Constitutive Relations – (Rock) Material Behavior Models

(Stress-strain relations)
(Thermodynamic equations of state)

Examples:
- (linear) elasticity
- (elasto) plasticity
- thermoelasticity
- viscoelasticity

Special case: salt behavior (creep)

Failure criteria: rock mass strength

Problems:
- size effects
- discontinuities
- shape effects
- pillars; confinement
- (apparent) time effects
  - strain rate (loading rate)
  - load duration
  - rock alteration (weathering)

Application: underground opening stability
Figure 1.17. Stress-strain curves for (a) linearly and (b) non-linearly elastic substances.

Figure 1.18. Stress-strain, and stress-strain rate curves for (a) perfectly plastic and (b) viscous substances.

Figure 1.19. Stress-strain curves for (a) an elasto-plastic material and (b) an elasto-plastic material with strain hardening.

Figure 1.23. Stress-strain curve showing loading and unloading paths for an elasto-plastic material.

"Creep Laws"

1. Empirical - curve fitting

2. Rheology - flow/solid mechanism modeling

3. Physical (micro-deformation)
Fig. 11.1.1

Fig. 11.1.2 Creep of alabaster in water (after Griggs, 1940). Numbers on the curves are values of the uniaxial compressive stress in bars.

Figure 2.2. Idealized strain-time ('creep') and strain rate-time curves.


Figure 11.1.1

Simple Rheological Models

Hookean spring

Newtonian dashpot

Maxwell: elastico-viscous

Kelvin, Voigt: firmo-viscous

Generalized Kelvin

Burgers

Figure 6.17 Simple linear viscoelastic models and their response to the creep test. (a) Two-constant liquid (Maxwell body). (b) Two-constant solid (Kelvin body). (c) Three-constant liquid (generalized Maxwell body). (d) Three-constant solid. (e) Four-constant liquid (Burgers body).

Figure 6.18 Creep in uniaxial compression of a rock that behaves as a Burgers body under deviotoric stress but an elastic body under hydrostatic compression.

Figure 6.19 Creep of Indiana limestone in unconfined compression [Data from Hardy, Kim, Stefanko, and Wang (1970).]

Fig. 11.1.2 Creep of alabaster in water (after Griggs, 1940). Numbers on the curves are values of the uniaxial compressive stress in bars.


FIGURE 17 Creep of alabaster

From: R.G.K. Morrison, 1976, A Philosophy of Ground Control, Department of Mining and Metallurgical Engineering, McGill University, Montreal.
Fig. 44: Creep curves of triaxially loaded halitic rock salt samples at constant maximum shear stresses


Fig. 45: Creep curves of a halitic rock salt under various triaxial loadings and test temperatures
Figure 1.24. Strain-time relationships for a Kelvin material.

Figure 1.25. Strain-time relationships for a Maxwell material.

Figure 1.26. Uniformly stressed plate with a circular hole.

Figure 1.27. Distribution of stresses around a circular hole in a uniformly stressed plate.

Figure 1.29. Radial displacement of a circular hole in (a) Kelvin and (b) Maxwell materials.

FIGURE 18 The effect of time on the flow of Solnhofen limestone, confining pressure of 10,000 atmospheres.

FIGURE 19 Analyses of time strain shown in Figure 18.

FIGURE 5 Stress-strain characteristics of a coal-measure shale: load applied in increments at 10-minute intervals (After D. W. Phillips).\(^{22}\)

FIGURE 6 Analysis of time-strain shown in Figure 5 at full load (11780 p.s.i.) and upon removal of load, showing time recovery (After D. W. Phillips).\(^{22}\)

From: Morrison, R.G.K., 1976, A Philosophy of Ground Control, Department of Mining and Metallurgical Engineering, McGill University, Montreal.
Fig. 16: Stress-strain curves of older rock salts at various rates of loading.

Fig. 4: Cubical compressive strength as function of the secondary mineral content of a halitic rock salt.

Fig. 17: Fracture curve of a halitic rock salt under uniaxial loading.

Fig. 33: Creep curves of various rock salts under constant axial stress and test temperature.

ANNEX:

Constitutive laws and material parameters for rock salt (literature)

1. Transient creep ("primary creep")

1.1 Empirical laws

\[ \epsilon = K \cdot \sigma \cdot \beta \cdot t^\gamma \]  
potential law (1,2,3,4, 5,6,7),

\[ \epsilon = A_0 \sigma \ln (1 - \alpha t) \]  
logarithmic law (8,9),

\[ \epsilon = B_0 (1 - e^{-bt}) \]  
exponential law (10,11),

\[ \frac{1}{\epsilon} = C_0 \sigma \beta \cdot e^{-\mu} \]  
strain hardening (12,13, 14). 

1.2 Rheological laws  \( (\sigma = \text{const.}) \)

\[ \epsilon = \frac{d}{E} \left(1 - e^{-\frac{E}{t}}\right) \]  
Kelvin-body (15),

\[ \epsilon = \frac{d}{E_0} + \frac{d}{E} \left(1 - e^{-\frac{E}{t}}\right) \]  
Ikamuraby (16),

\[ \epsilon = \sigma \sum \frac{\lambda_i}{E_i} \left(1 - e^{-\frac{E_i}{t}}\right) \]  
extended Kelvin-body (17).

1.3 Structural laws (dislocation-theory)

\[ \epsilon = K \cdot \sigma \cdot \beta \cdot t \cdot e^{-\frac{Q}{RT}} \]  
(18,19),

\[ \epsilon = K \cdot \sigma \cdot \beta \cdot (1 - e^{-bt}) \cdot e^{-\frac{Q}{RT}} \]  
(20).

The numbers in the brackets ( ) refer to the numbers of references in chapter four of this annex.
RHEOLOGICAL BEHAVIOR

2. STATIONARY CREEP ("SECONDARY CREEP")

2.1 Empirical laws

\[ \dot{\varepsilon} = A (\sigma - \sigma_0)^n \]  
\[ \dot{\varepsilon} = k \sigma^n \theta^m \]  
(21, 22)

2.2 Rheological laws (\( \theta = \text{const.} \))

\[ \dot{\varepsilon} = \frac{1}{n} (\sigma - \sigma_f) [\sigma > \sigma_f] \quad \text{Bingham-body} (25, 26) \]

\[ \dot{\varepsilon} = \frac{1}{n} (\sigma - \sigma_f) + \frac{1}{E} \theta [\sigma > \sigma_f] \quad \text{Schwadoff-body} (27) \]

2.3 Structural laws (dislocation-theory)

\[ \dot{\varepsilon} = \dot{\varepsilon}_0 \frac{\sigma}{RT} \quad \text{dislocation climb} (28, 29, 30) \]

\[ \dot{\varepsilon} = \dot{\varepsilon}_0 \frac{\sigma}{RT} \sin \theta \quad \text{dislocation glide} (31, 32) \]

\[ \dot{\varepsilon} = k_1 \sigma^n \frac{\sigma_0}{RT} + k_2 \sigma_0 \frac{\sigma_2}{RT} f(\theta) \quad \text{comb. mechanism} (33, 34) \]
3. TRANSIENT AND STATIONARY CREEP

3.1 Empirical laws \( (\dot{\Phi}, \sigma = \text{const.}) \)

\[
\dot{\varepsilon} = \varepsilon_0 + k \varepsilon + \alpha t^\gamma \tag{35}
\]

\[
\dot{\varepsilon} = \varepsilon_0 + k \varepsilon + \ln (1+\varepsilon) \tag{36}
\]

\[
\dot{\varepsilon} = \varepsilon_0 + k \varepsilon + \ln \left\{ \frac{n(1-n)}{n} e \right\} \tag{37}
\]

3.2 Rheological laws \( (\dot{\Phi} = \text{const.}) \)

\[
\dot{\varepsilon} = \sigma \cdot \left[ \frac{1}{E_0} + \frac{1}{E} (1-e^{-\eta t}) + \frac{1}{\eta_m \tau} \right] \text{ Burgers-body,} \tag{38}
\]

\[
\dot{\varepsilon} = \sigma \cdot \left[ \frac{1}{E_0} + \frac{1}{E} (1-e^{-\eta t}) \right] + (\sigma - \sigma_f) \frac{1}{\eta_m \tau} \text{ Schofield-ScottBlair-body, extended} \tag{39}
\]

\[
\dot{\varepsilon} = \sigma \left[ \frac{1}{E_0} + \frac{1}{E} (1-e^{-\eta t}) \right] + (\sigma - \sigma_f) \frac{1}{\eta_m \tau} \tag{40}
\]

3.3 Structural laws (dislocation-theory)

\[
\dot{\varepsilon} = \frac{1}{kT} \cdot n \left[ 1 - e^{-mt} \right] + A e^{-\gamma n \tau} \tag{20}
\]
However, the precise transition boundaries between creep mechanisms of halite are as yet undefined by experimental observation. Most petrographic data to date are from samples subjected to constant-rate testing, and not from creep tests. Moreover, the transition between mechanisms is gradual and the stress/temperature boundaries are not distinct, but are actually zones of transition.

Despite these problems, certain transition bounds in creep can tentatively be identified. For low-confining pressures of approximately 3.5 MPa or less, and at temperatures below 75°C, plastic deformation is controlled by fracture propagation of existent defects. Failure is characteristically brittle, consisting of a distinct failure plane or zone through the sample (Hansen and Carter, 1980). At higher pressures and temperatures, between 100 and 200°C, the controlling mechanism is
of time (less than a year) can be fitted equally well to both concepts (Her mann and Lauson, 1981). In contrast, the numerical determination of steady state values has shown to be quite consistent, regardless of the transient model employed in the combined transient and steady state expression (Herrmann et al., 1980). This lends some credence to the existence of such a term. It is noted that the impact of this difference in response models becomes only important at long time periods.

<table>
<thead>
<tr>
<th>Equation Format</th>
<th>Initial Concentration</th>
<th>Test Duration</th>
<th>Test Conditions &amp; Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ S = S_0 e^{-kt} ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Mixtures 1.0 g</td>
<td>Trivial Concentration Tests</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Az</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ A = 1.0 \times 10^{-4} ]</td>
<td>Swimmers 1.5 m</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
<tr>
<td>[ p = 1.0 ]</td>
<td>Laboratory Test, Artificial Sea</td>
<td>Assay 10%</td>
<td>Assay 10%</td>
</tr>
</tbody>
</table>

*Note: The table entries are placeholders for actual data.*
MEMORY ASPECTS

where predictions from the two concepts diverge significantly.

The final observation is that none of the present creep laws considers any influence of the previous specimen stress/strain history. However, definite memory aspects of creep have been observed in metals (Krempl, 1974), which would suggest the possible existence of memory in materials such as halite. It is postulated, therefore, that a rigorous description of rock salt response should incorporate the probable role of load-deformation history. All of the models discussed previously are deficient in this respect.

THEORETICAL FORMULATION

Problem Definition

The purpose of the present theoretical discussion is to construct a simple model to evaluate several possible aspects of salt creep. The model will not be a complete constitutive formulation, but rather a response model to simulate the time-dependent behavior of rock salt under constant stress. It is of importance to note that all of the empirical creep equations listed in Table 1 are also response models and that development of a general constitutive model utilizing these models...
Here, the case of the plain strain state is to be investigated. The cavern is assumed to be filled with brine, with a cavern head pressure of \( p_{h} \), \( w = 0 \text{ MPa} \). At a depth of 1000 m this results in a cavern internal pressure of \( p_{1} \approx 12 \text{ MPa} \). At this depth the rock pressure is about \( p_{0} = 22 \text{ MPa} \). The other rock characteristics can be obtained from Figure 25.

The time-dependent stresses, strains and displacements are calculated for the material laws given in the equations (6) to (10). The UTROEPV program developed out of the finite-element-method of the Lehrgebiet für Unterirdisches Bauen, LUB [1979], is drawn on for this. The elastic stress state resulting from the load case "brine-filled cavern" is taken as the initial stress state for the viscous calculations.

**Figure 26** Effective creep strains predicted with different creep laws

Figure 26 shows above all the effective strains in dependence on the time over a period of 1000 days. The effective strains result according to equation (11a) from the individual viscous strain components as

\[
\varepsilon_{\text{eff}} = \sqrt{\frac{1}{3} (\varepsilon_{x}^2 + \varepsilon_{y}^2 + \varepsilon_{z}^2 + \varepsilon_{xy}^2 + \varepsilon_{xz}^2 + \varepsilon_{yz}^2)}.
\]

(11a)

In view of the rational symmetry and the plain strain

\[
\varepsilon_{z} = \gamma_{yz} = 0
\]

(11b)
SUMMARY AND OUTLOOK

This paper is concerned with some aspects of laboratory tests with rock salt and with salt cavern design. First of all, a general review is given of the work to be carried out within the scope of rock mechanical investigations, for the design and preparations of cavern plants in rock salt and possible design criteria for the assessment of theoretical results. The presentation and discussion then follows of results from own laboratory tests on the strength and deformation behaviour of rock salt material from various locations. Finally, basing on the results of uniaxial creep tests, some problems are discussed which are connected with the formulation of viscous material laws and the data obtained with them which affect creep behaviour. In particular, a comparative investigation into the extrapolation of laboratory timings is carried out, which lie in the range of weeks and a few months, with reference to relevant periods of years for cavern plants.
Salt behavior

Figure 1. Preliminary deformation-mechanism map with an overlay of the envelopes of experimental investigations, after Hanson [3]. Grain size is 1 mm. Experimental ranges are from Poiteau [8], Burke, et al., (RCS) [9], Beard (H) [10], Hansen and Hellegard (BH) [11], Le Coate (L) [12], and Naueraik and Hannum (WH) [13].

As this regime begins has been derived from atomic binding considerations. For the onset of defectless flow in salt, the dimensionless deviatoric stress, $\sigma/\mu$, is equal to 0.086 at absolute zero temperature ($T/T_\text{m} = 0$). Clearly, this stress regime is of little engineering importance, since stresses of such a magnitude will never be reached in practical applications.

Dislocation Glide—Regime 2

Salt, which crystallizes in the cubic system, has several slip systems that permit it to deform readily by dislocation motion.
THERMOMECHANICAL PROBLEMS

Fig. 4: Continued

Borehole convergence, comparison with measured values
Salt "Creep" (Behavior) Issues

In Situ vs. Lab
- loading sequence (stress path)
- scale
- salt composition

In Situ variability - representativeness

Geometry: hole closure prediction
(constitutive model problems?)
(parameter problems?)
(boundary condition problems?)

Inhomogeneity modeling

Constitutive modeling
- formulations
- experimental evaluation

Deformation - Mechanism Maps

Field test interpretation
constitutive law parameters?
empirical prediction parameters?

How much understanding is required to assess repository performance?
Rock Strength

- Definition of failure
- Effective stress
  applicable in low permeability rocks?
- Pore fluid influence
- Influence of intermediate principal stress
- Influence of loading rate
- Influence of specimen size
- Anisotropic rock strength
- Rock with multiple discontinuities
- Strength of "granulated" marble
Pillar Strength

\[ S = S_1 v^a (w_p/h)^b = S_2 h^\alpha w_p^\beta \]

\( S \): pillar strength  
\( S_1, S_2 \): rock strength  
\( v, w_p, h \): pillar volume, width, height  
\( a, b, \alpha, \beta \): empirical parameters

Example: \[ S = S_1 v^{-0.118} (w_p/h)^{0.833} \]

\[ S_p = S_e (v_p/v_s)^{-0.118} [(w_p/h_p)/(w_s/h_s)]^{0.833} \]

(Hardy and Agapito, 1977, quoted by Brady and Brown)


Holland-Gaddy: \[ S_p = (S_e \sqrt{D} \sqrt{L})/T \] (coal pillars)

\( S_p, S_e \): pillar, sample strength  
\( D, L \): (cubic) sample, (shortest) pillar length  
\( T \): pillar (seam) thickness


Fairhurst: \[ S = k w^\alpha H^\beta \]

\( \alpha: 0.4-0.5 \quad \beta: -1 \text{ to } 0 \)

Figure 3.21 Effect of specimen size on unconfined compressive strength. [After Bieniawski and Van Heerden (1975).]

Figure 5.14. Effect of size on compressive strength of coal (after Singh, 1981).

Figure 5.15. Variation of rock strength with specimen size.

Figure 9.5. Compressive strength as a function of cube size for Pittsburgh coal (after Hustrulid, 1975).

Figure 9a. Effect of specimen width-to-height ratio on the strength of sandstone.

Figure 9.8. The effect of specimen width-to-height ratio on strength of coal (after Wang et al., 1977, and Bieniawski and van Heerden, 1975).

Figure 9.9. Pittsburgh seam: Strength ratio vs. w/h ratio of pillars.

Figure 9.10. Pittsburgh seam: Strength vs. pillar width to height ratio.

Figure 9.13. Design chart for Pittsburgh seam showing pillar strength versus pillar width for different pillar heights and different depths (roof span 5.5 m, factor of safety $f = 1.5$).

Figure 9.14. Design chart for room and pillar coal mining in the Pittsburgh seam showing depth below surface vs $w/k$ ratio for different percentage of coal extraction and factor of safety $f = 1.5$.

Rock Mass Strength


Rock failure criterion for underground opening design:

- cover full range of stress conditions
- account for discontinuities
- allow for projection to full-scale rock mass

Proposed empirical criterion:

\[
\sigma_1 = \sigma_3 + \sqrt{m\sigma_c \sigma_3 + \sigma_c^2}
\]

\(\sigma_1, \sigma_3\): major and minor principal stresses at failure

\(\sigma_c\): uniaxial compressive strength

\(m, s\): semi-empirical constants

Mohr envelope:

\[
\sigma = \sigma_3 + \frac{\tau_m^2}{\tau_m + m\sigma_c / 8}
\]

\[
\tau = (\sigma - \sigma_3) \sqrt{1 + \frac{m\sigma_c}{4\tau_m}}
\]

where \(\tau_m = (\sigma_1 - \sigma_3)/2\)
Table S. Approximate relationship between rock mass quality and constants (after Hock and Brown, 1980)

<table>
<thead>
<tr>
<th>Empirical failure criterion</th>
<th>Carbonate rocks with well developed crystal cleavage</th>
<th>Dolomite, limestones and marbles</th>
<th>Limestones, siliceous rocks, slate and slates (normal to cleavage)</th>
<th>Arenaceous rocks with strong crystal cleavage</th>
<th>Sandstones and quartzite</th>
<th>Fine grained polymictic igneous crystalline rocks</th>
<th>Acidic, dolerite, diabase and gabbro</th>
<th>Coarse grained polymictic igneous and metamorphic crystalline rocks</th>
<th>Amphibolite, gabbro, gneiss, granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_f = \sigma_1 + \sqrt{m\sigma_2^2 + s}$</td>
<td>$m$ = 7.0</td>
<td>$m$ = 10.0</td>
<td>$m$ = 15.0</td>
<td>$m$ = 17.0</td>
<td>$m$ = 25.0</td>
<td>$m$ = 3.5</td>
<td>$m$ = 5.0</td>
<td>$m$ = 7.5</td>
<td>$m$ = 8.5</td>
</tr>
<tr>
<td>$\sigma_3 = \text{major principal stress;}$</td>
<td>$s$ = 1.0</td>
<td>$s$ = 1.0</td>
<td>$s$ = 1.0</td>
<td>$s$ = 1.0</td>
<td>$s$ = 1.0</td>
<td>$s$ = 0.1</td>
<td>$s$ = 0.1</td>
<td>$s$ = 0.1</td>
<td>$s$ = 0.1</td>
</tr>
<tr>
<td>$\sigma_2 = \text{minor principal stress;}$</td>
<td>$\sigma_6 = \text{uniaxial compressive strength of intact rock;}$</td>
<td>$\sigma_7 = \text{empirical constants}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_1 = \text{empirical constants}$</td>
<td>$\sigma_2 = \text{empirical constants}$</td>
<td>$\sigma_3 = \text{empirical constants}$</td>
<td>$\sigma_4 = \text{empirical constants}$</td>
<td>$\sigma_5 = \text{empirical constants}$</td>
<td>$\sigma_6 = \text{empirical constants}$</td>
<td>$\sigma_7 = \text{empirical constants}$</td>
<td>$\sigma_8 = \text{empirical constants}$</td>
<td>$\sigma_9 = \text{empirical constants}$</td>
<td>$\sigma_{10} = \text{empirical constants}$</td>
</tr>
</tbody>
</table>

Intact rock samples

<table>
<thead>
<tr>
<th>Laboratory size specimens free from joints</th>
<th>$m$ = 7.0</th>
<th>$m$ = 10.0</th>
<th>$m$ = 15.0</th>
<th>$m$ = 17.0</th>
<th>$m$ = 25.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR = 100</td>
<td>Q rating 100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Very good quality rock mass

<table>
<thead>
<tr>
<th>Tightly interlocking undisturbed rock with unweathered joints at 1 to 3 m</th>
<th>$m$ = 3.5</th>
<th>$m$ = 5.0</th>
<th>$m$ = 7.5</th>
<th>$m$ = 8.5</th>
<th>$m$ = 12.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR = 85</td>
<td>Q rating 100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Good quality rock mass

<table>
<thead>
<tr>
<th>Fresh to slightly weathered rock, slightly disturbed with joints at 1 to 3 m</th>
<th>$m$ = 0.7</th>
<th>$m$ = 1.0</th>
<th>$m$ = 1.5</th>
<th>$m$ = 1.7</th>
<th>$m$ = 2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR = 65</td>
<td>Q rating 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fair quality rock mass

<table>
<thead>
<tr>
<th>Several sets of moderately weathered joints spaced at 0.3 to 1 m</th>
<th>$m$ = 0.14</th>
<th>$m$ = 0.20</th>
<th>$m$ = 0.30</th>
<th>$m$ = 0.34</th>
<th>$m$ = 0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR = 44</td>
<td>Q rating 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Poor quality rock mass

<table>
<thead>
<tr>
<th>Numerous weathered joints at 30 to 500 mm with some gouge; Clean compacted waste rock</th>
<th>$m$ = 0.04</th>
<th>$m$ = 0.05</th>
<th>$m$ = 0.08</th>
<th>$m$ = 0.09</th>
<th>$m$ = 0.13</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR = 35</td>
<td>Q rating 0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Very poor quality rock mass

<table>
<thead>
<tr>
<th>Numerous heavily weathered joints spaced &lt; 50 mm with gouge. Waste rock with fines</th>
<th>$m$ = 0.007</th>
<th>$m$ = 0.010</th>
<th>$m$ = 0.015</th>
<th>$m$ = 0.017</th>
<th>$m$ = 0.022</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR = 3</td>
<td>Q rating 0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notation: RMR - rock mass rating from the Geomechanics Classification; Q - quality of rock mass from the Q-System.