# Resistencia de Macizos Rocosos

CI52T
Mecánica de Rocas en Obras de Ingeniería
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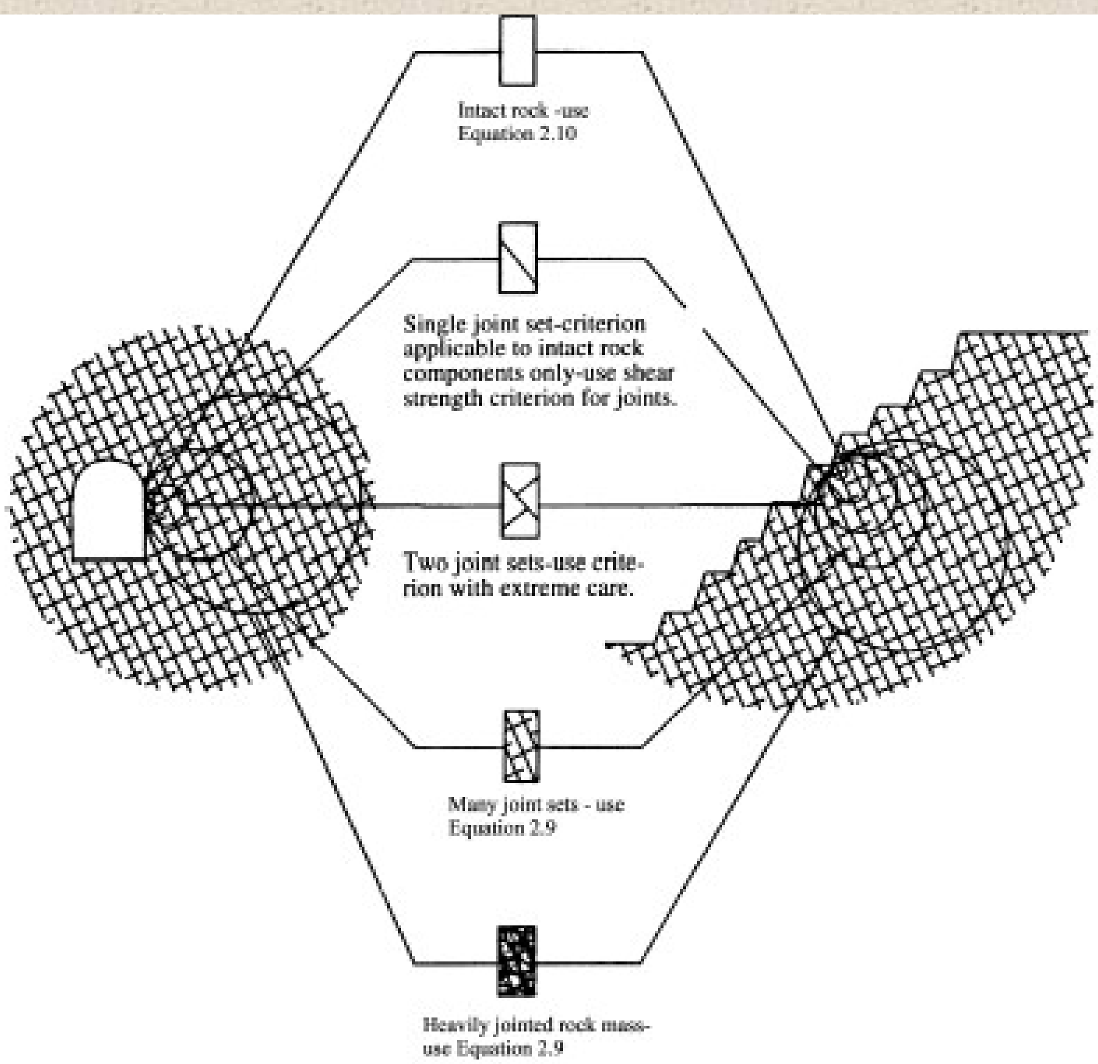
# Resistencia de Macizo Rocoso

- La resistencia de un macizo rocoso será función de la resistencia de la roca intacta, la resistencia de las discontinuidades y de cómo éstas se distribuyan en el macizo.
- Cuando la geometría de las discontinuidades controla la estabilidad del macizo, lo más correcto es considerar la resistencia de las estructuras.
- Cuando no hay un control definido de la geometría de discontinuidades, se aplican otros criterios de falla. El más común para obras de ingeniería civil es el de Hoek-Brown. Para obras subterráneas de mayor profundidad (mineras) hay otros criterios.

# Criterio de Hoek-Brown

- Definido por Hoek y Brown en 1980, para un caso particular. Ha tenido numerosas actualizaciones, la última de 2002.
- Considera que el macizo rocoso, a la escala de la obra de ingeniería en que se trabaja, puede considerarse isótropo. Esto significa que hay un número suficiente de discontinuidades poco espaciadas en comparación con la estructura (talud, túnel, etc.).
- La aplicación del criterio se considera como un "escalamiento" desde la roca intacta al macizo rocoso.



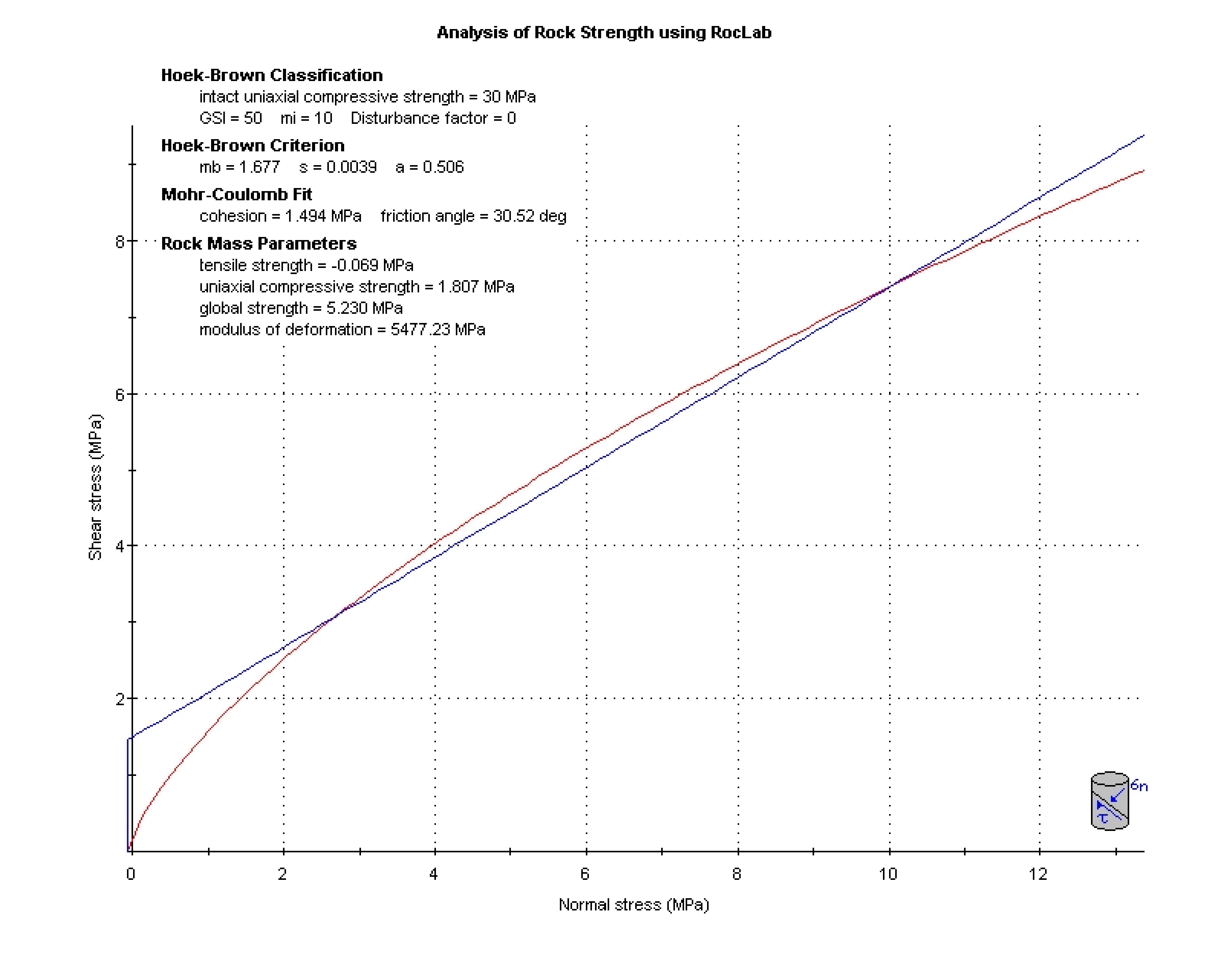
Intact rock -use
Equation 2.10
Single joint set-criterion
applicable to intact rock
components only-use shear
strength criterion for joints.
Two joint sets-use crite-
rion with extreme care.
Many joint sets - use
Equation 2.9
Heavily jointed rock mass-
use Equation 2.9

# Criterio Generalizado de Hoek-Brown

- Definido por Hoek & Brown (1997), como:

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left[m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right]^a$$

- Donde $m_b$, s y a son constantes del macizo rocoso.
- El criterio generalizado de Hoek-Brown es no lineal, por lo tanto la conversión a Mohr-Coulomb es dependiente de $\sigma_3$'.


Analysis of Rock Strength using RocLab
Hoek-Brown Classification
intact uniaxial compressive strength = 30 MPa
GSI = 50 mi = 10 Disturbance factor = 0
Hoek-Brown Criterion
mb = 1.677 s = 0.0039 a = 0.506
Mohr-Coulomb Fit
cohesion = 1.494 MPa friction angle = 30.52 deg
Rock Mass Parameters
tensile strength = -0.069 MPa
uniaxial compressive strength = 1.807 MPa
global strength = 5.230 MPa
modulus of deformation = 5477.23 MPa
Shear stress (MPa)
Normal stress (MPa)
0
2
4
6
8
10
12

# Criterio de Roca Intacta

- Para roca intacta, el criterio se expresa por:

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left[m_i \frac{\sigma_3'}{\sigma_{ci}} + 1\right]^{0,5}$$

- Idealmente, los valores de $\sigma_{ci}$ (resistencia a la compresión simple) y $m_i$ se deben obtener por ajuste de una serie de ensayos triaxiales con $0<\sigma_3'< \sigma_{ci}$ .
- Alternativamente, se usa valor de UCS para ensayos de compresión simple o estimaciones de terreno para estimar $\sigma_{ci}$ ; y $m_i$ de tablas según el tipo de roca.

Table 2.1 Mean and standard deviation of $m_i$ for a few selected rock types, based on data from Doruk (1991). From Helgstedt (1997).

| Rock type | Number of test sets | Range of $m_i$-values | Average $m_i$-value | Standard deviation of $m_i$-value | Suggested $m_i$-value (Hoek, Kaiser and Bawden, 1995) |
|---|---|---|---|---|---|
| Dolomite | 8 | 5.2 - 18.2 | 11.4 | 4.3 | 8-10 |
| Granite | 18 | 7.9 - 42.6 | 25.3 | 9.5 | 33 |
| Limestone | 26 | 3.9 - 51.7 | 11.2 | 9.4 | 8-10 |
| Marble | 14 | 4.7 - 16.0 | 8.0 | 3.2 | 9 |
| Mudstone | 7 | 8.6 - 46.6 | 19.2 | 14.5 | 9 |
| Quartzite | 7 | 5.6 - 28.4 | 18.2 | 7.3 | 24 |
| Sandstone | 57 | 4.7 - 35.5 | 16.0 | 8.6 | 19 |

- De acuerdo con Hoek et al. (2002), los valores de las constantes de macizo rocosos se obtienen de:

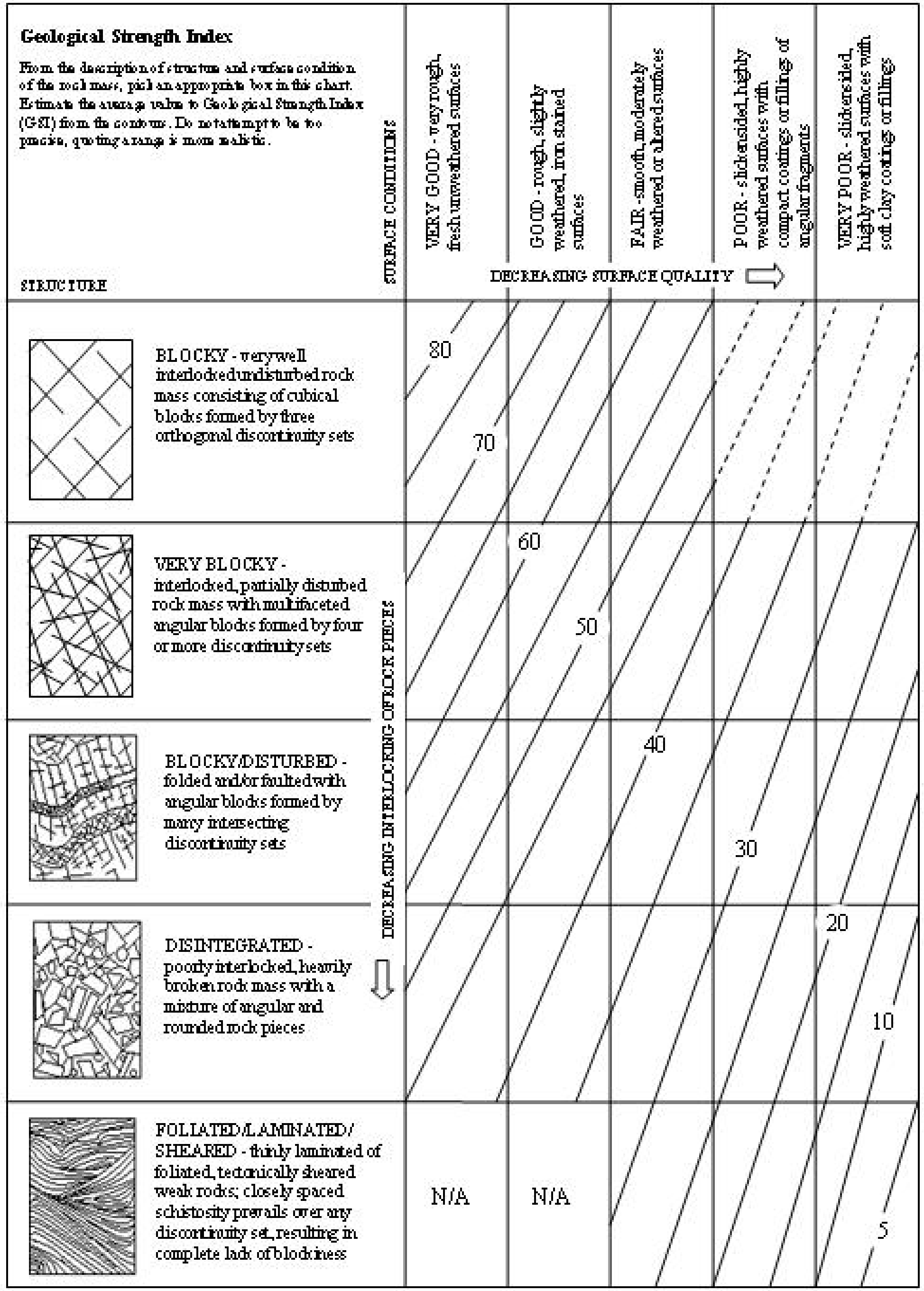
$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right)$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right)$$

- Donde GSI es el Geological Strength Index, obtenido en terreno, y D es un factor de corrección llamada Factor de Perturbación.

# GSI


Geological Strength Index
From the description of structure and surface condition of the rock mass, pick an appropriate box in this chart. Estimate the average value to Geological Strength Index (GSI) from the contours. Do not attempt to be too precise, quoting a range is more realistic.
STRUCTURE
SURFACE CONDITIONS
VERY GOOD - very rough, fresh unweathered surfaces
GOOD - rough, slightly weathered, iron stained surfaces
FAIR - smooth, moderately weathered or altered surfaces
POOR - slickensided, highly weathered surfaces with compact coatings or fillings of angular fragments
VERY POOR - slickensided, highly weathered surfaces with soft clay coatings or fillings
DECREASING SURFACE QUALITY
BLOCKY - very well interlocked undisturbed rock mass consisting of cubical blocks formed by three orthogonal discontinuity sets
VERY BLOCKY - interlocked, partially disturbed rock mass with multifaceted angular blocks formed by four or more discontinuity sets
BLOCKY/DISTURBED - folded and/or faulted with angular blocks formed by many intersecting discontinuity sets
DISINTEGRATED - poorly interlocked, heavily broken rock mass with a mixture of angular and rounded rock pieces
FOLIATED/LAMINATED/SHEARED - thinly laminated of foliated, tectonically sheared weak rocks; closely spaced schistosity prevails over any discontinuity set, resulting in complete lack of blockiness
DECREASING INTERLOCKING OF ROCK PIECES
80
70
60
50
40
30
20
10
5
N/A
N/A

# Factor de perturbación (D)

**Disturbance Factor D**

Application: Tunnels Slopes

Excellent quality controlled blasting or excavation by Tunnel Boring Machine results in minimal disturbance to the confined rock mass surrounding a tunnel.

D=0

Mechanical or hand excavation in poor quality rock masses (no blasting) results in minimal disturbance to the surrounding rock mass.

D=0

Where squeezing problems result in significant floor heave, disturbance can be severe unless a temporary invert, as shown in the photograph, is placed.

D=0.5
No Invert

Very poor quality blasting in a hard rock tunnel results in severe local damage, extending 2 or 3 m, in the surrounding rock mass.

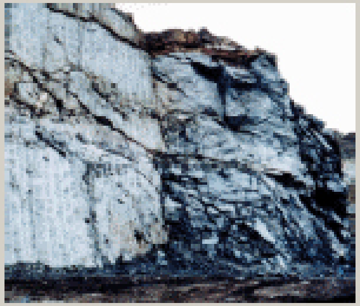
D=0.8

Disturbance Factor: 0

OK Cancel

**Disturbance Factor D**

Application: ○ Tunnels ◉ Slopes



Small scale blasting in civil engineering slopes results in modest rock mass damage, particularly if controlled blasting is used as shown on the left hand side of the photograph. However, stress relief results in some disturbance.

D=0.7 Good Blasting

D=1.0 Poor Blasting

Very large open pit mine slopes suffer significant disturbance due to heavy production blasting and also due to stress relief from overburden removal.

In some softer rocks excavation can be carried out by ripping and dozing and the degree of damage to the slopes is less.

D=1.0 Production Blasting

D=0.7 Mechanical Excavation

Disturbance Factor: 0

OK Cancel

Laderas


D=1


D=0.5


D=0


D=0.3

# Otros parámetros de macizo rocoso (Hoek-Brown 2002)

- Resistencia a la tracción:

$$\sigma_{tm} = -\frac{s\,\sigma_{ci}}{m_b}$$

- Resistencia a la Compresión:

$$\sigma_c = \sigma_{ci} s^{a}$$

# Módulo de Deformación de Macizo Rocoso:

$\sigma_{ci}$<100MPa

$$Erm(GPa) = \left(1 - \frac{D}{2}\right)\sqrt{\frac{\sigma_{ci}}{100}}\,10^{((GSI-10)/40)}$$

$\sigma_{ci}$>100MPa

$$Erm(GPa) = \left(1 - \frac{D}{2}\right)10^{((GSI-10)/40)}$$

Hoek et al., 2002

$$E_{\mathrm{rm}} = E_{\mathrm{i}}\left(0.02 + \frac{1 - D/2}{1 + \mathrm{e}^{((60+15D-\mathrm{GSI})/11)}}\right)$$

Hoek & Diederichs, 2006

# Conversión a Mohr-Coulomb

$$\phi' = \sin^{-1}\left[\frac{6am_b(s+m_b\sigma'_{3n})^{a-1}}{2(1+a)(2+a)+6am_b(s+m_b\sigma'_{3n})^{a-1}}\right]$$

$$c' = \frac{\sigma_{ci}\left[(1+2a)s+(1-a)m_b\sigma'_{3n}\right](s+m_b\sigma'_{3n})^{a-1}}{(1+a)(2+a)\sqrt{1+\left(6am_b(s+m_b\sigma'_{3n})^{a-1}\right)/((1+a)(2+a))}}$$

where $\sigma_{3n} = \sigma'_{3\max}/\sigma_{ci}$

# Resistencia Global de Macizo Rocoso

- Hoek et al. (2002) definieron un nuevo concepto de “resistencia global” del macizo rocoso, que interpreta el comportamiento general del macizo y sirve de comparación. La resistencia global está dada por:

$$\sigma_{cm} = \frac{2c'\cos\phi}{1-\sin\phi}$$

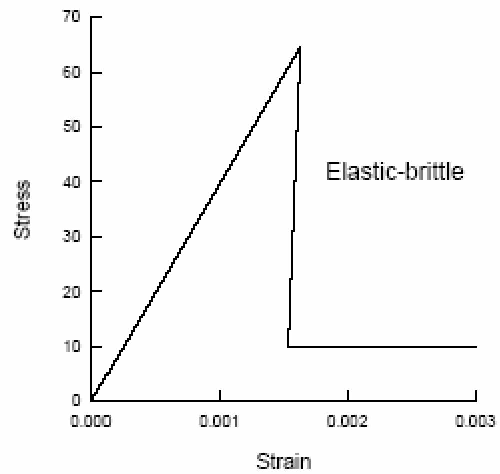
- Para $\sigma_t < \sigma_3' < \sigma_{ci}/4$

# Valores referenciales y comportamiento post-falla sugerido

Macizos Rocosos de Buena calidad

Table 11.7: Typical properties for a very good quality hard rock mass

| | | |
|---|---|---|
| Intact rock strength | $\sigma_{ci}$ | 150 MPa |
| Hoek-Brown constant | $m_i$ | 25 |
| Geological Strength Index | GSI | 75 |
| Friction angle | $\phi'$ | 46° |
| Cohesive strength | $c'$ | 13 MPa |
| Rock mass compressive strength | $\sigma_{cm}$ | 64.8 MPa |
| Rock mass tensile strength | $\sigma_{tm}$ | -0.9 MPa |
| Deformation modulus | $E_m$ | 42000 MPa |
| Poisson's ratio | $\nu$ | 0.2 |
| Dilation angle | $\alpha$ | $\phi'/4 = 11.5°$ |
| *Post-peak characteristics* | | |
| Friction angle | $\phi_f'$ | 38° |
| Cohesive strength | $c_f'$ | 0 |
| Deformation modulus | $E_{fm}$ | 10000 MPa |



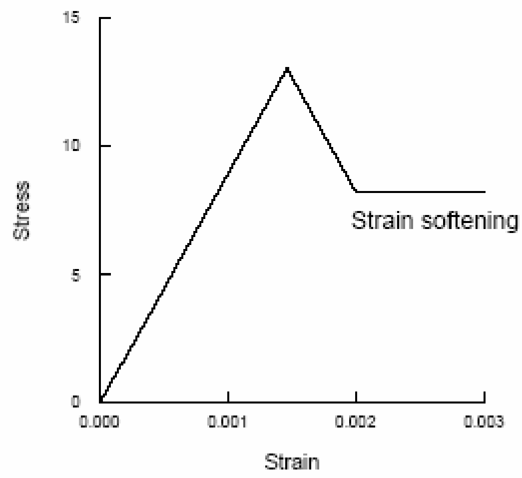

(a) Very good quality hard rock mass

Hoek y Brown, 1997; Hoek, 2000

## Macizos Rocosos de moderada calidad

Table 10.8: Typical properties for an average rock mass.

| | | |
|---|---|---|
| Intact rock strength | $\sigma_{ci}$ | 80 MPa |
| Hoek-Brown constant | $m_i$ | 12 |
| Geological Strength Index | GSI | 50 |
| Friction angle | $\phi'$ | 33° |
| Cohesive strength | $c'$ | 3.5 MPa |
| Rock mass compressive strength | $\sigma_{cm}$ | 13 MPa |
| Rock mass tensile strength | $\sigma_{tm}$ | -0.15 |
| Deformation modulus | $E_m$ | 9000 MPa |
| Poisson's ratio | $\nu$ | 0.25 |
| Dilation angle | $\alpha$ | $\phi'/8 = 4°$ |
| *Post-peak characteristics* | | |
| Broken rock mass strength | $\sigma_{fcm}$ | 8 MPa |
| Deformation modulus | $E_{fm}$ | 5000 MPa |

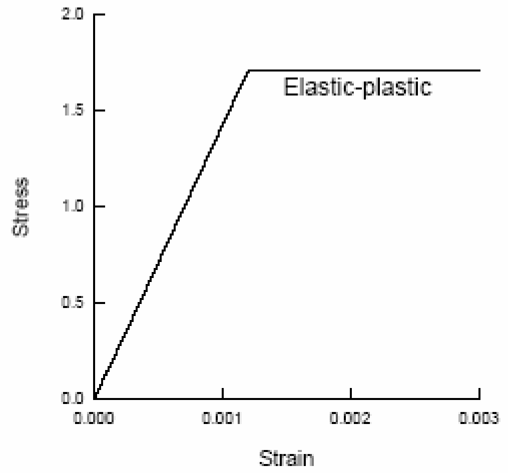



(b) Average quality rock mass

## Macizos Rocosos de baja calidad

Table 11.9: Typical properties for a very poor quality rock mass

| | | |
|---|---|---|
| Intact rock strength | $\sigma_{ci}$ | 20 MPa |
| Hoek-Brown constant | $m_i$ | 8 |
| Geological Strength Index | GSI | 30 |
| Friction angle | $\phi'$ | 24° |
| Cohesive strength | $c'$ | 0.55 MPa |
| Rock mass compressive strength | $\sigma_{cm}$ | 1.7 MPa |
| Rock mass tensile strength | $\sigma_{tm}$ | -0.01 MPa |
| Deformation modulus | $E_m$ | 1400 MPa |
| Poisson's ratio | $\nu$ | 0.3 |
| Dilation angle | $\alpha$ | zero |
| *Post-peak characteristics* | | |
| Broken rock mass strength | $\sigma_{fcm}$ | 1.7 MPa |
| Deformation modulus | $E_{fm}$ | 1400 MPa |




(c) Very poor quality soft rock mass

- Roclab: Software para análisis de Hoek-Brown (www.rocscience.com)