

Rock mass grouting

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1 Introduction

Rock mass grouting is a process with the aim to improve specific properties of the rock mass, mainly strength, stiffness or watertightness. The process consists of pressing a liquid-like material into the rock mass fractures, which later on solidifies due to chemical reactions (see fig. 1). Several corresponding standards and recommendations exist, for instance EN 12715, DIN 4093 or the ISRM report on rock grouting (ISRM 1996).

Typical applications are:

- Improvement of mechanical and hydraulic properties of dam foundations
- Stabilizing / sealing of slopes or excavation disturbed zones
- Backfilling of spaces between rock mass and construction (e.g. for tunnels or shafts)
- Backfilling of underground openings (e.g. karst caves)
- Stabilizing certain old constructions for sub-sequent reopening
- Preventing spreading of hazardous contaminants
- Micro pile umbrella to stabilize tunnel faces
- Settlement control incl. heave operations

Grouted anchors are not discussed within this chapter (consult e-book chapter 16: 'rock bolting').

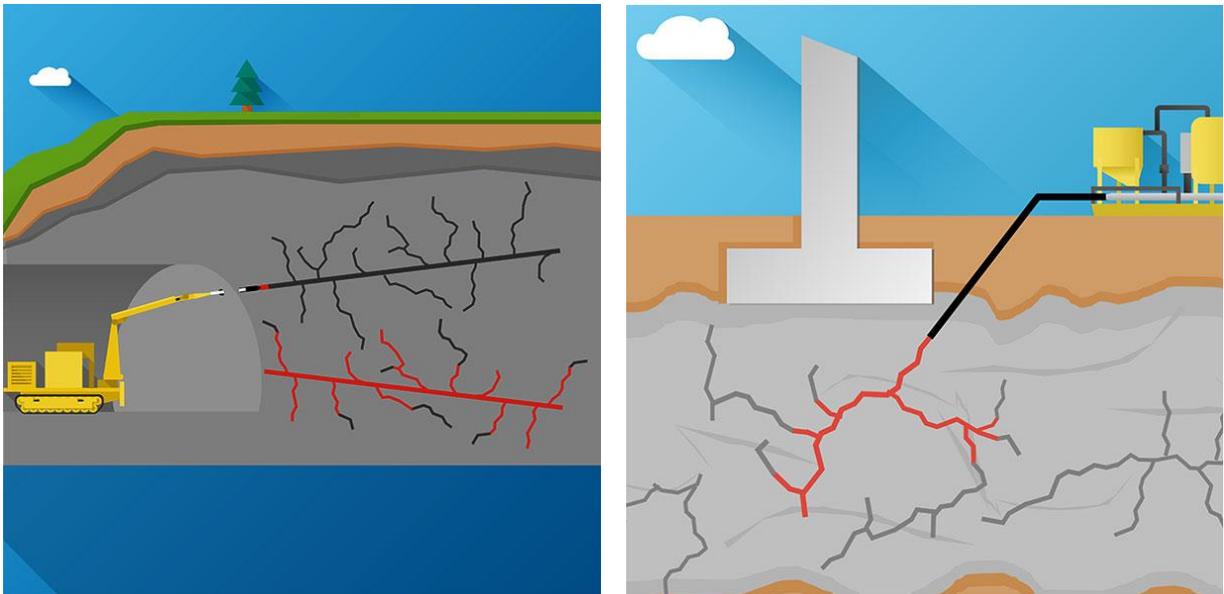


Fig. 1: Principle of rock mass grouting (company material)

2 Grouting materials and properties

The following grouting materials are common:

- Cements with or without additives like ashes, fillers, accelerators, silica fumes etc.
- Resins and Hardener
- Silicates
- Polyurethane
- Periclase

The most common grouting material is cement. According to the chemical composition one has to distinguish between ordinary cement and Portland cement with different grain size distribution. The following properties should be considered:

- Rheological properties during the injection process
- Penetrability into the rock mass
- Curing (hardening) or gelling properties of grout
- Long-term behaviour of grout
- Bleed of grout

Rheology of grout can be described by either the Newtonian (solutions) or the Bingham (granular suspensions) model (fig. 2). The properties can be modified by additives, like accelerators or plastifiers. So-called superplastifiers are often used up to about 2 % of the cement weight to avoid clumping. Water / cement ratio often starts at about 3 to 2 and can be reduced until refusal is observed. Accelerators can be added if curing process has to be speeded-up.

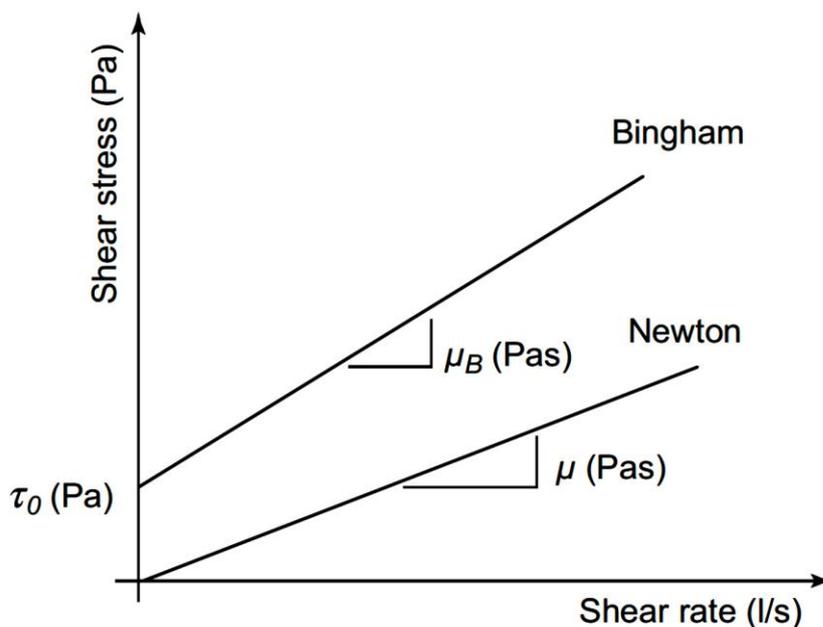


Fig. 2: Basic rheological models for grout

The capability of the grout to penetrate into the fractures depends on:

- the grain size of the grout,
- the used additives,
- the grouting time,
- the fracture aperture,
- the rheological properties of the grout,
- the grouting pressure.

For the choice of grout material the groutability ratio (= width of fissure / D_{95} of grout) can be used. The groutability ratio should be greater or equal to about 5. Typical representatives for Newtonian grouts are silica solutions, epoxy or polyurethane, whereas cement-based grouts follow the Bingham type.

Tab. 1: Comparison between different types of grout

Type of grout	Advantages	Disadvantages
Bingham	Low costs	Limited penetration depth
	Easy to handle	Long setting time
	High stiffness	Low strength
Newtonian	High penetration depth	Low stiffness
	Fast setting time	High costs
	Non washing out	Difficult operation

Tab. 2: Importance of properties for different fracture width (Eriksson 2002)

Grout property	← 0.1 mm	0.1 mm–0.2 mm	0.2 mm →
High yield value	–	–	+
Low viscosity	++	++	+
High penetrability	++	+	–
Low bleed	–	+	++

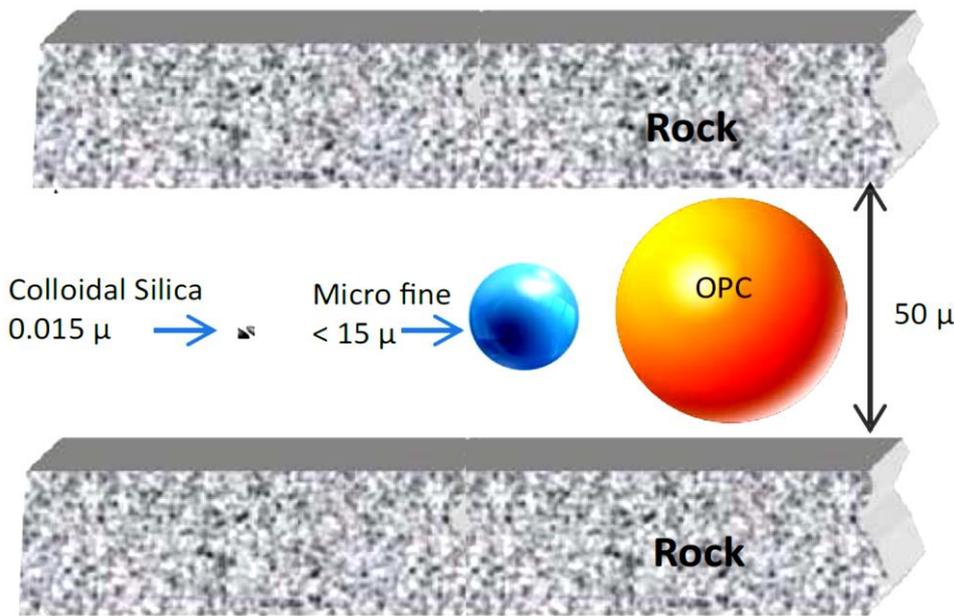


Fig. 3: Illustration of typical grain sizes of different grout materials; OPC = Ordinary Portland Cement (Subash et al. 2016)

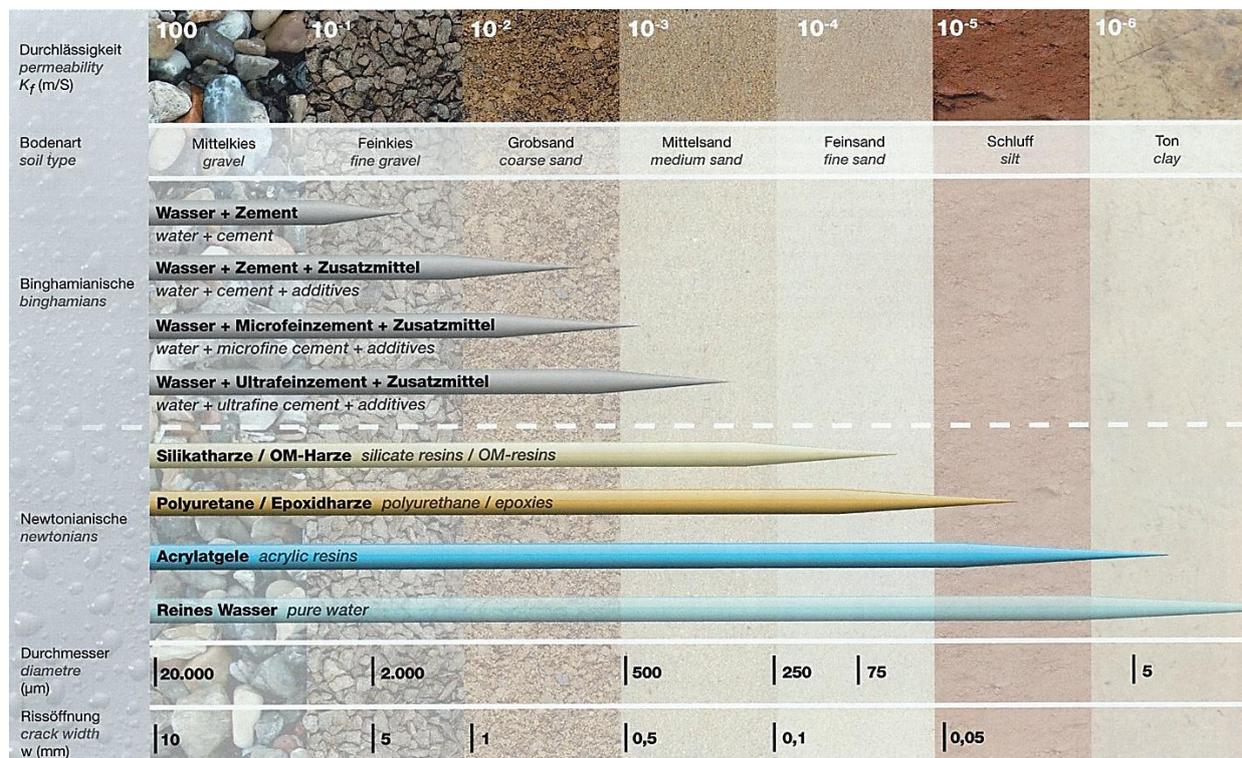


Fig. 4: Grouting materials vs. soil/rock type (THP: company material)

Fig. 4 illustrates the operating distance of different typical grouting materials in different types of soil and soft rock. Decisive are open pore or crack width (see last two lines in Fig. 4). Depending on these parameters and the desired penetration depth the corresponding grouting material has to be chosen.

3 Grouting technique and technologies

Prerequisite for rock grouting is drilling of boreholes. Drilling equipment and technology (especially chosen borehole diameter, borehole depth, borehole direction and distance between boreholes) has to be adjusted, so that the subsequent grouting can be conducted in a proper way.

Grouting itself needs the following technical components (see also Fig. 6 and 7):

- Mixer / Agitator
- Pump
- Hoses
- Packers
- Grout header
- Measurement tools (flowmeter, pressure gauge)

There are different types of packers, e.g. single use packers which stay in the borehole or reusable packers. Depending on applied grout pressure one can distinguish between low pressure (< 6 MPa) and high pressure (> 6 MPa) hoses. Technical grouting parameters are given in tab. 3 and fig. 5.

During the grouting process flow rate and pressure are monitored. There are two different philosophies of grouting:

- 1) Use of relatively low pressure to let the fracture system undisturbed (permeation grouting)
- 2) Use of relatively high pressure to open fractures (frac grouting)

The grouting process can be finished if following criteria are reached (Emmelin et al. 2007):

- Maximum grouting
- Maximum grouting volume
- Grout flowrate lower than critical values

Tab. 3: Important technical parameters for injection process in relation to fracture width (Eriksson 2002)

Technical issues	← 0.1 mm	0.1 mm–0.2 mm	0.2 mm →
High pressure	++	+	–
Low minimum flow	++	+	–
High max volume	–	+	++
Small distance between grouting holes	++	+	–

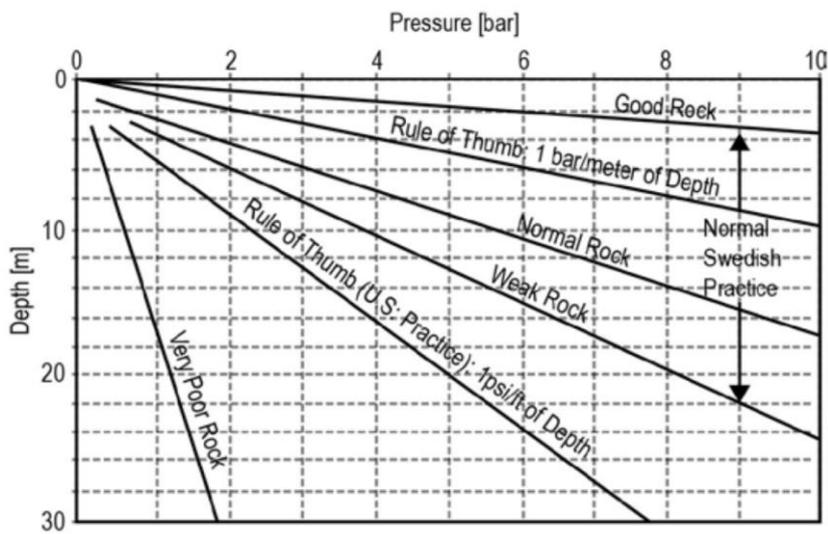


Fig. 5: Typical injection pressures for near-surface grouting (Weaver 1991)



Fig. 6: Grout pumps / rigs (company material)



Fig. 7: Inflatable grout packers (left), grout hose (middle) and grout header (right) (company material)

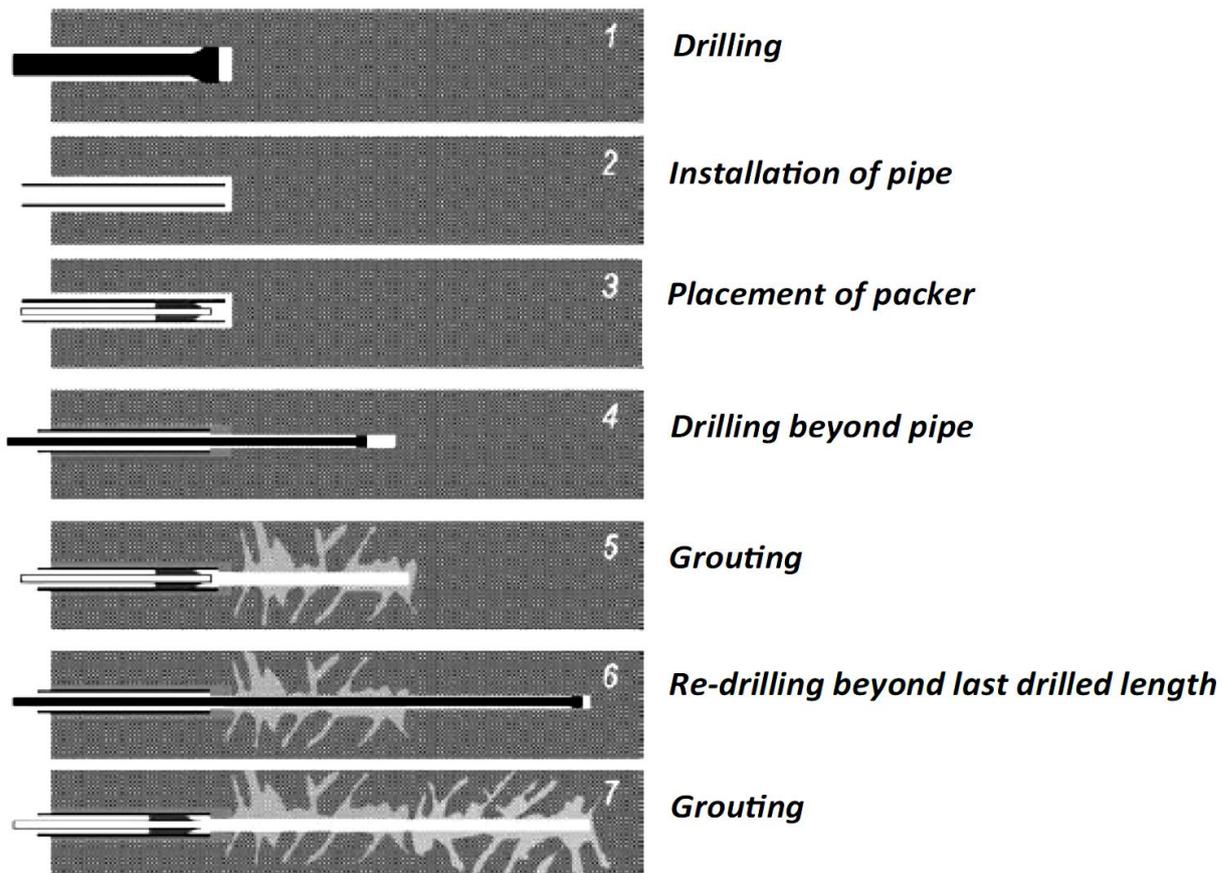


Fig. 8: Pre-grouting technology (Subash et al. 2016)

Nowadays special software tools are available to monitor all grouting parameters in real-time. This allows to adjust grouting parameters like pressure, flowrate, volume, viscosity, mix type etc. during the grouting process. In addition: all these data can be stored for documentation and subsequent analysis.

In terms of the improvement of hydraulic properties the following holds (tab. 4): High values of required sealing efficiency and / or low required hydraulic conductivity makes the grouting process more difficult and expensive.

Tab. 4: Sealing efficiency (Stille 2012, Rafi 2013)

Required Sealing Efficiency	<90%	90-99%	>99%
Required Conductivity			
$>10^{-7}$ m/s	Uncomplicated Grouting	Fair Grouting	Difficult Grouting
10^{-7} to 10^{-8} m/s	Fair Grouting	Difficult Grouting	Very Difficult Grouting
$< 10^{-8}$ m/s	Difficult Grouting	Very Difficult Grouting	Very Difficult Grouting

4 Applications

Fig. 8 illustrates typical applications of rock mass grouting. Grouting can be performed as pre-excitation or post-excitation grouting in tunnelling and underground mining (fig. 9, 10 and 11). In tunnelling the applied borehole diameter is typically between 45 mm and 64 mm (NTS 2011), borehole length up to several 10th of Meters. The boreholes should be straight with deviation smaller 5 %. Spacing between boreholes should be chosen in such a way that an overlapping of grouted area is achieved (grout curtain). Exemplary, fig. 12 documents the results of a successful grouting operation with the aim to improve strength and stiffness of the rock mass.

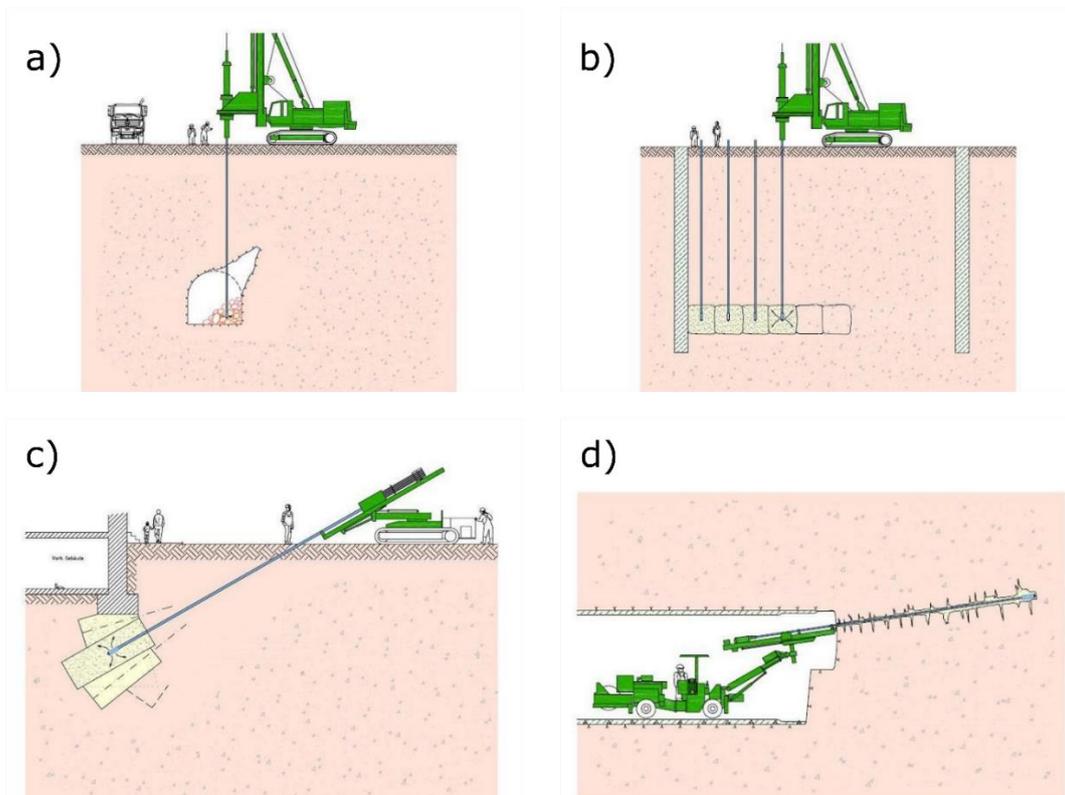


Fig. 9: Typical application of grouting: a) Filling of underground excavation or caves; b) grouting sealing slab; c) foundation improvement or compensation grouting; d) pre-grouting in tunnelling (company material)

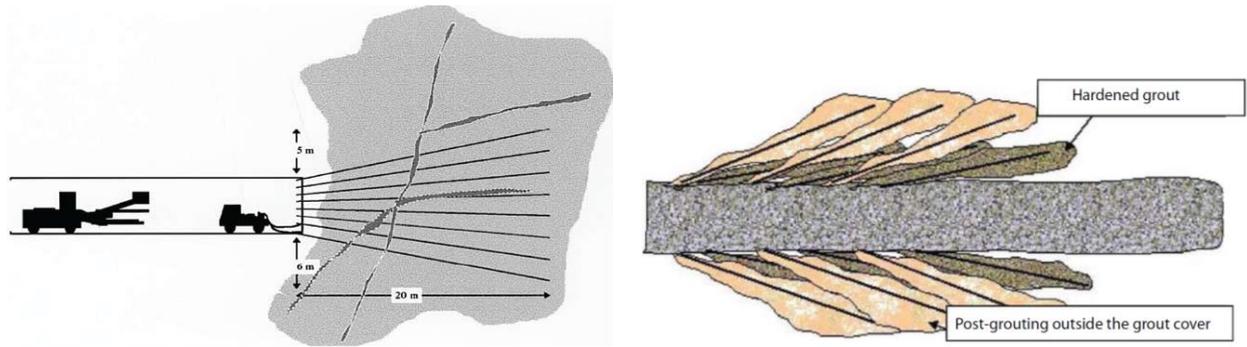


Fig. 10: Principle of pre-excitation grouting (left) and post-excitation grouting (right) (NTS 2011)



Fig 11: Permeation grouting in a tunnel (company material)

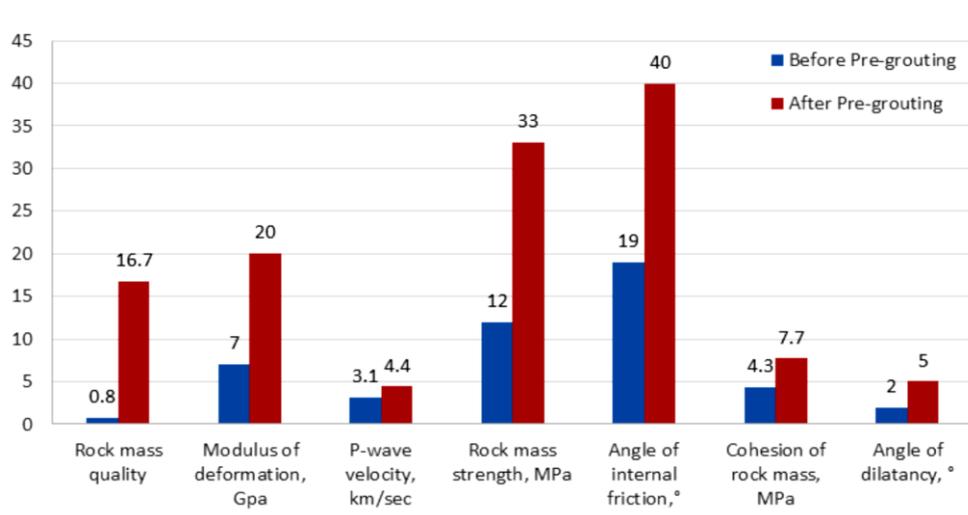


Fig. 12: Example for typical improvement of mechanical rock mass properties due to grouting (Subash et al. 2016)

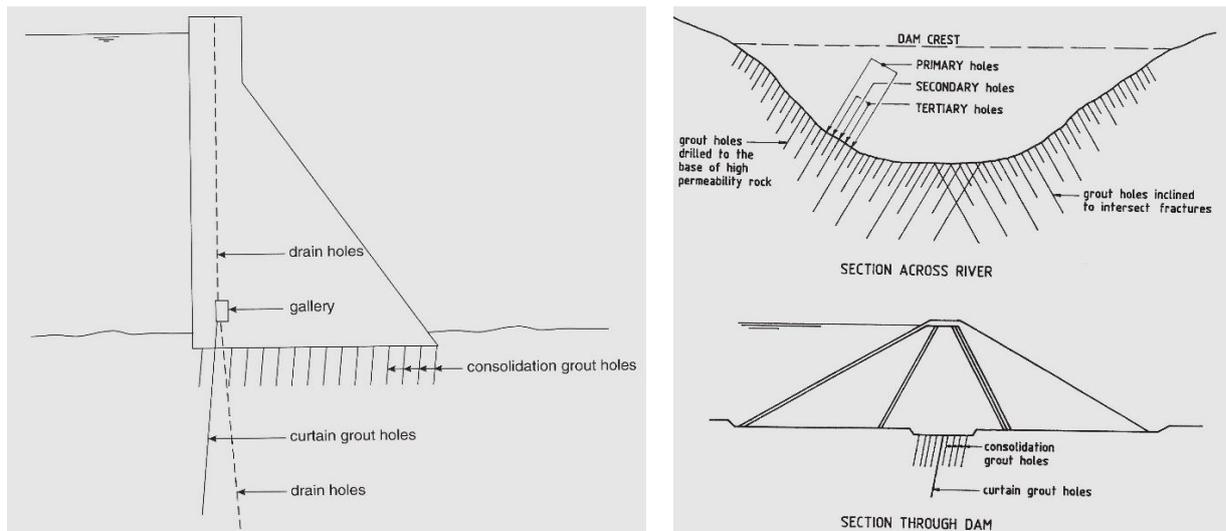


Fig. 13: Illustration of curtain and foundation grouting for a dam construction (Fell et al. 2005)

Dam constructions need always grouting in form of curtain grouting and / or consolidation grouting to achieve the following aims:

- Reduction of settlements / inclinations of dam construction
- Reduction of uplift pressure
- Reduction of seepage erosion
- Reduction of leakages in dam foundation and neighbouring rock mass

Often, the grouting curtain has to be re-newed after some time. Remedial grouting, especially if the reservoir cannot be depleted, is a risky and technically complicated job. Spross et al. (2016) give an example how the observational method can be applied for such a task. Da Silva (2019) provides a review of grouting for rehabilitation of concrete dams and CWC (2018) contains a detailed description of rehabilitation measures, especially grouting, for large dams.

5 Grout spread

The grout spread is governed by properties of grout, fracture geometry and the execution of the grouting. Typically, the grouting process can be subdivided into 3 phases (fig. 14):

- Phase of constant flow rate
- Phase of constant pressure
- Phase of constant energy (pressure x injected grout volume = const.)

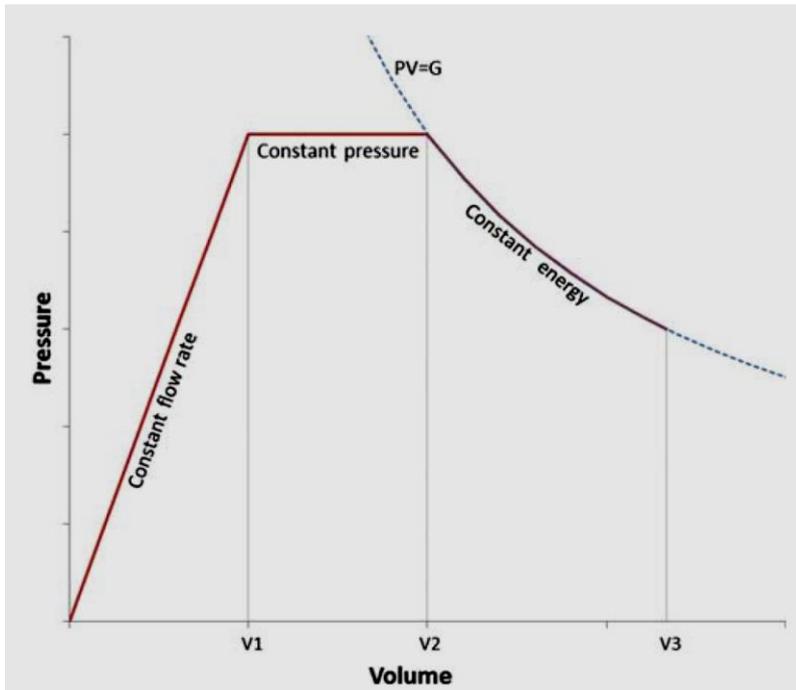


Fig. 14: Sequence of the grout driving process (El Tani & Stille, 2017)

For a plane fracture of height $2H$ and width w the following analytical solutions are obtained (El Tani & Stille, 2017):

- For Newtonian fluids and constant flow rate Q_0 :

$$L = \frac{Q_0}{2HW} (t - t_0) + L_0$$

$$P = \left(\frac{3\eta Q_0^2}{4w^2 H^4} (t - t_0) + \frac{P_0}{f_0} \right) f$$

- For Newtonian fluids and constant pressure P_0

$$L = \sqrt{\frac{2H^2 P_0}{3\eta} (T - T_0) - L_0}$$

$$Q = \frac{2wH^3 P_0}{3\eta f} \frac{1}{\sqrt{L_0^2 + \frac{2P_0 H^2}{3\eta} (T - T_0)}}$$

- For Newtonian fluids and constant driving energy G

$$L = \sqrt[3]{\frac{GH}{2\eta w} (T - T_0) + L_0^3}$$

$$Q = \frac{GH^2}{3\eta f} \frac{1}{\left(L_0^3 + \frac{GH}{2\eta w}(T - T_0)\right)^{2/3}}$$

$$P = \frac{G}{2Hw} \frac{1}{\sqrt{L_0^3 + \frac{GH}{2\eta w}(T - T_0)}}$$

where:

L, L_0 spread of grout / initial spread of grout

P, P_0 injection pressure, initial injection pressure

Q, Q_0 flow rate, initial flow rate

T, T_0 maturity time, initial maturity time

G driving energy

η initial dynamic grout viscosity

f ratio of actual grout viscosity to initial grout viscosity

For Bingham type grout (cements) corresponding analytical solutions are not available and numerical solutions should be applied. Nevertheless, the maximum spread can be assessed by the following formula, where τ_0 represents the shear stress yield value of the grout:

$$L_{\max} = \frac{HP}{\tau_0}$$

An often used partial procedure to assess groutability is the “Lugeon”-based procedure. “Lugeon L ” is defined as follows: 1 L = 1 liter of water per minute injected into 1 m of borehole at an injection pressure of 1 MPa. “Lugeon” can be considered as a special measure of hydraulic conductivity K [m/s], which is dependent on intrinsic permeability k [m/s], specific weight of water γ [N/m³] and dynamic viscosity of water μ [Pa s]:

$$K = \frac{k \cdot \gamma}{\mu}$$

In practice, the Lugeon value (1 Lugeon = 1.3×10^{-7} m/s) for a particular portion of the foundation is found by isolating a known length of borehole by packers, measuring the rate of water injection under a selected pressure, and then calculating the Lugeon value based on those parameters. Normally, the grout has properties different from water.

For the grout an equivalent hydraulic conductivity can be estimated by using the following relation:

$$\gamma_{\text{grout}} \cdot \mu_{\text{water}} = \gamma_{\text{water}} \cdot \mu_{\text{grout}}$$

In engineering practice adopted from the field of petroleum engineering, the so-called Marsh Funnel Viscosities are used (USACE, 2017):

$$L_{\text{apparent}} = L_{\text{water}} \cdot \frac{\mu_{\text{Marsh grout}}}{\mu_{\text{Marsh water}}}$$

The value of L_{apparent} provides information about the penetration of the grout into the fractures in the immediate vicinity of the borehole. A value of L_{apparent}/L smaller than 1 indicates, that the grout penetration is less than penetration with water. A ratio of L_{apparent}/L close to one should be achieved, which can be reached by either increasing the pressure or changing the grout material (properties). However, potential pressure increase should be restricted to avoid undesirable fracturing or other destabilisation effects. According to the Lugeon value the rock mass can be classified as follows(USACE, 2017):

- $L > 100$: Readily groutable (well connected fracture network, large fractures, high frequency of fractures)
- $L \approx 10$: Marginally groutable
- $L \approx 1$: Barely groutable
- $L \approx 0.1$: Lower bound of groutability (extensive effort is needed)

Exemplary, Fig. 15 shows the results of Lugeon-tests before and after grouting in comparison to the target value.

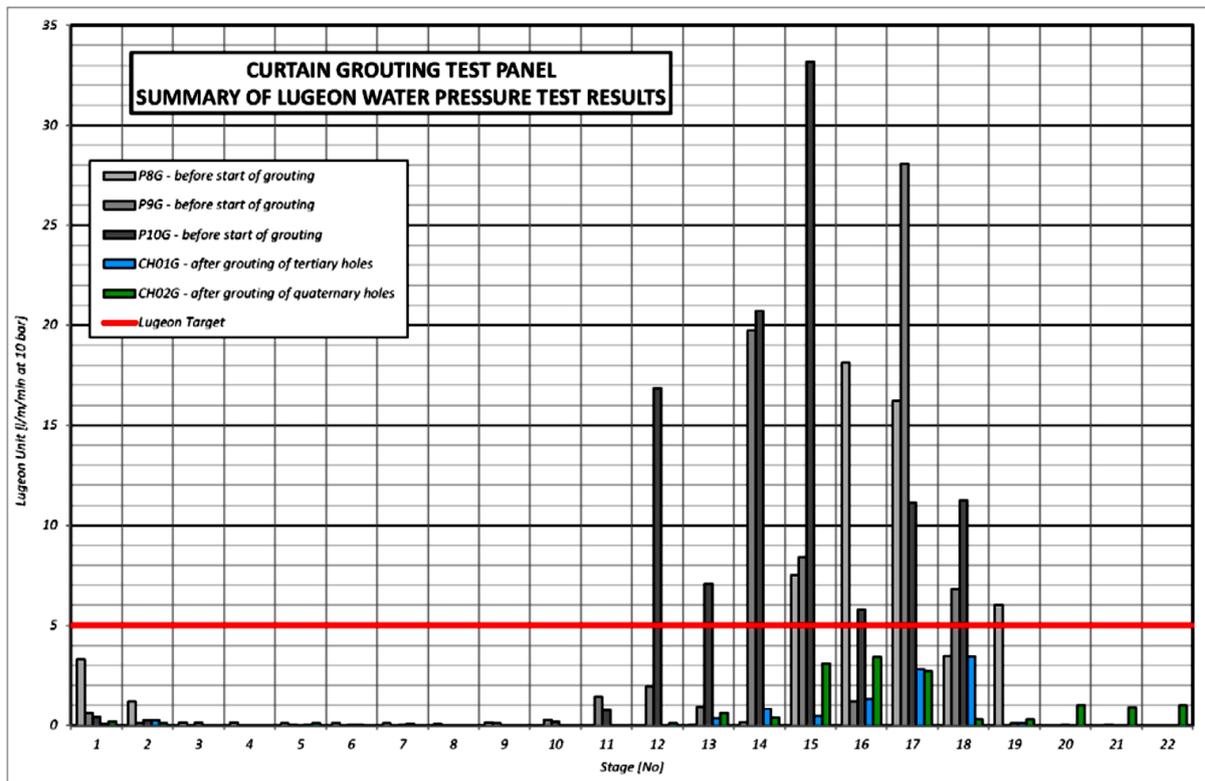


Fig. 15: Example: Results of Lugeon-tests before (gray) and after (blue and green) grouting (El Tani & Stille, 2017)

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