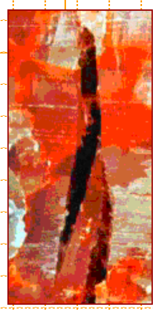
$$\sigma_{theor} = \frac{F_{max}}{a^2} \approx \frac{E}{10}$$

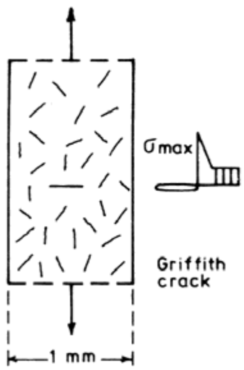
Now for most rocks, the Young's modulus, E, is of the order 10-100 GPa. If so, then the theoretical tensile strength of these rocks should be 1-10 GPa.

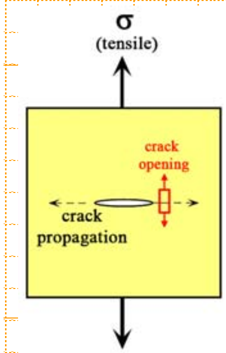
However, this is at least 1000 times greater than the true tensile strength of rock!!!

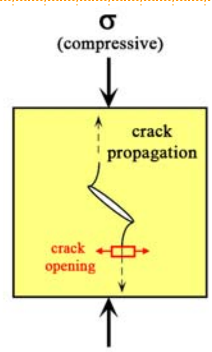
Griffith Theory

To explain this discrepancy, Griffith (1920) postulated that in the case of a linear elastic material, brittle fracture is initiated through tensile stress concentrations at the tips of small, thin cracks randomly distributed within an otherwise isotropic material.



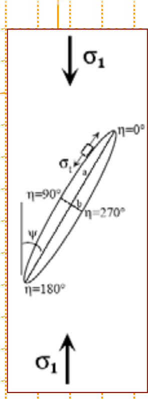


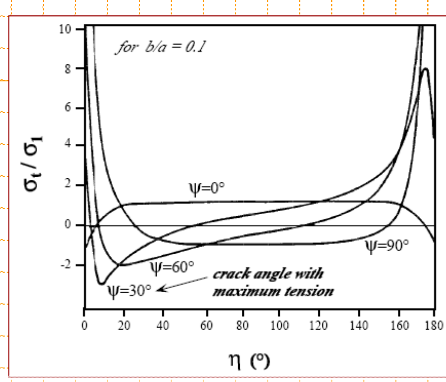


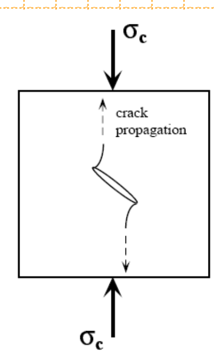


Crack Propagation in Compression

Under uniaxial compressive loading conditions, the highest tangential stress concentration on an elliptical crack boundary was inclined 30° to the major principal stress. As these cracks develop, they will rotate to align themselves with the major principal stress, σ_1.

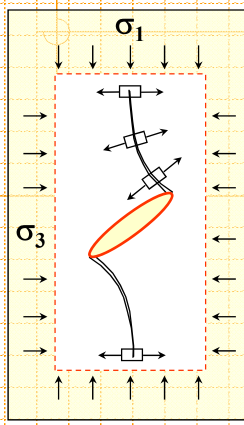






Lajtai (1971)

Crack Propagation in Compression

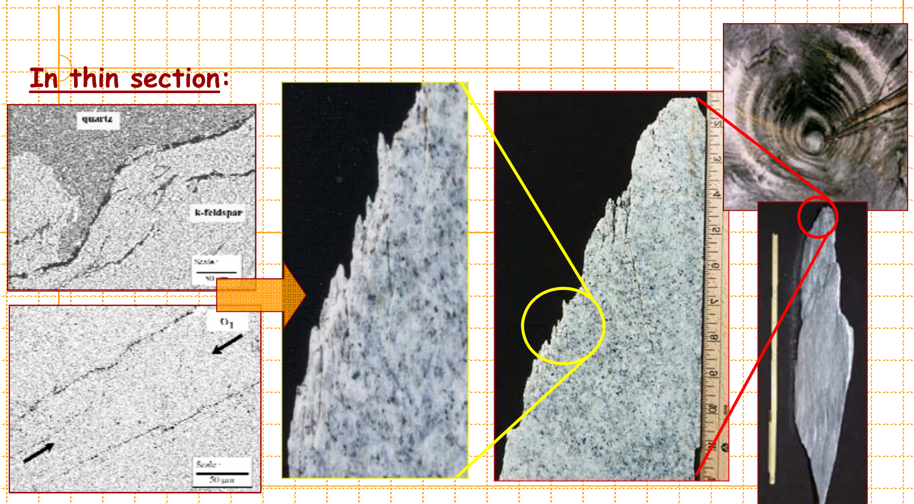


Experimentally, it has been shown that brittle fractures propagate in the direction of σ_1. Cracks develop in this way to allow the newly forming crack faces to open/dilate in the direction of least resistance (i.e. normal to σ_1 in the direction of σ_3).

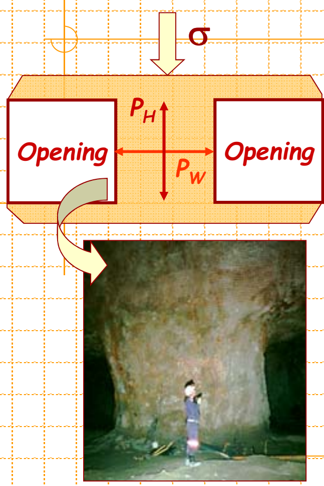
This is most easily accommodated in uniaxial compression since σ_3 = 0. For example, along a free surface!!

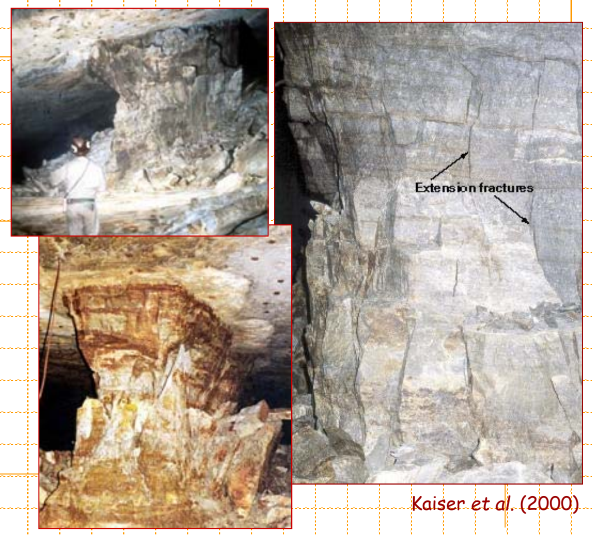
AECL's URL – Brittle Failure

In thin section:



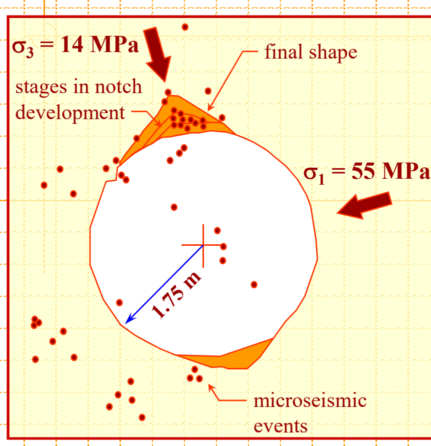
Pillar Failures through Stress-Induced Fracturing

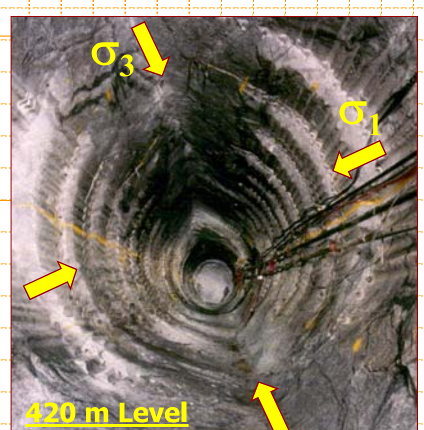




Kaiser *et al.* (2000)

Damage Around an Underground Excavation



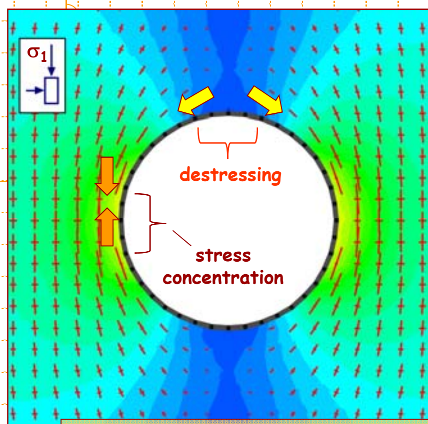


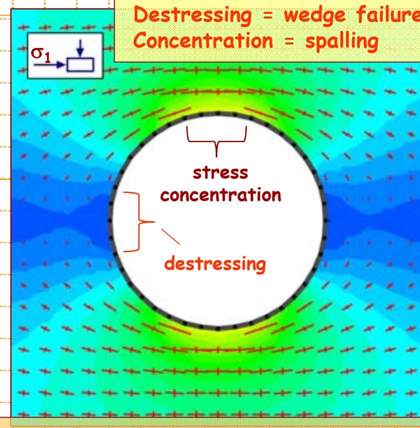
Martin (1997)

Orientation of σ_1 & Induced Stresses

Potential Ground Control Issues:

Destressing = wedge failures
Concentration = spalling

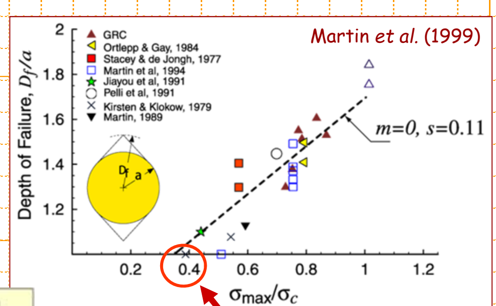




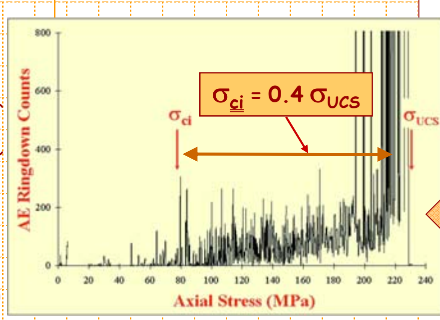
Stresses can be visualized as flowing around the excavation periphery in the direction of the major principle stress (σ_1). Where they diverge, relaxation occurs; where they converge, stress increases occur.

Failure Around Underground Excavations

Observations from underground mining in massive brittle rocks suggest that failure initiates when the maximum tangential boundary stress reaches approximately 40% of the unconfined compressive strength.



$\sigma_{max} = 0.4\ \sigma_{UCS}$

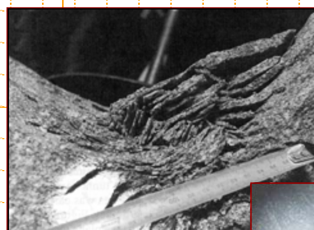


Eberhardt et al. (1999)

This correlates with experimental studies of brittle rock failure that show that stress-induced damage initiates at approximately 40%.

Failure Around Underground Excavations

In other words, stress-induced failure process begins at stress levels well below the rock's unconfined compressive strength.



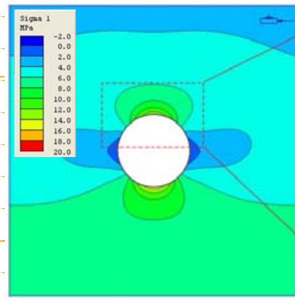
Example: Tunnel Spalling & Depth of Failure

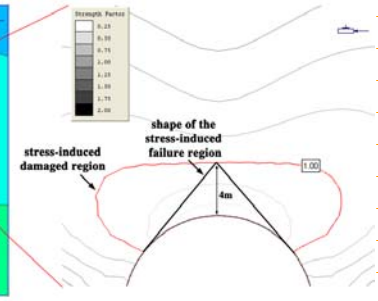
Problem: A 14-m diameter, 100-m deep tunnel is to be excavated in a weak but massive sedimentary rock unit with an average compressive strength of 25 MPa. The tunnel will be excavated by a tunnel boring machine. In-situ stress tests revealed that the major principal stress is horizontal and three times higher than the vertical stress. This has raised concerns of potential ground control problems related to stress-induced fracturing and slabbing of the rock.

As such, the designers need to estimate the potential depth of stress-induced slabbing in order to select the proper rock support measures.

Example: Tunnel Spalling & Depth of Failure

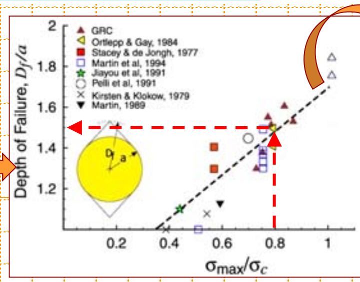
Assuming a vertical stress of 2.5 MPa (calculated from the overburden), and adopting a horizontal to vertical stress ratio of 3, a maximum tangential stress of 20 MPa in the tunnel roof is calculated.





$$\frac{\sigma_{max}}{\sigma_c} = \frac{20}{25}\,MPa = 0.8$$

Using Martin et al. (1999)'s empirical relationship



$$\frac{D_f}{a} = 1.5$$

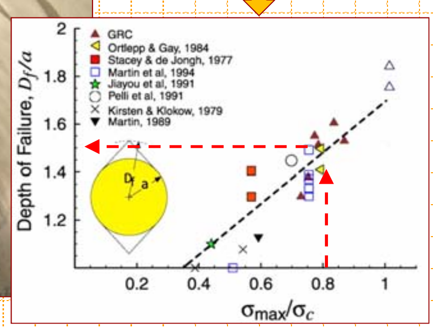
$$D_f = 1.5 * 8m = 12m$$

$$D_f - a = 4m$$

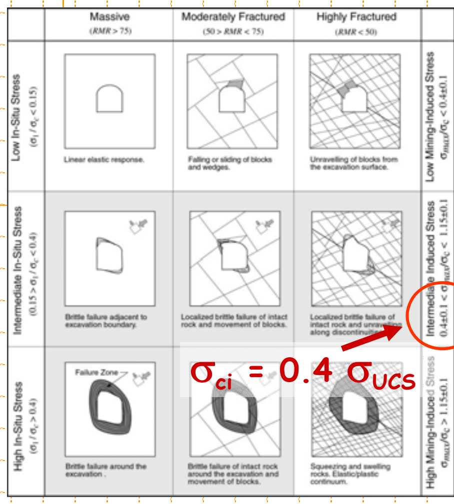
This means that, potentially, the slabbing may extend 4 m into the roof.

Tunnel Spalling & Depth of Failure

Using Martin et al. (1999)'s empirical relationship

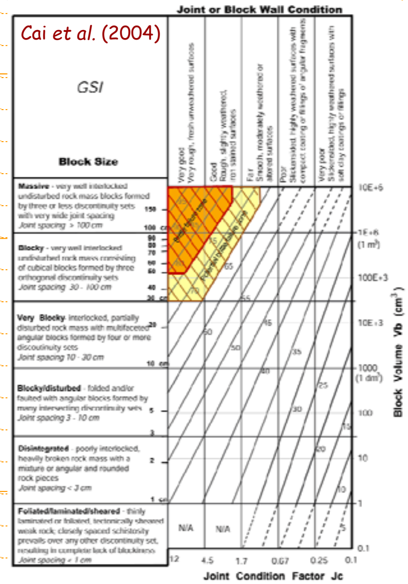


Brittle Failure Around Underground Excavations



$\sigma_{ci} = 0.4\ \sigma_{UCS}$

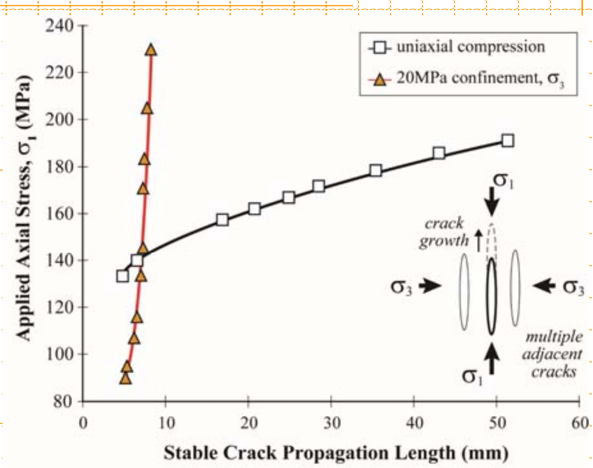
Martin *et al.* (1999)



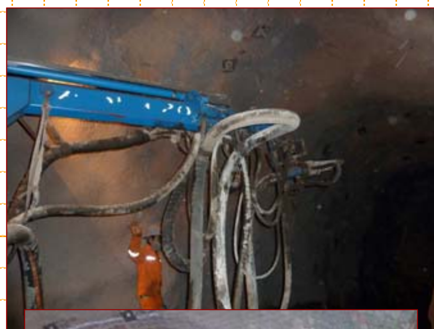
Influence of Confining Stress

Under low confinement, cracks can more easily open (in the σ_3 direction) and therefore propagate, leading to increased crack interactions and an acceleration of brittle failure. In contrast, the addition of confining stress works to make crack opening more difficult and therefore suppresses crack propagation. Confining stress therefore plays an important role in mitigating brittle failure.

Eberhardt et al. (1998a)



Ground Control through Confinement



Rockbursting – Strainbursts

Rockburst: A sudden and violent failure of rock where rock fragments are ejected into the excavation. Energy is released as seismic energy radiated in the form of strain waves.

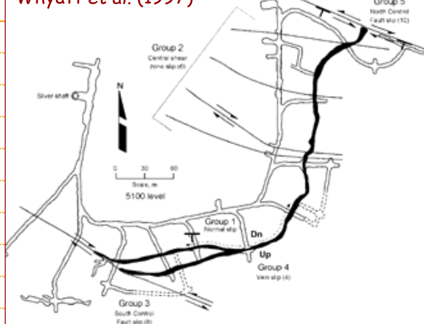
- Usually occurs after blasting, as face is unable to adjust to the immediately stress increase
- Immediate unloading of confinement from a triaxial to uniaxial stress condition, stored energy released as seismic energy
- Commonly occurs when drifting through contact between a brittle and relative soft rock (i.e. highly dependent on local mine rock stiffness)

Strainburst: A self-initiated rockburst that develops due to a disequilibrium between high stresses and rock strength (i.e. dynamic unstable fracturing).

Rockbursting – Slip Bursts

Slip burst: Slip bursts are characterized as a stick-slip shear movement on a discontinuity. These bursts are less likely to be triggered by a particular blast, and more likely to occur afterwards. Slip occurs when the ratio of shear to normal (effective) stress along the fault plane reaches a critical value (its shear strength).

Whyatt *et al.* (1997)



Slip bursts at the Lucky Friday Mine.

- Similar to mechanics of an earthquake
- Fault slip typically intersects the mine openings
- In most cases, mining activity causes slip by removing normal stress, although some local intensification of shear stress may also occur
- Changes in stress along a fault are often linked to mine activities by time-dependent deformation processes. These time-dependent processes can act over long periods of time, regardless of continued mining

Rockbursting & Worker Safety

Lecture References

Bieniawski, ZT (1967). Mechanism of brittle rock fracture: Part I - Theory of the fracture process. *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts* **4**(4): 395-406.

Brace, WF & Bombolakis, EG (1963). A note on brittle crack growth in compression. *Journal of Geophysical Research*, **68**(12): 3709-3713.

Eberhardt, E, Stead, D, Stimpson, B & Lajtai, EZ (1998a). The effect of neighbouring cracks on elliptical crack initiation and propagation in uniaxial and triaxial stress fields. *Engineering Fracture Mechanics* **59**(2): 103-115.

Eberhardt, E, Stead, D, Stimpson, B & Read, RS (1998b). Identifying crack initiation and propagation thresholds in brittle rock. *Canadian Geotechnical Journal* **35**(2): 222-233.

Eberhardt, E, Stead, D & Stimpson, B (1999). Quantifying pre-peak progressive fracture damage in rock during uniaxial loading. *International Journal of Rock Mechanics and Mining Sciences* **36**(3): 361-380.

Goodman, RE (1989). Introduction to Rock Mechanics. John Wiley & Sons: New York.

Griffith, AA (1920). The phenomena of rupture and flow in solids. *Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences*, **221**(587): 163-198.

Griffith, AA (1924). The theory of rupture. In *Proceedings of the First International Congress for Applied Mechanics, Delft*, pp. 55-63.

Harrison, JP & Hudson, JA (2000). Engineering Rock Mechanics – Part 2: Illustrative Worked Examples. Elsevier Science: Oxford.

Lecture References

Hoek, E & Brown, ET (1980). Underground Excavations in Rock. Institution of Mining and Metallurgy: London.

Ingraffea, AR (1987). Theory of crack initiation and propagation in rock. In *Fracture Mechanics of Rock*. Academic Press Inc. Ltd.: London, pp. 71-110.

Lajtai, EZ (1971). A theoretical and experimental evaluation of the Griffith theory of brittle fracture. *Tectonophysics*, **11**: 129-156.

Kaiser, PK, Diederichs, MS, Martin, D, Sharpe, J & Steiner, W (2000). Underground works in hard rock tunnelling and mining. In *GeoEng2000, Melbourne*. Technomic Publishing Company: Lancaster, pp. 841-926.

Martin, CD, Kaiser, PK & McCreath, DR (1999). Hoek-Brown parameters for predicting the depth of brittle failure around tunnels. *Canadian Geotechnical Journal* **36**(1): 136-151.

Whyatt, JK, Blake, W & Williams, TJ (1997). Classification of large seismic events at the Lucky Friday Mine. *Transactions of the Institution of Mining and Metallurgy, Section A: Mining Industry*, **106**: A148-A162.