Rock Strength (Shear strength, compressive strength, tensile strength, fracture strength, crushing strength, etc…)
Common Symbols in RM

- \(E, \nu:\) Young’s modulus, Poisson’s ratio
- \(\phi:\) Porosity (e.g. 0.25, or 25%)
- \(c', \phi', T_0:\) Cohesion, friction / tensile strength
- \(T, p, p_0:\) Temperature, pressure, initial pres.
- \(\sigma_v, \sigma_h:\) Vertical and horizontal stress
- \(\sigma_{\text{hmin}}, \sigma_{\text{HMAX}}:\) Smallest, largest horizontal \(\sigma\)
- \(\sigma_1, \sigma_2, \sigma_3:\) Major, intermediate, minor stress
- \(\rho, \gamma:\) Density, unit weight \((\gamma = \rho \cdot g)\)
- \(K, C:\) Bulk modulus, compressibility

*These are the most common symbols we use*
Chalk Fracture Experiments...

a. Three-point loading

Compressive stress

Surface of fracture

Fracture location directly under 2P

Tensile stress

P

2P

b. Four-point loading

Compressive stress

Surface of fracture

Fracture location indeterminate, but between the two vertical loads

Tensile stress

P

P

P

P

c. Pure axial tension

Surface of fracture

Fracture location indeterminate

T

P

T

d. Pure torsion (moment)

Surface of fracture is a helical shape

Maximum tensile stress orientation

M

M
What is Strength?

- It turns out that the “strength” of a geomaterial is a highly complex subject…
- There still remain issues on which experts are not in full agreement (e.g. scale dependency of tensile strength, “creep failure”…)
- Strength can be a simple measure, such as unconfined compressive strength (UCS)
- It can be complex (shear stress under a full 3-dimensional stress state, under temperature and elevated pore pressure conditions, etc.)
Yield Modes around a Borehole...

Brittle beam bucking under high uniaxial local loads
Crushing in breakout apex
Destabilized column is “popping” out

High $p_w$ leads to slip of a joint or fault.
Usually occurs only with high MW

Axial extension fractures: tensile failure when $p_w > \sigma_\theta$
Shear failure in low cohesion rock precedes sloughing of cavings

High MW – Low MW

Plus some others...
- Fissile shale sloughing if the borehole axis is close to parallel to fissility axis
- Swelling, weakening, turning to “mush”
- Borehole surface spalling from high $\sigma_\theta$, perhaps arising from heating, low $\sigma'_\theta$
Strength Issues & a SAGD Chamber

- Hydraulic fracture and caprock integrity
- Interface shear
- Shale barrier breakup
- Shear dilatancy
- \( k, \phi \) & C changes
- Cold dilation
Rock Strength

- Strength is the capacity to sustain (support):
  - Shear stress (shear strength)
  - Compressive normal stress (crushing strength)
  - Tensile stress (tensile strength)
  - Bending stress (bending or beam strength)

- All of these depend on effective stresses ($\sigma'$), thus, we must know the pore pressure ($p$ or $p_o$)

- Rock specimen strength is different than rock mass strength (joints, fissures, fissility...)

- Tests are done on cores, chips, analogues...
Rock Mass vs Sample Strength

Field scale: grains to kilometers. Lab scale: grains to 100 mm diameter specimen.

Sample damage can change properties!

Scale differences and flaws mean that direct extrapolation of test results to the field is difficult in Petroleum Geomechanics.
How We Measure Rock Strength…

- Simple measurements (called “index” tests)
  - Uniaxial Compressive Strength (UCS), $\sigma'_3 = 0$
  - Tensile strength (pure tension, hard for rocks!)
  - Indirect tensile test (Brazilian test)
  - Point-load, beam-bending, scratch test, needle…

- Direct shear tests of a planar surface
  - A joint surface, bedding plane, fault plane, sheared plane, lithologic interface, etc.
  - The surface is loaded, then sheared, and the resistance to shear loads is recorded
Cracks and Flaws

**Flaws in Rock:**
- Pores
- Grain boundaries
- Joints
- Fractures
- Faults, etc.

The flaw tip concentrates stresses, making brittle rupture much easier.
Stress Concentrations

www.webpages.uidaho.edu/~simkat/geol542.html

Hoek and Bieniawski 1965, Int J Frac Mech 193) 137-155
“Griffith\(^1\)” Cracks…

- Flaws serve as local stress concentrators
- The applied stress is far lower than the yield value for the “intact” material...
- Stress concentration at the flaw tip locally overcomes material strength
  \[ f(\text{crack length, orientation, sharpness}) \]
- Strength of a “flawed” brittle material is therefore **far lower** than an “intact” material
- All rocks are flawed! Hence, weak in tension, strong in compression

---

Nevertheless... Tensile Strength...

- Tensile strength ($T_o$) is extremely difficult to measure: it is direction-dependent, flaw-dependent, sample size-dependent, ...
- An indirect method, the Brazilian disk test, is used
- For a large reservoir, $T_o$ may be assumed to be zero because of joints, bedding planes, etc.
Other Index Tests of Strength

- Index tests: strength “indices” only
- Point load tests on core disks or chunks
- Brinnell Hardness test, or penetration test
- Scratch test on slabbed core sections
- Sclerometer or steel bar rebound tests
- All these use correlation charts for strength estimates
**Recommendation**

- Include a strength index test program in all your core analyses (good for drilling…)
- Service companies can provide this systematically upon request
- The data bank can be linked to compaction potential, drillability, other factors…
- It may help identify particularly troublesome zones that could cause troubles
- Any systematically collected data will prove useful for correlations and engineering
Cautions!

- However, index values are estimates only!
- Scale is a problem!
  - What is the scale of interest to the problem?
  - Is testing a drill chip a test of sufficient scale?
  - Is it possible to index test fractured reservoirs?
- Geometry is an issue!
  - How is strength affected by a 2 mm thick shale lamination in an otherwise intact sandstone?
  - Is strength anisotropic?
  - What is orientation w.r.t. the anisotropy?
Core #2 ~27500' below sea level

Scratch test results

This core section is quite homogeneous throughout

~ 1 foot (300 mm) length

Red line is output from the load cell
Blue line is a moving average value of the force

Correlation to UCS (psi)
Core #1 ~28000' below sea level

Scratch test results

Red line is output from the load cell. Blue line is an averaged value of the force.

Heterogeneous and damaged core

~ 1' (300 mm)
Core #2  ~27500’ below sea level

Scratch test results

Heterogeneous, damaged core

~ 1 foot (300 mm) length
Rock Strength - Shear Strength

- Shear strength: a vital geomechanics measure, used for design
- Shearing is associated with:
  - Borehole instabilities, breakouts, failure
  - Reservoir shear and induced seismicity
  - Casing shear and well collapse
  - Reactivation of old faults, creation of new ones
  - Hydraulic fracture in soft, weak reservoirs
  - Loss of cohesion and sand production
  - Bit penetration, particularly PCD bits

\( \sigma'_n \) is normal effective stress
\( \tau \) is the shear stress, || to slip plane
How We Measure Rock Strength...

- Direct measurements with confinement ($\sigma'_3$)
  - Compressive Strength: Triaxial Testing Machine
  - Encase the core in an impermeable sleeve
  - Confining stress is applied $\sigma_3$ first
    - $\sigma_a$ is then increased while…
    - Pore pressure constant
    - Record $\Delta\sigma_a$, $\varepsilon_a$, $\varepsilon_r$, $\Delta V$

- More exotic tests…
  - $\Delta T$, $\Delta p$, even $\Delta$chemistry
  - Creep tests (constant $\sigma$, measure $\dot{\varepsilon}$)
  - Hollow cylinders…
High Confining Pressure Frame

Cell

Press

Core Lab Inc.

Frame

$\sigma'_a$

$\sigma'_r$
The Triaxial Cell

\[ \sigma_a \]

\( \sigma_a \) applied through oil pressure

\( \sigma_r \)

load platen

\( \Delta V_p \)

p control, \( \Delta V_p \)

thin porous stainless steel cap for drainage

\( \varepsilon_a, \varepsilon_r \)

strain gauges

seals

impermeable membrane

CSIRO-Australia
Triaxial Test Apparatus

- A confining stress $\sigma'_3$ is applied (membrane)
- The pore pressure is zero, or constant
- The axial stress is increased slowly until well past peak strength
- Deformation behavior is measured during test
- $T, p_o$... can be varied in sophisticated systems

(Franklin and Hoek, 1970.)
Some Issues in Testing

- Sample disturbance
- Sample homogeneity
- Representativeness
- Specimen preparation
- Lateral $\varepsilon$ data? $\Delta V$?
- $\Delta p$ response (shales)?
- Testing must be done by a commercial lab with good QC
- Even then, results are critically examined

$\phi = 30\%$ in situ, $35\%$ in the core lab

Shaley zone, sheared
 Oil sand, intact

$\sigma'_a$
$\sigma'_r$
Shear Failure of Sandstone

- High quality cylinder
- \( L = 2D \)
- Flat ends
- High angle shear plane
- Zone of dilation and crushing

\[ \sigma_a = \sigma_1 \]
\[ \sigma_r = \sigma_3 \]
A $\sigma'$ - $\varepsilon$ Curve for a Rock Specimen

- $\sigma_1 - \sigma_3$
- $\gamma$ - peak strength
- Damage starts
- Cohesion breaking
- "Elastic" part of $\sigma'$-$\varepsilon$ curve
- Seating, microcrack closure
- Massive damage, shear plane develops
- Sudden stress drop (brittle)
- Continued damage

$\sigma'_a = \sigma'_1$
$\sigma'_r = \sigma'_3$

Shear planes

Ultimate or residual strength

Axial strain

Stress difference
Yield and Strain-Weakening...

- At one $\sigma'_3$ value...
  - $Y_P$: peak shear strength
  - $Y_R$: residual strength
- Red curve is at a high confining stress – $\sigma'_3$
- Blue curve, low $\sigma'_3$
- E.g.: high pore pressure = low $\sigma'_3$, low strength, brittle behavior!
- Low $p_o$… higher strength, ductile

\[ \sigma' - \varepsilon \text{ behavior} \]

\[ Y_P \]

\[ Y_R \]

Ductile yield

Strain-weakening

Brittle rupture

Axial strain - $\varepsilon_a$
Measurement of $\Delta$(Pore Volume)

- The specimen is isolated from all liquids in the cell.
- The pore space is liquid-saturated (water or oil).
- As the axial stress is increased, $\Delta V$ measured.
- This gives an estimate of the dilation of the rock as it shears.
Dilatancy During Rock Shearing

- When rocks shear under low $\sigma'_3$, they dilate (+V)
- Dilation = $+\Delta V$ increase in pore V, microcracks
- Rock is weakened, but with higher $\phi$, $k$ values
- For reservoirs and high $p$, $\sigma'_3$ is low; dilation enhances permeability, an important factor in heavy oils...
Behavioral Model Representation

Constitutive models:

A: Linear elastic, no deviatoric dilation
B: Perfect plasticity, no deviatoric dilation
C: Instantaneously strain-weakening, post failure dilation angle
D: Gradual weakening, post failure dilation
E: General response, simulated with more complex models…
Full Triaxial Data Set Example

- $\sigma'_3 = 14.0$ MPa
- $\sigma'_3 = 7.0$ MPa
- $\sigma'_3 = 2.0$ MPa
- UCS, $\sigma'_3 = 0$

Strain- %

Volume change measurement (dilation)
Rock Strength: the M-C Plot

- To plot a yield criterion from triaxial tests, on equally scaled $\tau$, $\sigma'$ axes, plot $\sigma'_1$ and $\sigma'_3$ at failure, join with a semicircle, then the tangent = $Y$

\[
\begin{align*}
\tau & \quad \text{Shear stress} \\
\sigma' & \quad \text{Normal stress} \\
\sigma'_1 & \quad \text{Normal stress} \\
\sigma'_3 & \quad \text{Normal stress} \\
\end{align*}
\]

4 triaxial tests are plotted here, plus the tensile strength from other tests
Standard Approximation for $Y$

Known as the **Mohr-Coulomb** (M-C) failure criterion

Rocks are weak in tension!!

$Y = \text{M-C Yield Criterion:}$

$\tau_f = c' + \sigma'_n \cdot \tan\phi'$ for $\sigma'_n \geq T_o$

$\tau_f = 0$ for $\sigma'_n < T_o$

$\sigma'_n$ - normal stress

$T_o$ - real $Y$

$c'$ - cohesion

$\phi'$ - linear approximation

$\tau$ - shear stress
Some Real Data

Coulomb Failure Envelope - Ormat Desert Peak 35-13
Depth 2437 ft

Effective Compressive Strength
Friction Angle = 45.9°
Linear Cohesion = 21.86 MPa

Effective Residual Compressive Strength
Friction Angle = 39.6°
Linear Cohesion = 3.31 MPa
Rock Failure Modes and $\sigma'_3$

- **Axial Compression**
  - $\sigma_1$
  - $\sigma_2$
  - $\sigma_3$

- **Axial Extension**
  - $\sigma_1$
  - $\sigma_2$
  - $\sigma_3$

- **Tensile fracture**
  - $\sigma_1$
  - $\sigma_3$

- **“Transitional-tensile” fracture**
  - $\sigma_1$
  - $\sigma_3$

- **Coulomb shear fracture**
  - $\sigma_1$
  - $\sigma_3$

- **Brittle-plastic transition**
  - $\sigma_1$
  - $\sigma_3$

- **Plastic yielding**
  - $\sigma_1$
  - $\sigma_3$

Davis and Reynolds, 1996

van der Pluijm and Marshak, 1997

*This should be "stress" instead of "pressure"*
Use a Reasonable Y Approximation

Mohr-Coulomb failure (or yield) criterion

Rocks are weak in tension: can we assume that $T_0 = 0$ for large scale problems?

This is a better approximation for cases of low confining stress.
Different Methods to Present Yield

- In the literature, there are > five different methods to plot rock yield (failure) criteria.
- The next slides show other plots.
- I prefer the Standard Mohr plot…
  - Simple, clear, easy circle construction for $\sigma$.
- There are also many yield criteria: Lade, Druker-Prager, Modified Von Mises…
- I suggest: stick with the M-C criterion, it is robust, well understood, direct… except when you have to plot stress paths…
Plot \( \sigma'_1, \sigma'_3 \) values at peak strength on axes

- Fit a curve or a straight line to the data points
- \( y \)-intercept is \( C_0 \) or UCS

\[
\sigma'_1 - \sigma'_3 \cdot \tan^2 \alpha - C_0 = 0
\]

- (Note that circles to solve for stresses can only be used on a conventional M-C plot, not on this one!)
p × q Plotting Method

- \( p = (\sigma'_1 + \sigma'_2)/2 \)
- \( q = (\sigma'_1 - \sigma'_2)/2 \)
- \( p \) is mean \( \sigma'_n \)
- \( q \) is shear stress
- Most common in soil mechanics (stress path plot)
- Sometimes used in petroleum rock mechanics

\[ q = C_0/2 + p \cdot \tan \alpha \]
Why Approximations for $Y$?

- Linear approximations of $Y$ are easy to understand: cohesion plus friction effects.
- When yield (failure) criteria are plotted from real lab data, there is a lot of scatter.
- Numerical modeling is the only way to use the full curvilinear $Y$ envelopes…
- Thus, a linear approximation allows:
  - Quick calculations and estimates
  - A clearer picture of the physics
  - But! Use the right stress range to improve results of simple calculations.
Still the Best (in my view)!

Mohr-Coulomb yield criterion

\[ \sigma' - \text{normal stress} \]

\[ \tau - \text{shear stress} - \frac{\sigma_1 - \sigma_2}{2} \]

\[ \sigma'_{\text{a}} = \sigma'_{\text{1}} \]

\[ \sigma'_{\text{r}} = \sigma'_{\text{3}} \]

\[ \sigma'_n \]

\[ T_0 \sim 0.12 \cdot \text{UCS} \]

1-F Rock Strength
What is “Failure”?

- Be very careful!!
  Failure is a **loss of function**. Rock yield is a loss of strength.
- Don’t confuse them!!
- For example:
  - Most boreholes have “yielded” zones
  - But, the hole has not collapsed! …or “failed”!
  - It still fulfills its function (allowing drill advance)
More sophisticated rock tests are also possible and useful in some circumstances:

- Hollow cylinders, cavity tests...
- Creep tests for salt and soft shales
- Thermal effects tests
- Shale properties with different geochemistry
- Drillability tests… etc.
Shear of Weak Sand

1-F Rock Strength

Courtesy Norwegian Geotechnical Institute
List of Tests* from Core Lab Ltd.

- Triaxial and uniaxial testing for $E$, $\nu$, UCS
- Sonic velocity testing for dynamic Young's Modulus and Poisson's Ratio ($E_D$, $\nu_D$)
- Mohr-Coulomb envelope analysis and construction
- Sonic velocity & acoustic impedance under $\sigma'$
- Sonic velocity in crude oils and brines
- Seismic velocity testing at 10Hz
- Hydrostatic and uniaxial pore volume compressibility
- Calibration of sonic and dipole log

*Downloaded list from their website
Tests...
List of Tests from Core Lab Ltd. - B

- Fracture azimuth and max stress azimuth (sonic velocity anisotropy)
- Evaluation of natural fracture conductivity
- Thick wall cylinder test (sand production onset)
- Fracture toughness analysis
- Brinell hardness test for closure stress analysis
- Proppant embedment testing vs. closure stress
- Brazilian indirect tensile strength
- Point load tensile test for wellbore stability analysis

www.corelab.com/PetroleumServices/Advanced/RockMech.asp
As $\sigma_a$ increased, $\varepsilon_a$ took place as well

However, when yield took place, deformation only along slip plane!

We cannot speak about strain any more, only slip or deformation

Also, there is elastic strain and plastic strain…
Diagenesis and Strength

- **Diagenesis** effects on the Mohr-Coulomb strength envelope

  - Shear stress
  - Normal stress

  - Chemical cementation
  - Densification (more interlock)
  - Cohesion
  - Diagenetic strength increase
  - Original sediment

Triaxial Test Stresses

- **σ_a** = **σ'_1**
- **τ_max** planes
- **σ_r** = **σ'_3**
- **σ_r**

1-F Rock Strength
Extreme Diagenesis Case…

Xal overgrowths, interpenetrative structure!
Rock Strength – Shear Box Tests

- Strength of joints or faults require shear box tests
- Specimen must be available and aligned properly in a shear box
- Different stress values (N) are used

![Shear Box Diagram]

- $S$ - shear force
- $N$ - normal force
- Area - $A$
- Cohesion - $c$
- Linear “fit”
- Curvilinear “fit”
- Data point

1-F Rock Strength
Shearbox Apparatus

- Normal load (stress)
- Reaction frame with high stiffness
- Split box for rock specimens to be tested
  - Different sizes can be mounted in the device
- Shear displacement on lower half of “box”
- Rails allow continuous “self-centering”
Yield Criterion in Shearbox Tests

- Also a Mohr-Coulomb plot

- The points representing normal load and shear load are plotted on axes of equal

- As with triaxial test data, a straight line fit is often used

- This $Y$ is for the joint surface only, not for the entire rock mass…

\[
\frac{N}{A} = \sigma'_n
\]

\[
\frac{S}{A} = \tau
\]

- Linear “fit”
- Curvilinear “fit”

Data point
Cohesion and Friction...

- Bonded grains
- Crystal strength
- Interlocking grains
- Cohesive strength builds up rapidly with strain
- But! Permanently lost with fabric damage and debonding of grains
Friction

- Frictional resistance to slip between surfaces
- Must have movement ($\varepsilon$) to mobilize it
- Slip of microfissures can contribute
- Slip of grains at their contacts develops
- Friction is not destroyed by strain and damage
- Friction is affected by normal effective stress
- Friction builds up more slowly with strain

$$\tau_{mob} = \text{cohesion} + \text{friction}$$

$$\tau_f = c' + \mu \sigma'_n$$

This is merely the M-C curve
Estimating Rock Strength

- Laboratory tests OK in some cases (salt, clay), and are useful as indicators in all cases
- Problems of fissures and discontinuities
- Problems of anisotropy (eg: fissility planes)
- Often, a reasonable guess, tempered with data, is adequate, but not always
- Size of the structure (eg: well or reservoir) is a factor, particularly in jointed strata - scale
- Strength is a vital factor, but often it is difficult to choose the “right” strength value
Strength Anisotropy

![Diagram showing the relationship between UCS and bedding inclination](image)

- **UCS** vs. **θ**
  - UCS values decrease as θ increases from 0 to 90 degrees.
  - There is a peak in UCS at θ = 30 degrees and another at θ = 60 degrees.

**Key Points**
- Vertical core and bedding inclination are important factors in determining rock strength.
- Understanding anisotropy helps in predicting the behavior of rocks under different stress conditions.
Crushing Strength

- Some materials (North Sea Chalk, coal, diatomite, high porosity UCSS*) can crush
- Crushing is collapse of pores, crushing of grains, under isotropic stress (minimal $\tau$)
- Tests involve increasing all-around effective stress ($\sigma'$) equally, measuring $\Delta V/\Delta \sigma'$
- Tests can involve reducing $p$ in a highly stresses specimen (ie: $\sigma'$ increases as $p$ drops)

*UCSS = unconsolidated sandstone
**Cracks, Grain Contacts, Strength**

- Point-to-point contacts are much weaker than long (diagenetic) contacts, lower $\mathbf{Y}$
- Large open microfissures also lead to lower strength (cracks = stress concentrators)
- Oriented contacts or microfissures give rise to anisotropy of rock strength as well
- Rocks with anisotropic fabric or exposed to differential stress fields over geological time develop strength anisotropy as well
In granular media, contact forces \((f_n, f_s)\) govern strength.

\[ f_s]_f = c' + \mu \cdot f_n \]

Again, the Mohr-Coulomb frictional concept…
A Non-Crushing Rock

- 25% porosity SiO$_2$ sandstone (99.5% Q)
- Contacts are diagenetic in nature…
- This gives a very high stiffness, even though…
- The rock is totally devoid of cohesion!
- Athabasca oil sands, Faja del Orinoco sands, are “similar” to this
Crushing Strength

- Apply $p, \sigma$ ($\sigma > p$), allow to equilibrate ($\sigma' = \sigma - p$)
- Increase $\sigma'$ by increasing $\sigma$ or dropping $p$
  \[ \Delta\sigma' = \Delta\sigma - \Delta p \]
- Record $\Delta V/V$, plot versus effective stress
- The curve is the crushing behavior with $+\Delta\sigma'$
Collapsing in a Chalk

\[ \tau = \frac{\sigma_1 - \sigma_2}{2} \]

Mohr-Coulomb yield criterion

\[ \sigma'_{a} = \sigma'_{1} \]

\[ \sigma'_{r} = \sigma'_{3} \]

shear planes

cohesion

Initial state

Fabric collapse

shear yield, then collapse

\[ \sigma'_{n} \]

normal stress

\[ \sigma'_{3} \]

\[ \sigma'_{1} \]
Stress Changes Leading to Collapse

Mohr-Coulomb yield criterion

$\tau - \text{shear stress} = \frac{\sigma_1 - \sigma_2}{2}$

$\sigma'_n$

$\sigma'_a = \sigma'_1$

$\sigma'_r = \sigma'_3$

Initial state

Increased pore pressure leading to shear, then collapse

Initial state

Increased effective stress leading to pore collapse

Fabric collapse

shear planes

cohesion

Increased effective stress leading to pore collapse

$t_f$
Griffith Flaw Theory

- Rock is a “flawed” material
- Flaws are stressed (τ) by deviatoric loads
- Tensile $\sigma_0$ develops at tips
- Rock is weak in tension
- Tensile cracks form easily
- They propagate $\perp$ to $\sigma_3$
- As $L \uparrow$, acceleration
- Sudden rupture ensues
Low Confining Stress (Low $\sigma'_3$)

- Low $\sigma'_3$: brittle rupture
- Fractures develop parallel to $\sigma'_1$
- Specimen may separate into several “columns”
- When column L/w ratio becomes large, buckling or crushing
- Rupture is sudden
- $\varepsilon$ energy is released
Yield at Higher $\sigma'_3$

At high stress, general damage occurs; much microfissuring, then coalescence takes place ("bifurcation")

Crystal debonding

Stress-induced anisotropy

Microfissure fabric at yield

Intercrystalline forces at yield

High $\sigma_3$
Low $\sigma_3$, Jointing Dominates

This becomes important in fractured shale drilling, HF design, mechanics of NFCR’s, shale gas and oil…
How Do We “Test” This Rock Mass?

- Joints and fractures can be at scales of mm to several meters
- Large φ core: 115 mm
- Core plugs: 20-35 mm
- If joints dominate, small-scale core tests are “indicators” only
- This issue of “scale” enters into all Petroleum Geomechanics analyses
Lessons Learned

- Strength is a complex issue
- We develop behavior “models” to understand strength and to apply it in practice
- Rock mass vs. rock specimen strength problem
- Problems of scale, heterogeneity…
- Nevertheless, rock strength can be measured and used to predict slip, crushing, triggering of fault movement, and so on.
- Combination of field and lab data is best…