Numerical investigation on confinement dependent rock mass strength at depth

<u>Bo-Hyun Kim, Ph. D.</u>
Senior Research Engineer
MIRARCO-Mining innovation, Laurentian University

Peter K. Kaiser, Ph. D., P. Eng.
CEO & President
CEMI-Centre for Excellence in Mining Innovation

Mirarco MINING INNOVATION

LaurentianUniversity UniversitéLaurentienne

Problem definitions

- Rational stresses and rock mass strength characterisation are needed at pre-feasibility stage in order to proceed to realistic design for rock structure.

- However, using *conventional methodology* established from data related to shallow to moderate depth (0 to 1000m) suggest that rock mass at great depth (out from the world of experience) is weak compared to the stress level.

Critical range of confinement

- Strongly affected by a range of confinement.

- *“Note that the range of minor principal stress value over which these tests are carried out is critical in determining reliable values for the two constants. In deriving the original value of σ_{ci} and m_i Hoek and Brown used a range of* $\boldsymbol{0<\sigma_3<0.5*\sigma_{ci}}$ *and, in order to be consistent, it is essential that the same range be used in any laboratory triaxial tests on intact rock specimens.” (Hoek and Brown, 1997)*

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Answers

I calculate a value of mi to be around 100 yet RocLab limits mi to be between 1 and 50. Why?

1. Your values of mi of around 100 are almost certainly associated with too small a range of confining stresses in your triaxial testing. This is a problem that I come across very frequently. The original definition of mi is based on triaxial tests up to one half of the uniaxial compressive strength of the intact material. The following quote is from Hoek and Brown, 1997, "Practical estimates of rock mass strength" published in the Int. J. Rock. Mech. Min Sci.

   "Note that the range of minor principal stress (sig3) values over which these tests are carried out is critical in determining reliable values for the two constants. In deriving the original values of sigci and mi, Hoek and Brown used a range of 0 < sig3< 0.5*sigci and, in order to be consistent, it is essential that the same range be used in any laboratory triaxial tests on intact rock specimens."

   For example, if you analyze the following data set for Carrara marble using *RocLab* you obtain sigci = 82.28 and mi = 8.68.

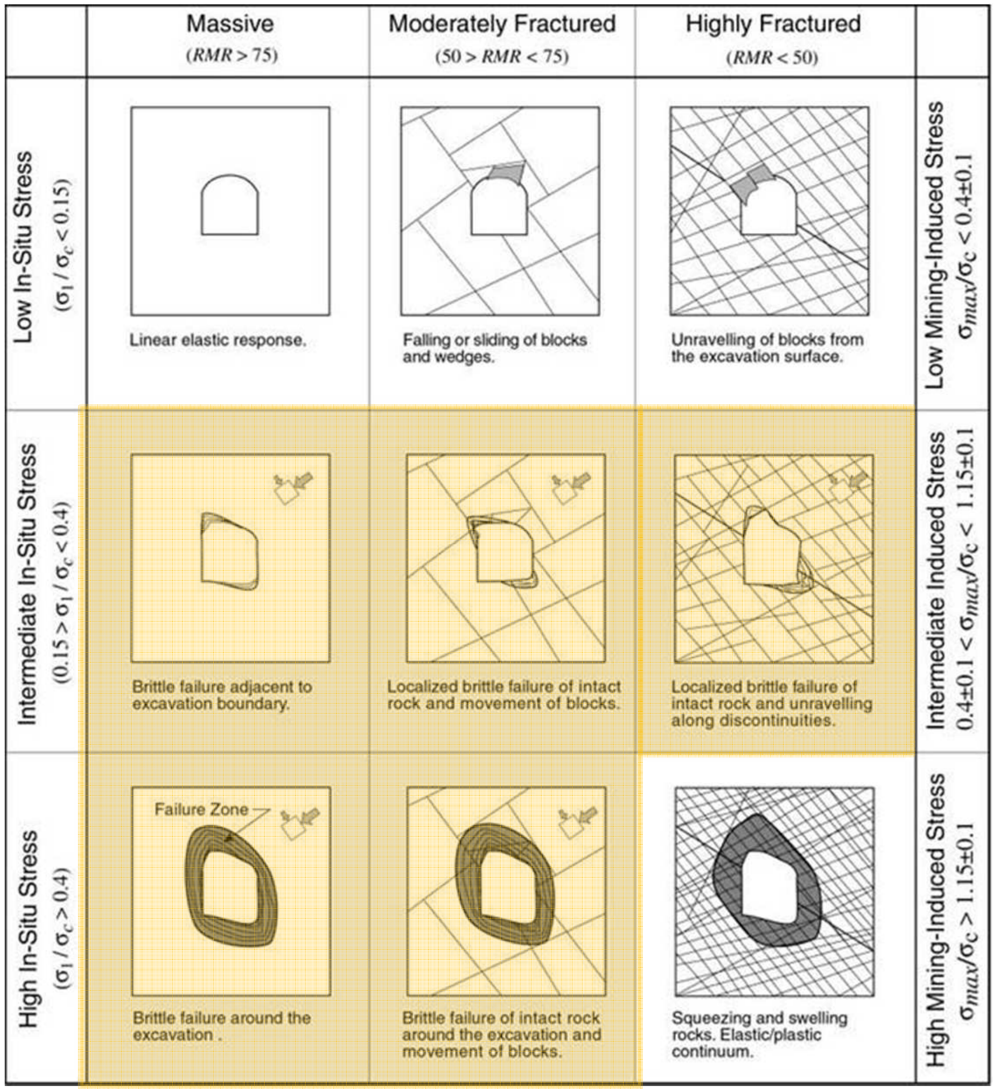
1.72	78.61
3.45	89.33
5.17	99.81
6.9	123.79
6.9	125.23
10.34	125.65
10.34	138.37
13.79	137.38
13.79	146.6
17.24	150.77
17.24	160.76
20.69	173.79
27.59	187.9
34.48	205.99
34.48	213.58

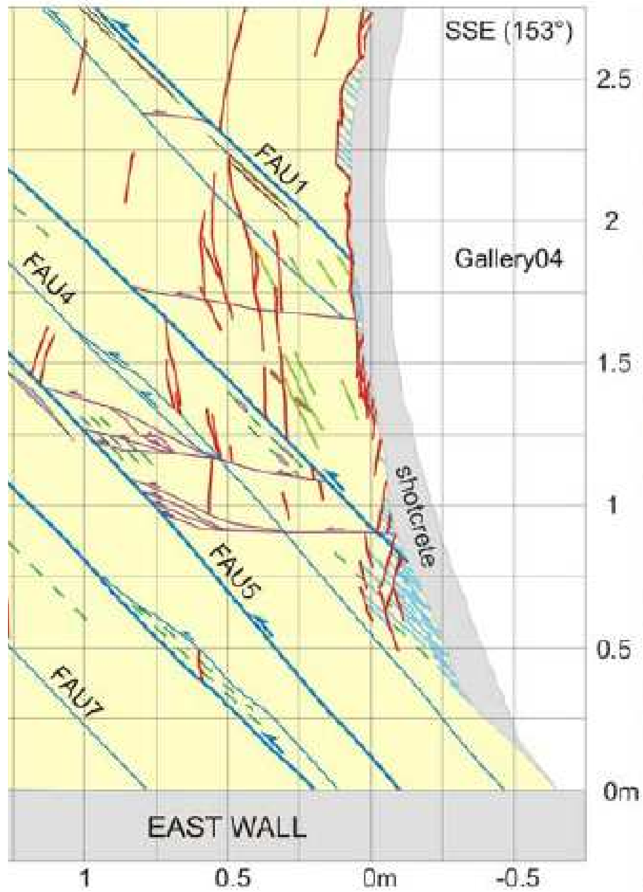
Note that the maximum value of sig3 is too low in this case - it should be about 40 MPa but this is a real data set and it is all that I have.

On the other hand, if I analyze only the first 4 data points, up to sig3 = 6.9 MPa, I obtain sigci = 48.92 and mi = 32.13. If this data set was for hard rock I could easily get mi values of over 100 by limiting the range of sig3 values.

All the values quoted in the various Hoek-Brown papers are derived from triaxial test data with the correct range of sig3 values - this was one of the criteria that we set in determining whether or not the data were acceptable. The typical range of mi values if from about 5, for soft ductile rocks, to 35 for very hard brittle rocks. Hence we set the range of 1 < mi < 50 in RockLab to cover this range.

Tunnel failure modes
(Kaiser *et al*, 2000)



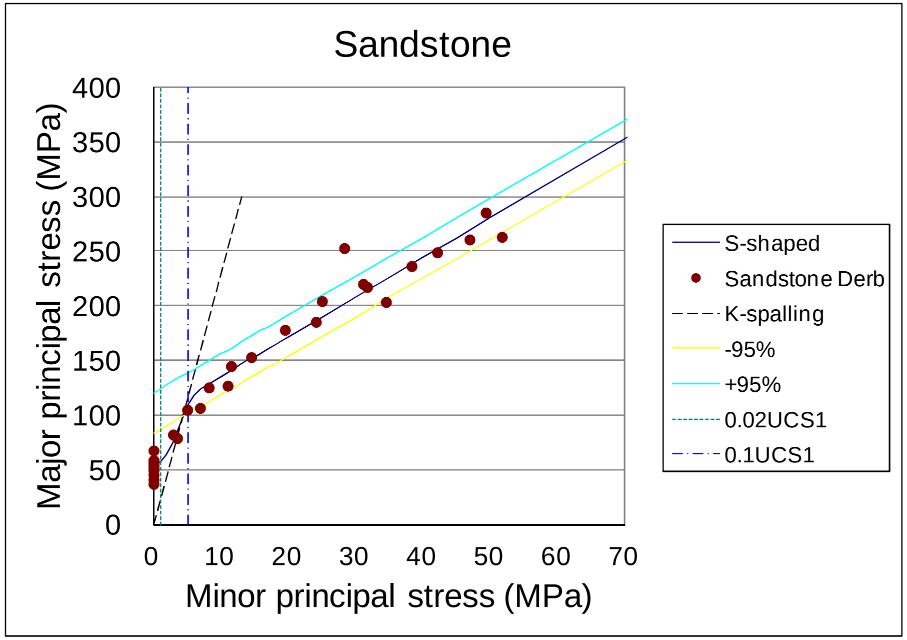


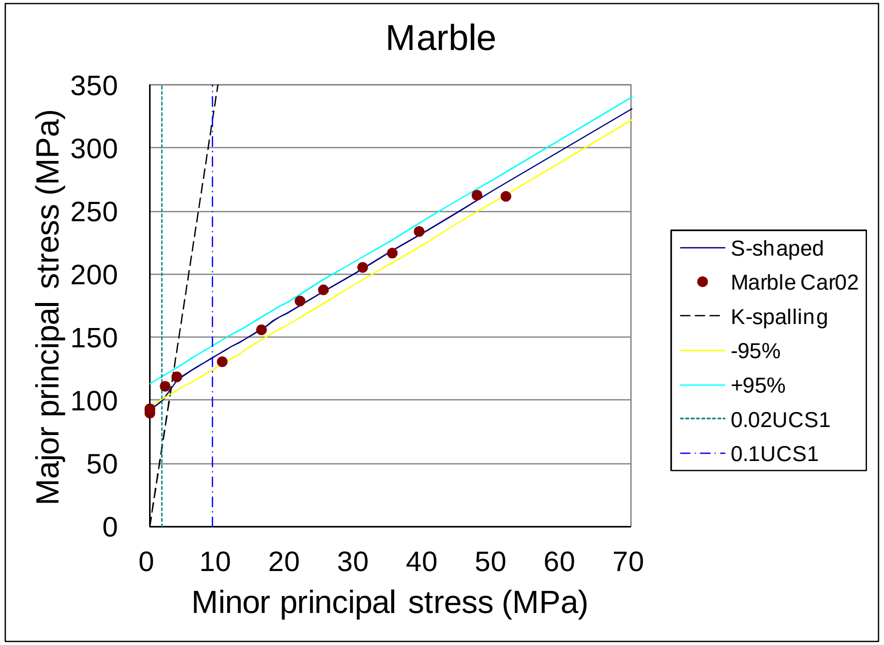
Brittle fractures observed near tunnel in Opalinus Clay (Yong *et al*., 2008)

S-shape brittle failure criterion (Kaiser & Kim, 2008; Kim & Kaiser, 2009)

$$\sigma_1 = k_2\sigma_3 + UCS_{II} + \left[\frac{(UCS_I - UCS_{II})}{1+e^{(\sigma_3^{'}-\sigma_3^0)/\delta\sigma_3}}\right]$$

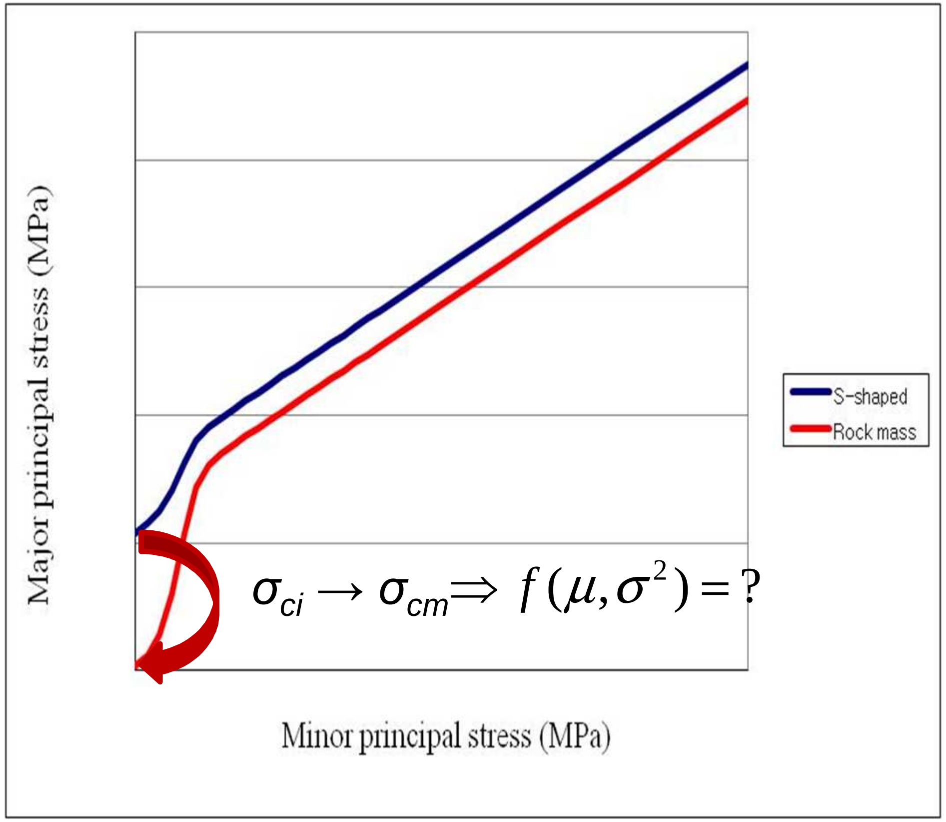
$$\sigma_3^0 = \frac{(UCS_I - UCS_{II})}{2(k_s - k_2)} \qquad \delta\sigma_3 = A\sigma_3^0 \; (A = 0.1 \sim 0.3)$$





Goal & Approaches

- Goal
  - Investigation into correlation between heterogeneity of rock sample in terms of material properties and uniaxial compressive strength degradation.
- Approaches
  - Hoek-Brown plasticity model is chosen.
  - Baseline: No variability of material properties accounted for analysis at all.
  - Variability of plastic property: Only Hoek-Brown constant, *s* is varied by triangular distribution function.
  - **Back calculate the strength degradation constant *s* and *GSI* from the results.**



Back calculation using HB constant (*s*)

$$\sigma_{cm} = \sqrt{s}\,\sigma_{ci}$$

$$\therefore \quad s = \left(\frac{\sigma_{cm}(calculated\, by\, FLAC3D)}{\sigma_{ci}\,(input\ value = 100MPa)} \right)^2$$

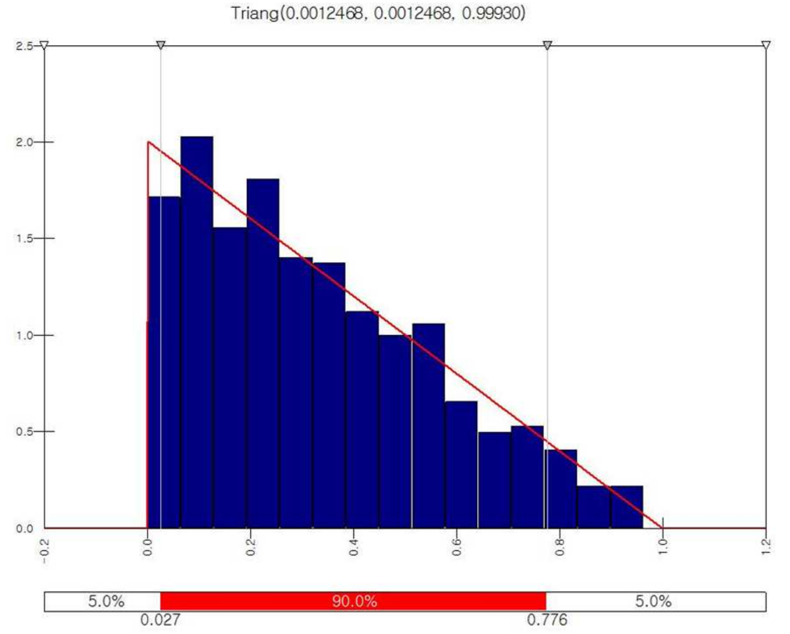
$$s = \exp\left(\frac{GSI - 100}{9} \right)$$

$$\Rightarrow GSI = 9\ln(s) + 100$$

Input data

- Variable HB constant, *s* by triangular distribution function

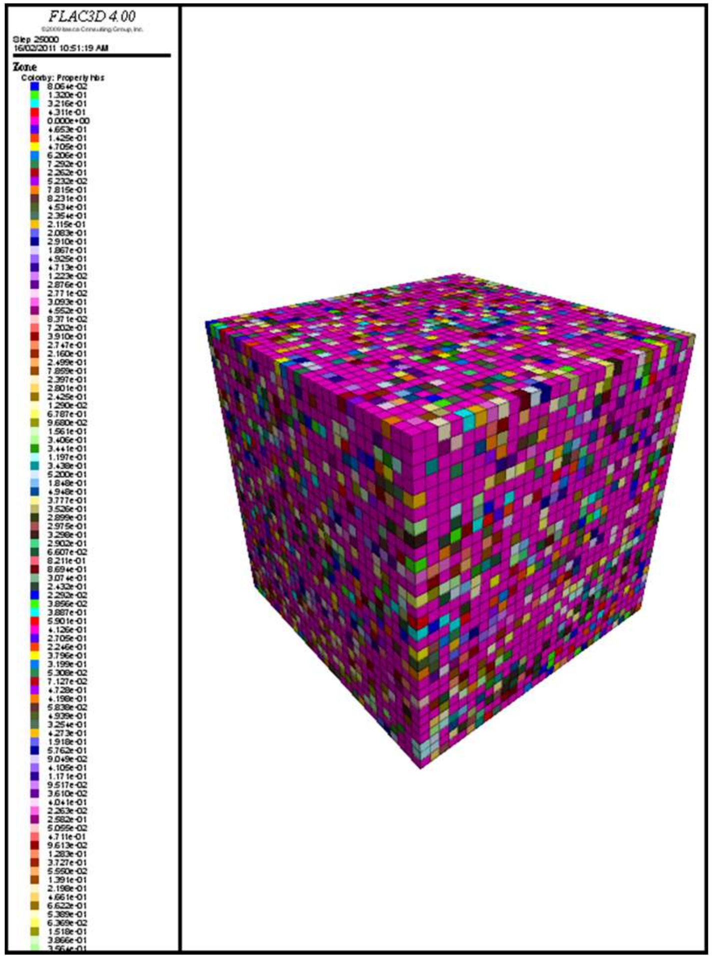
- *UCS* = 100MPa.
- m_i = 15.
- *E* = 37.5GPa.
- *v* = 0.25.
- *GSI* = 100 (for a).
- s_{mean} = 0.33.
  - Min = 0.0013.
  - Mode = 0.0013.
  - Max = 1.



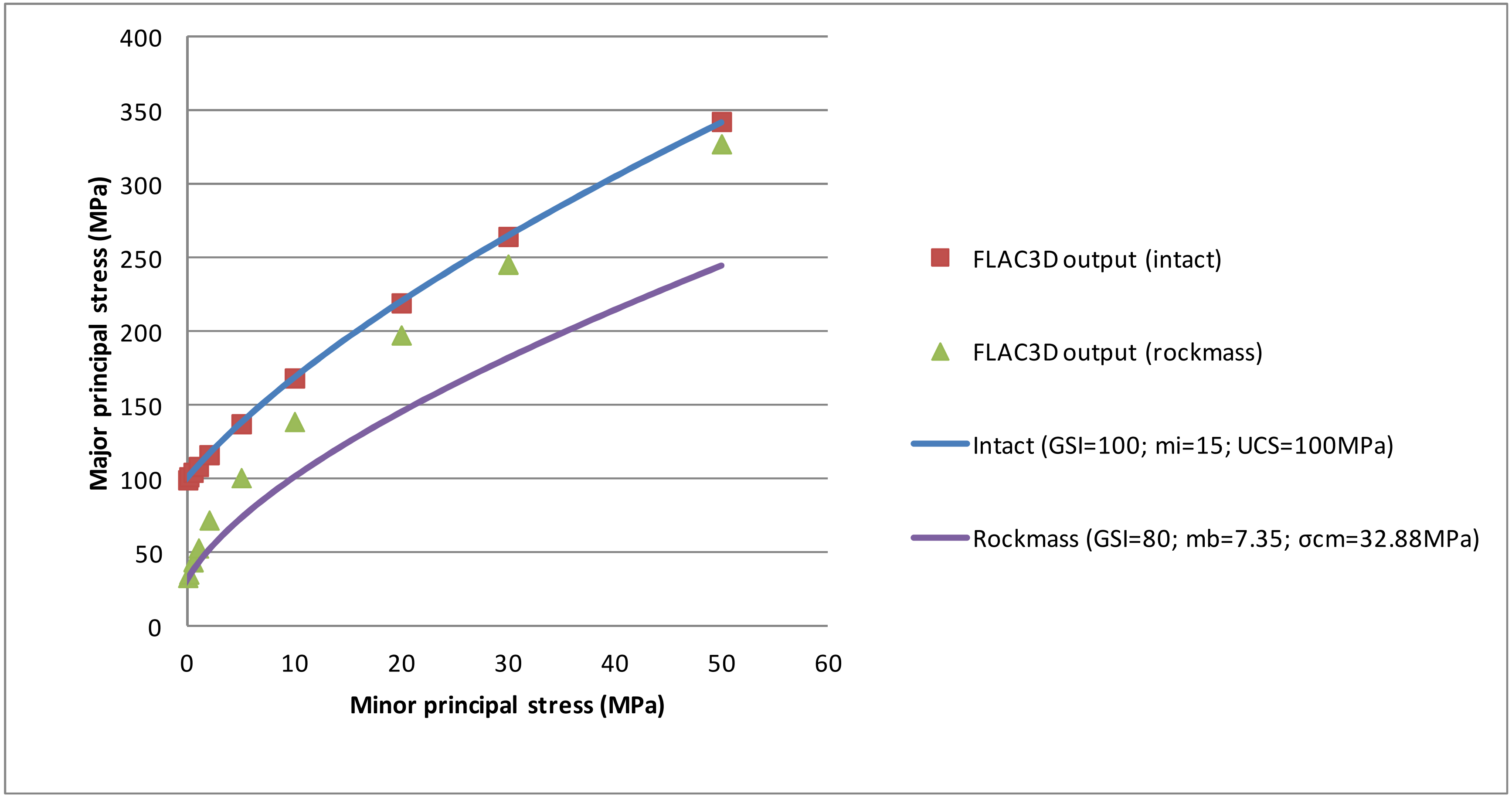
Symmetric: no effect (mean=mode).
Right-skewed: getting stronger (mean<mode).
Left-skewed: getting weaker (mean>mode).

FLAC3D model

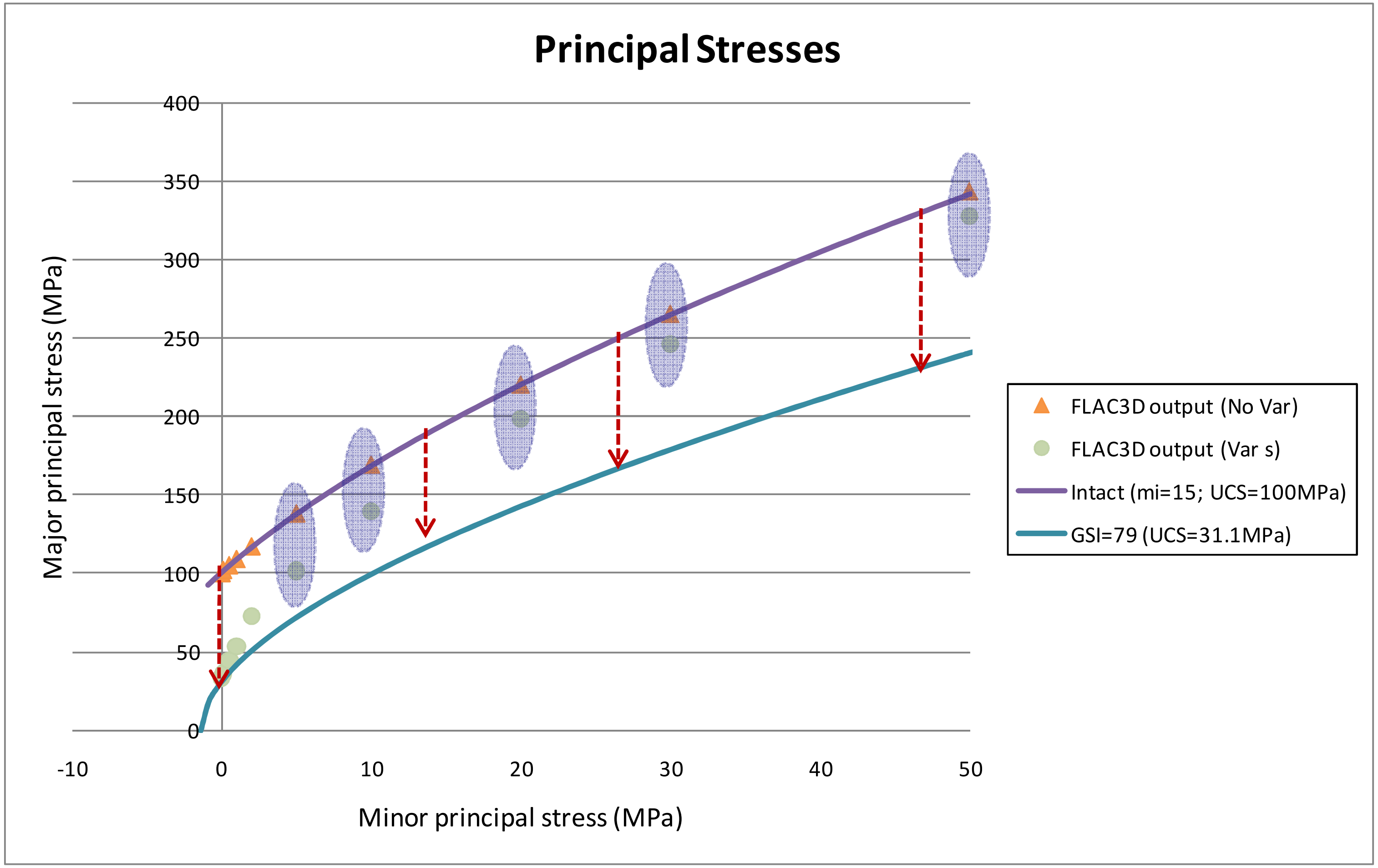
- Cubic sample.
  - 30 x 30 x 30cm.
- Both top and bottom are applied by a velocity loading.
- The velocity is determined as a function of maximum allowed strain.
- Both average vertical stress and strain are calculated while the sample is loading.
- Confining pressures.
  - 0.0, 0.1, 0.5, 1.0, 2.0, 5.0, 10.0, 20.0, 30.0 and 50.0MPa.



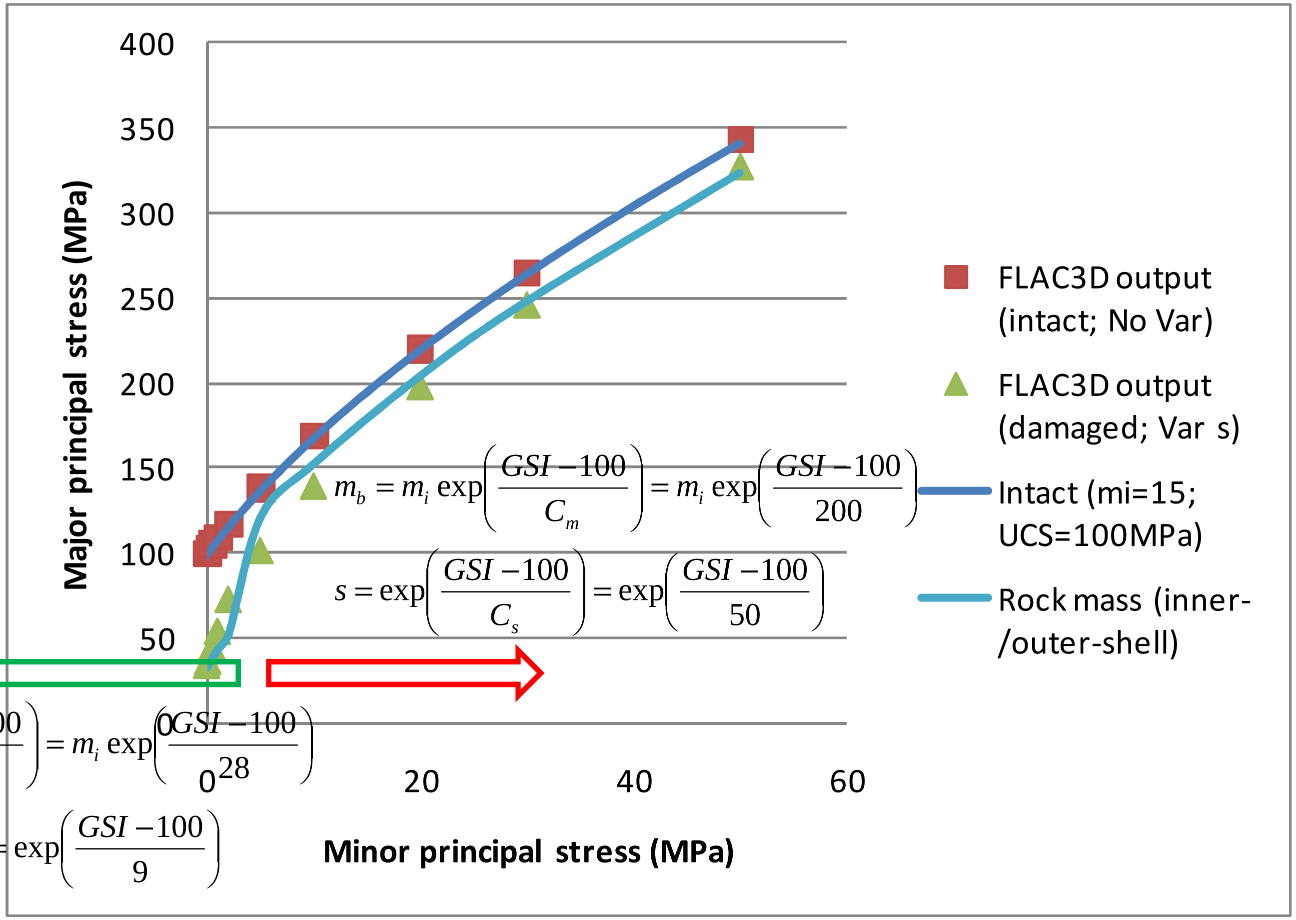
Strength degradation from intact to rock mass by Hoek-Brown criterion



Calculated principal stresses vs. HB envelops (*GSI*)



Rock mass strength due to confinement



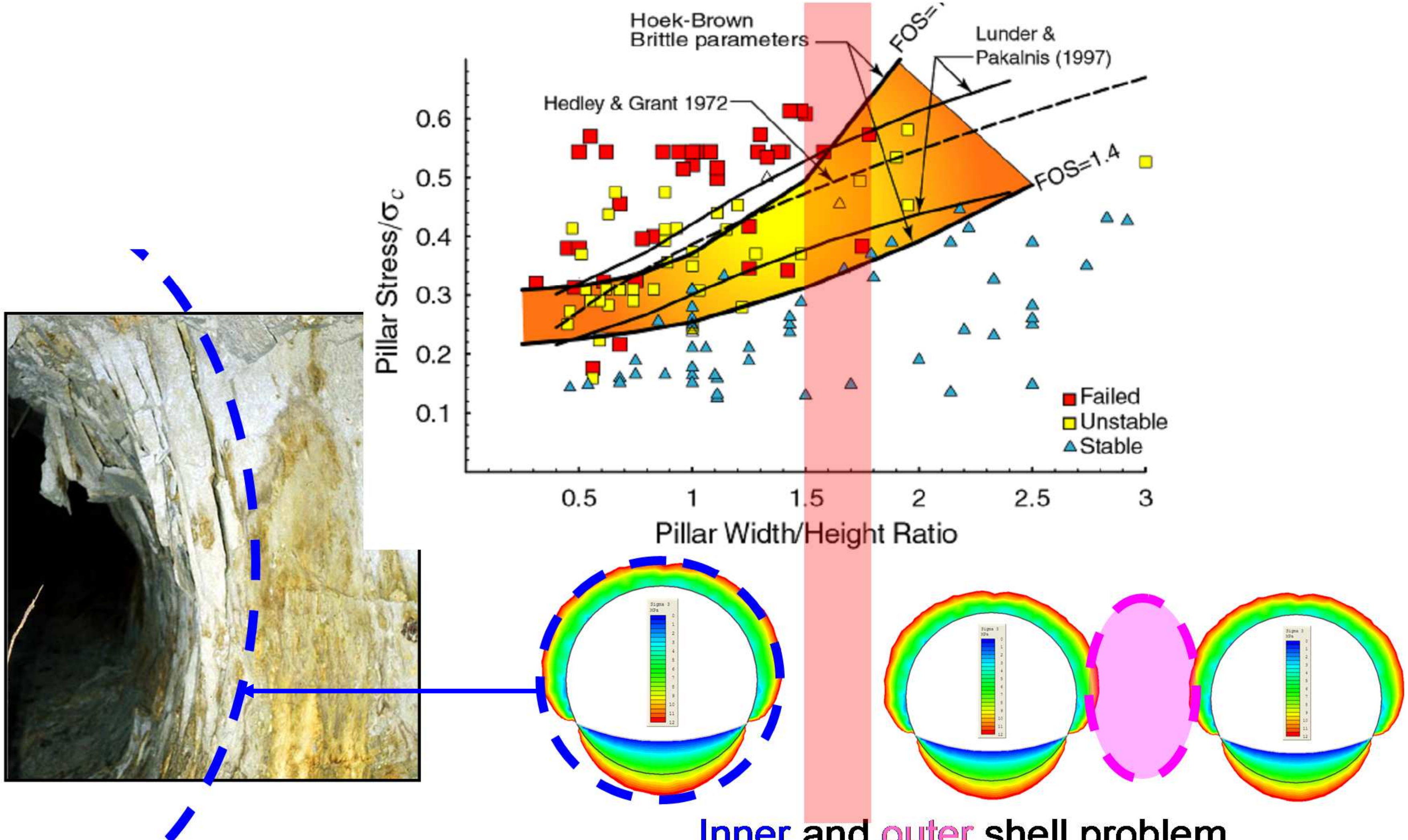
$$m_b = m_i \exp\left(\frac{GSI - 100}{C_m}\right) = m_i \exp\left(\frac{GSI - 100}{200}\right)$$

$$s = \exp\left(\frac{GSI - 100}{C_s}\right) = \exp\left(\frac{GSI - 100}{50}\right)$$

$$m_b = m_i \exp\left(\frac{GSI - 100}{C_m}\right) = m_i \exp\left(\frac{GSI - 100}{28}\right)$$

$$s = \exp\left(\frac{GSI - 100}{C_s}\right) = \exp\left(\frac{GSI - 100}{9}\right)$$

Implications for underground excavation



Inner and outer shell problem

Discussion

- Since the constant (*s*) is varied by the PDF the cohesion is loss and the friction is mobilised simultaneously while the sample is loading.

- It is clear that the rock mass strength is affected by confinement, condition, moreover, its behaviour which is a failure mode strongly depends on at depth.

- The result indicates the factor of strength degradation is not constant but variable due to confinement level.
  - For inner-shell: $C_s = 9$.
  - For outer-shell: $C_s \approx 50$.

- Since only single case is investigated for the variability of the constant (*s*) more simulations are required to convince the factor for outer-shell domain and to propose a full range of strength degradation curves associated with rock mass quality e.g. the *GSI*.


TUSEN TAKK!
THANK YOU!