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Expert Comments to EN 12715

Grouting

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Inhalt

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0. PREFACE

Grouting in mining and Civil Engineering-construction as a means to fight percolation of gas or water and deformations of ground has been practiced for more than 200 years. But only since the 1930s has grouting become an engineering discipline of its own; studied, researched and publicized as such. Early applications were recorded as grouting procedures at locks in Holland, coal mines in the Ruhr area and grout curtains underneath dams, all of which provided invaluable knowledge and findings. Kutzner (1991) among others, provided German literature, together with Ewert and Lombardi, while Bruce and Weaver explored the subject matter in the US. Two European standards have since been published; EN 12715 “Grouting” (2001) and the ISRM “Report on Grouting” (1996). This document, however, aims to provide expert comments and complementary explanations to the former.

Injections are – from design stage to verification – an interactive and iterative process, requiring cooperation from experts across a variety of disciplines. Both experience as well as expertise are absolutely essential.

Figure 1. Grouting work in pioneering days: Exploratory drilling at Kaprun HPP, CRAELIUS CX 42 drill, INSOND (1950)

1. SCOPE

This document will primarily discuss grouting using particulate suspensions (including hydraulic binders in water) applied in soil and rock.

Precompression grouting (in high-pressure galleries), roof gap injections, structural grouting, displacement grouting and compensation grouting will, however, not be discussed.

In order to keep this document short, all relevant standards and documents are, whenever appropriate, being referenced instead of quoted in full. Partial reading of chapters, or reading out of order, is not recommended.

Chapter titles and numbers correspond to those of EN 12715 (2001). Chapters 0 and 12 have been added for this document, with chapters 13 to 17 containing appendices and indexes.

The aim of all geotechnical injections (grouting procedures) is the improvement of ground characteristics with respect to permeability and/or mechanical parameters of the soil or rock, in order to satisfy construction requirements.

Injections take full effect by the permeation of voids in the ground (e.g. joints, fissures, pores) by liquids (e.g. solutions, suspensions), where the latter set and harden. This increases stiffness and strength of the ground (soil or rock), permeability will be reduced and rigidity increased.

Soil in general is considered suitable for permeation grouting using particulate grouts of hydraulic binders, if

- the content of fines (particle size < 0.063 mm) does not exceed 5-7%,
- the ratio D_{15} ground/d_{85} grain size of the grout equals ~ 20-24,
- target permeability is > $5*10^{-7}$ m/s, and
- the targeted modulus of deformation is not to exceed 250 MPa.

Empirically, effective acceptance rates for particulate grouts of hydraulic binders are between 15% and 20% of total ground volume.

Grouting in rock is generally possible for geometric joint apertures of > 50 µm. The intrusion of small amounts of pressurized liquid into joints can already cause deformation processes (widening, especially in the case of joint sets in rock) helping to overcome hydraulic resistances and filtration processes. These, usually small-scale elastic and/or plastic, dilations make it possible that even apertures of 2_{ai} < 50 µm become injectable. In such cases suspensions at ratios of 2_{ai} / d_{85} grain size in the suspension ≤ 3 (see also figure 12) may become applicable. Even with these dilation effects, the usual joint volume injectable (and thus also the grout volume) remains less than 3% - without considering the volume of the open borehole – of total rock volume. Fault zones and karst should be considered a special case of their own.

Grouting targets of hydraulic conductivities of $5*10^{-8}$ m/s are only achievable under specific conditions. Improvements of the stiffness in fault zones by grouting are to be expected to remain under a factor of 3.

The use of thermoplastic grouts under high hydraulic groundwater gradients has already been proven successful. By using special epoxy resins it has been possible to grout discontinuities in concrete and rock for the purpose of transmitting tensile forces.

Any decision to proceed with an injection is always subject to technical and economic considerations, and should also always be compared to alternative methods of soil improvement.

2. NORMATIVE REFERENCES

ÖNORM EN 197-1: 2014-07-15 - Zement - Teil 1: Zusammensetzung, Anforderungen und Konformitätskriterien von Normalzement.

ÖNORM EN 934 - Zusatzmittel für Beton, Mörtel und Einpressmörtel.

ÖNORM EN 1008:2002-10-01 - Zugabewasser von Beton - Festlegungen für die Probenahme, Prüfung und Beurteilung der Eignung von Wasser, einschließlich bei der Betonherstellung anfallendem Wasser, als Zugabewasser für Beton.

ÖNORM EN 1997-2:2010-08-15 - Eurocode 7 - Entwurf, Berechnung und Bemessung in der Geotechnik - Teil 2: Erkundung und Untersuchung des Baugrunds.

ÖNORM B 2203-1:2001-12-01 - Untertagebauarbeiten - Werkvertragsnorm - Teil 1: Zyklischer Vortrieb.

ÖNORM B 4400-1:2010-03-15 - Geotechnik - Teil 1: Benennung, Beschreibung und Klassifizierung von Böden - Regeln zur Umsetzung der ÖNORMEN EN ISO 14688-1 und -2 sowie grundlegende Symbole und Einheiten.

ÖNORM B 4400-2:2010-03-15 - Geotechnik - Teil 2: Benennungen und Definitionen, Beschreibung und Klassifizierung von Fels - Regeln zur Umsetzung der ÖNORM EN ISO 14689-1.

ÖNORM B 4415:2009-07-31 - Geotechnik - Untersuchung von Bodenproben - Bestimmung der einaxialen Druckfestigkeit unter Einbeziehung der VORNORM ÖNORM CEN ISO/TS 17892-7.

ÖNORM EN 12715:2001-02-01 - Ausführung von besonderen geotechnischen Arbeiten (Spezialtiefbau) Injektionen.

ÖNORM EN ISO 14688-1:2013-11-15 - Geotechnische Erkundung und Untersuchung - Benennung, Beschreibung und Klassifizierung von Boden - Teil 1: Benennung und Beschreibung.

ÖNORM EN ISO 14688-2:2013-11-15 - Geotechnische Erkundung und Untersuchung - Benennung, Beschreibung und Klassifizierung von Boden - Teil 2: Grundlagen für Bodenklassifizierungen.

ÖNORM EN ISO 14689-1: 2004 05 01- Geotechnische Erkundung und Untersuchung - Benennung, Beschreibung und Klassifizierung von Fels - Teil 1: Benennung und Beschreibung (ISO 14689-1:2003).

ÖNORM EN 197-1: 2014-07-15 - Zement - Teil 1: Zusammensetzung, Anforderungen und Konformitätskriterien von Normalzement.

ÖNORM EN 934 - Zusatzmittel für Beton, Mörtel und Einpressmörtel.

3. DEFINITIONS AND SYMBOLS

In order to explain specific phenomena or dynamics certain terms, phrases or examples may be used which do not necessarily concur with their common usage. It is important to consider this when consulting the figures, tables and formulas used in this document.

The following definitions shall be considered in addition to those mentioned in EN 12715.

Adhesion testing (Feder)
This adhesion test aims to measure the yield stress value for a given suspension. 100-grit sanding paper is submerged into the suspension. The weight of the suspension sticking to the paper determines the yield stress.

Agglomeration
Agglomeration of particles (flocculation) can be, among others, a result of electrostatic charges between particles and liquids. The addition of polymers or thoroughly homogenizing the suspension (e.g. use of high shear force mixers) are possible solutions to the problem.

Amenability theory
The apparent-Lugeon method is known in the US as amenability theory. It describes the accessibility of a given joint (or fracture) for a given suspension. Using the apparent-Lugeon method leads to using a suspension suitable for 75% of given joints.

Borehole mouth (Mouth of the borehole, borehole collar)
Top of the borehole.

Cement grouting
On the following pages the term cement grouting will be used synonymously for all varieties of grout containing binders of any kind.

Constrained boundaries
Constrained boundaries describe joint geometries getting narrower with increasing distance from the borehole. Open boundaries describe the opposite case: widening joint geometries with increasing distance from the borehole.

Cubic Law
This law of fluid flow may be derived using just the Navier-Stokes equations by assuming the simplified case of laminar flow in a joint between two smooth, parallel plates. In such a case we arrive at the permeability (k) of a single joint

$$k = \frac{h^2}{12} \quad (1)$$

and the transmissivity (T)

$$T \equiv kA = \frac{wh^3}{12} \quad (2)$$

h:	(hydraulic) joint aperture	[m]
w:	width of parallel flow	[m]
k:	permeability	[m^2]
A:	area	[m^2]
T:	transmissivity	[m^4]

Transmissivity in this case equals the (hydraulic) joint aperture to the third power, thus leading to the term Cubic Law being used (Witherspoon et al., 1980).

D_{15}/d_{85} ratio (N-criterion)

The D_{15}/d_{85} ratio (N-criterion) helps determine the groutability of soil and is based on empirical experience with various filter criteria.

Determining Yield Point

Determining the yield point can be achieved via several procedures. Table 1 below lists some of the procedures used, as well as some of their advantages and disadvantages.

Annotations for table 1:

x:	yes or small
xx:	medium
xxx:	large
xxxx:	very large

Table 1. Determining yield points using different procedures (unpublished Kainrath, 2016)

	procedure				suitable for		measurement	
Method	**basic**	**special knowledge**	**effort**	**equipment**	**absolute measurements**	**relative measurements**	**measurement uncertainty**	**robustness**
ball harp	x		x	ball harp		x	xxx	xxx
flow curve (Bingham)		x	xxx	viscosimeter, cup & cylinder	x		x	x
vane	x		xx	viscosimeter, vane	x		x	x
Kasumeter	x		xx	Kasumeter		x	xxx	xx
plate cohesion tests	x		xx	after Lombardi		x	xxx	xx
adhesion test on sandpaper	x		x	100-grit sandpaper		x	-	xxxx

Discontinuity

Usually a distinct and discrete planar interruption of continuity in rock mass. Causes are related to the formation history of the rock mass and can be sedimentary, tectonic or mechanical (e.g. shrinkage) in nature.

The terms discontinuity, joint, or fracture are often used interchangeably. The latter usually describes a void surrounded by joint planes.

Dispersion test

Drops of grout (suspension) are squeezed between two glass plates (similar to hematological tests) and viewed under a microscope or scaled magnifying glass of at least 8 x magnification (linen tester with 0.1 mm scaling) against light. Mineral distribution and possible agglomeration of solids in the mix can be detected. This test serves as a practical means of investigating the homogeneity of the suspension, as well as effective grain surface wetting.

Effective grouting pressure

Effective grouting pressure describes the average pressure acting inside the void (e.g. joint). The pressure drop curve (see also pressure at rest) can be used to approximate this effective pressure. Local joint- or pore water pressures must be considered when establishing effective differential grouting pressure.

Fillers

Fillers are inert additives mixed into the grout.

Filter press

The filter press serves to measure the loss of free water in a given suspension under pressure, in order to determine the stability of the suspension.

The filter press is standardized by the American Petroleum Institute (API) and is being used in the field of drilling fluids engineering. It consists of a mud (fluid) reservoir with an outlet at the bottom protected by filter paper and grating. The fluid is pressurized at 7 bars (101.5 psi) by means of CO_2-gas from a cartridge mounted on top of the reservoir. The resulting gradient causes (after a predefined time) redundant mixing water to bleed out of the suspension. The amount of filtrate can be used to measure the stability of the mixture under actual injection conditions. This test should be seen as an addition to the standard sedimentation test in standardized cylinders under gravity.

Geometric Aperture

The (mean) geometric aperture (Kohl, 1992) describes the (mean) physical distance between joint walls. The geometric aperture is, therefore, most important for the application of filter criteria.

Annotations for figure 2:

- a_h: hydraulic joint aperture
- a_m: (mean) geometric width

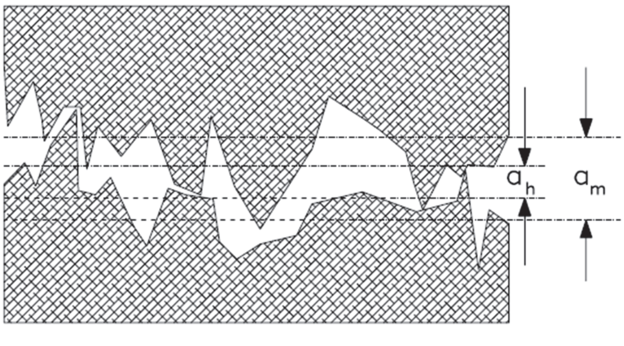


Figure 2. Schematic representation of hydraulic and geometric joint aperture (Kohl, 1992)

GIN

The Grouting Intensity Number (GIN) is a concept to limit the energy of the injection process per meter borehole/stage and is based on the approach suggested by Lombardi (Lombardi et al., 1993). This “grouting intensity” is the product of the volume of grout injected (at a given point of time) and the pressure applied (measured at the pump) per meter of stage, and expressed in [bar∗l/m] (see also chapter 7.3.4.4).

Grouting pressure
The term “grouting pressure” is frequently used to address different kinds of pressure:

- Injection pressure at the pump
- Pressure at the borehole mouth
- Effective grouting pressure
- Pressure at rest

Grouting pressure can - due to hydraulic losses - decrease drastically (up to 80% and more) between injection pump and grouted voids. It is of primary importance to differentiate between these pressures and to make clear which of the above pressures is being described and where it exerts its forces. Grouting pressure is one of the most important parameters for grouting and for judging the progress of an injection. Simply using “grouting pressure“, therefore, without any further differentiation (i.e. measured where and under which conditions) is insufficient information for the evaluation of a grouting procedure.

Hardening test (of suspension films)
A test conducted in addition to sampling for common stiffness trials. This hardening test observes the influence of the reduced reaction heat – in a thin film compared to a larger sample volume – to the (relatively longer) setting time.

Hydraulic binder injection
Injections using hydraulic binders (see also cement injections).

Hydraulic (joint) aperture
The hydraulic (joint) aperture describes the distance - determined by hydraulic trials - between two parallel walls defining the joint itself. The hydraulic (joint) aperture, therefore, defines the cross-sectional flow area for given fluid in accordance with testing parameters and conditions (pressure, gradient, flow rate, viscosity, roughness, etc.). The hydraulic aperture is always significantly smaller than the geometric joint aperture, due to it being defined by narrow passages within the joint itself (figure 2). The hydraulic aperture is also pressure-dependent, inasmuch as it takes into account any deformation of the joint under test pressure.

Hydrofracking (Fracking)
Hydrofracking is the hydraulic fracturing of rock. Resulting fractures are predominantly permanent (plastic deformation).

Hydrojacking (Jacking)
Hydrojacking is a hydraulic widening, dilating, forced opening or spreading of joints or joint systems. Commonly (in the case of rock grouting) it is used to describe fracture dilation under injection pressure. Rock deformation in connection with jacking is predominantly temporary (elastic deformation).

Injection pressure at the pump = working (operating) pressure
During grouting this pressure is being measured directly at the injection pump. (see also Grouting Pressure).

Joint
See discontinuity.

Marsh cone, Marsh cone time
The Marsh cone is a cone (funnel) made out of impact-resistant plastic and a calibrated orifice at the bottom. A mesh at the top of the funnel retains particles potentially clogging the tube at the bottom. Marsh cone time is the time (measured in seconds) 1 liter of sample liquid (cone size: 1.5 liters) needs to flow through the tube.

Marsh viscosity
„Tests are carried out with the Marsh cone. The duration of flow, of a given volume of liquid, expressed in seconds, is called the "Marsh viscosity." (EN 12715, p 40)

Modulus of deformation
See also stiffness.

Open boundaries
See constrained boundaries.

Permeation
Permeation (grouting) is the filling of voids in pores or joints without noticeable deformation occurring. Permeation achieves a partial saturation of the ground suitable for the respective grouting target, resulting in reduced permeability and generally increased stiffness.

Pinhole test
The pinhole test is an elution and erodibility test. Water – at a predefined gradient – is made to flow through a small hole drilled through a (hardened) sample. The loss of material indicates grout persistence. The test was originally invented to test durability of thin wall diaphragm mixtures.

Pore throat
Interstitial constrictions in soil. Also referred to as pore space or pore width.

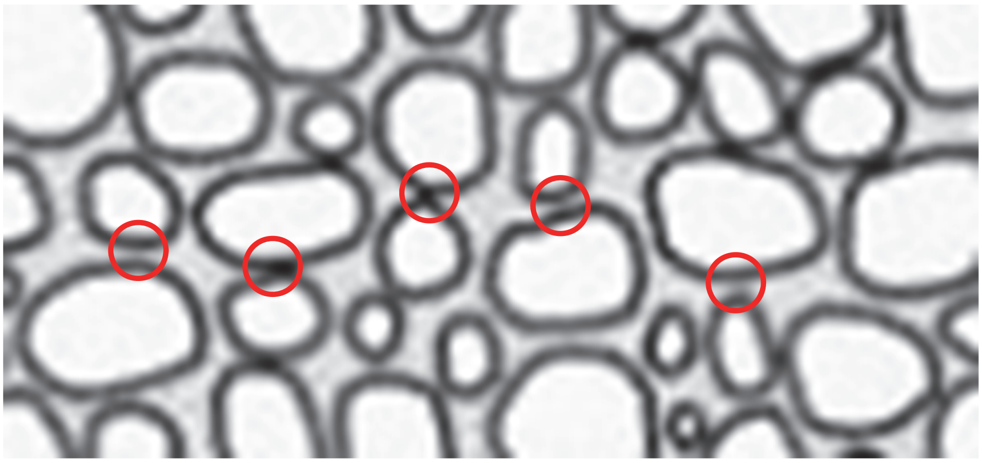


Figure 3. Pore throat distribution in soil. Example of a pore throat (marked red), (unpublished Reichl, 2017)

<u>Pore throat size distribution</u>

Pores in the soil are connected with each other via pore throats (interstitial constrictions). The diameter of the pore throats depends on the grain size distribution from which - by applying a statistical model - a throat size distribution may be derived. This can be used to estimate groutability of the ground and maximum grain size of potential grouts.

<u>Pressure at rest</u>

Pressure at rest describes the existing pressure in voids at a suspension flow velocity of 0 - either after the complete dissipation of the grout after a borehole "shut in" or at termination of grouting. In order to determine the pressure at rest it's necessary to stop the pump, cutting off any reflux, and measure the loss in pressure between shut-off valve and the ground (see also reservoir pressure).

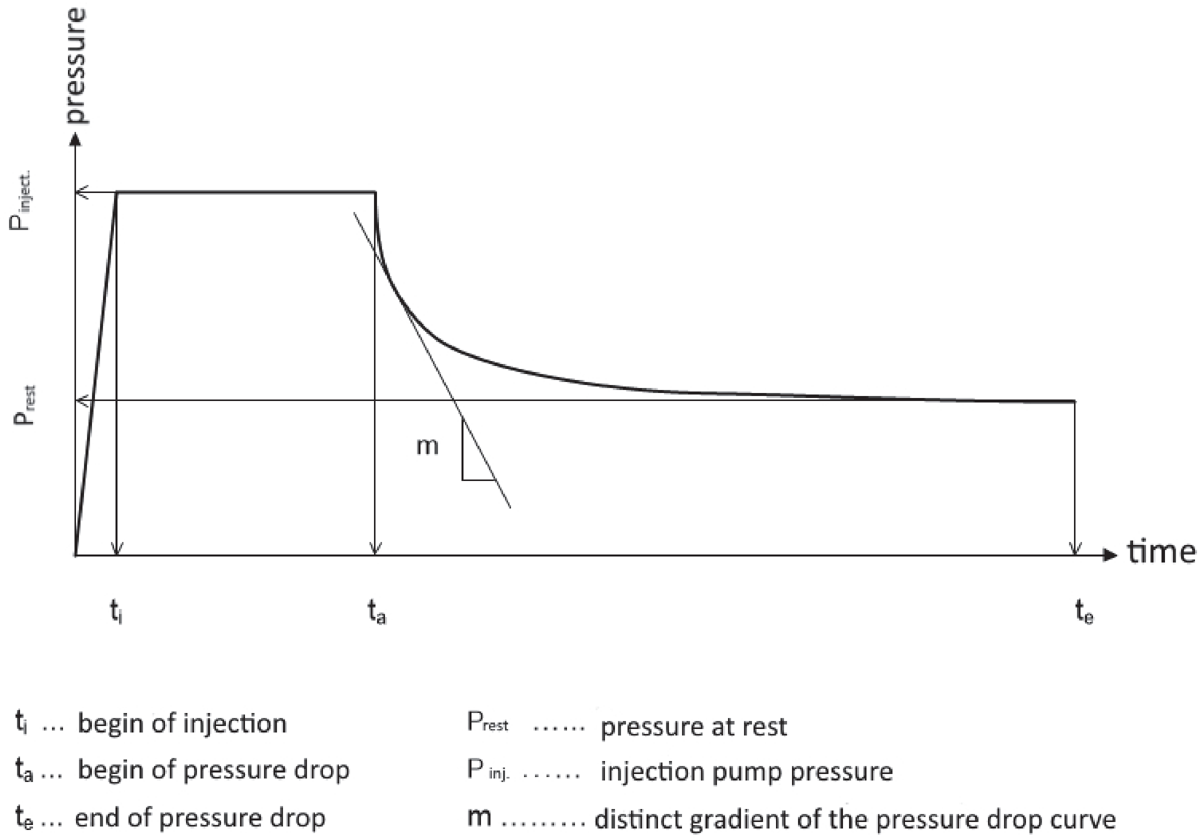


Figure 4. Schematic of a pressure drop curve (Reichl, 2000)

Usually it takes 3 – 5 minutes after having stopped the pump until reaching pressure at rest. Depending on grout viscosity this timeframe might be longer.

<u>Pressure at the borehole mouth</u>

Grouting pressure measured at the borehole mouth.

<u>Reservoir Pressure</u>

The in situ pressure of fluids within the pores or joints in the ground; usually hydrostatic in nature, but may also be influenced/augmented by gas under pressure or artesian pressure. The term is being used in the oil industries, where it describes the pressure within a reservoir.

Shut in
The process of stopping flow (production or injection) - of commonly gas or fluids - into or out of a borehole by closing the shut-off valve. By this, the grout (or production from a well) is being locked into the borehole and into the underground.

Sleeve grout
A low strength grout (< 1.5 MPa uniaxial compressive strength) used to fill the annular space between borehole wall and sleeve pipe. Sleeve grouts prevent grout travelling along the annular space.

Soil porosity n
The porosity of a soil is its ratio of open space volume to soil volume.

Split spacing grouting
Split spacing describes a sequence in which secondary, tertiary, etc. grout holes are placed midway between preceding ones, respectively.

Stiffness
Stiffness describes the relation between stresses and strains. Distinction has to be made between stiffness of the ground/rock in general and specific moduli determined via specific tests, such as modulus of elasticity, oedometer modulus and dilatometer modulus. Stiffness must therefore, always be described in relation to the type/nature of loading. Laboratory experiments can reflect deformation in situ only to a limited degree. Therefore, often a more realistic assessment of soil/rock stiffness can be obtained by back calculation of measured field data or by performing in situ tests.

Stop criteria (refusal criteria, closure criteria)
Commonly referred to as refusal or closure criteria and indeed used interchangeably, subtle differences do exist. Refusal describes stop criteria used when referring to pressures or flow rates at specific boreholes or pumps. Closure usually refers to stop criteria describing overall grouting targets and their achievability.

Top down
Top down describes the sequential drilling, injecting, setting and re-drilling through the already injected stage – from borehole mouth to bottom in a series of discrete steps or stages.

Viscosimeter (= Viscometer)
An instrument used to measure the flow resistance of a fluid. Usually rotational viscosimeters with speed control (in rare cases shear stress controlled) are being used. To measure viscosity a cylinder is being submerged into a cup filled with the fluid and rotated at different speeds (Searle system). The torque maintaining the set speed is proportional to the viscosity. All information on the viscosity, shear stress and the shear rate is calculated from the torque required at different speeds (shear rate) and the geometric factors of cup and cylinder. To perform absolute measurements, only standardized cylinders must be used (figure 5).

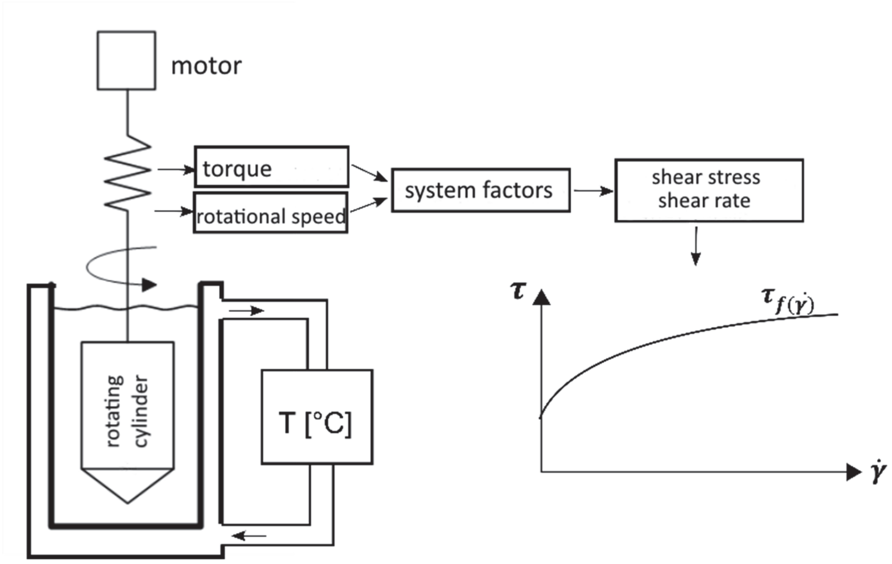


Figure 5. Schematic illustrating viscosimeter testing (Kainrath, 2012)

<u>Void</u>
See also discontinuity. Karst voids are the result of dissolution processes.

<u>Void ratio e</u>
The void ratio is a measurement determining the ratio of voids to solid volume.

<u>V-shape fracture</u>
The limit of grout dissipation (see also "constrained boundaries") at which the hydraulically widened joint tapers off.

<u>w/b ratio</u>
The w/b ratio describes the ratio by weight of water and binder in a mixture.

<u>w/c ratio (WCR)</u>
The water/cement ratio is the ratio by weight of water to dry cement content of the mixture.

<u>Yield point</u>
Liquids possessing a yield point only begin to flow once a minimum shear stress (τ_0) has been surpassed. This minimum shear stress point is commonly referred to as yield point, older publications also use the term cohesion.

4. INFORMATION NEEDED

The following flow chart illustrates all design and execution phases of a grouting procedure. The chart identifies different phases which are concurrent with common Austrian (administrative) proceedings. Depending on the extent and impact of the grouting procedures it may be necessary to also account for implications on groundwater and environment before filing all necessary paperwork. Specifications (SPEC) relate to space constraints (grout reach, uplift of existing buildings), legal constraints, environmental limits and grouts' perennial consistency. For all parties involved a schedule of duties and responsibilities should be defined well in advance, which should be adapted in the course of the project as required. Grouting experts in the client's sphere of responsibility are indispensable as well.

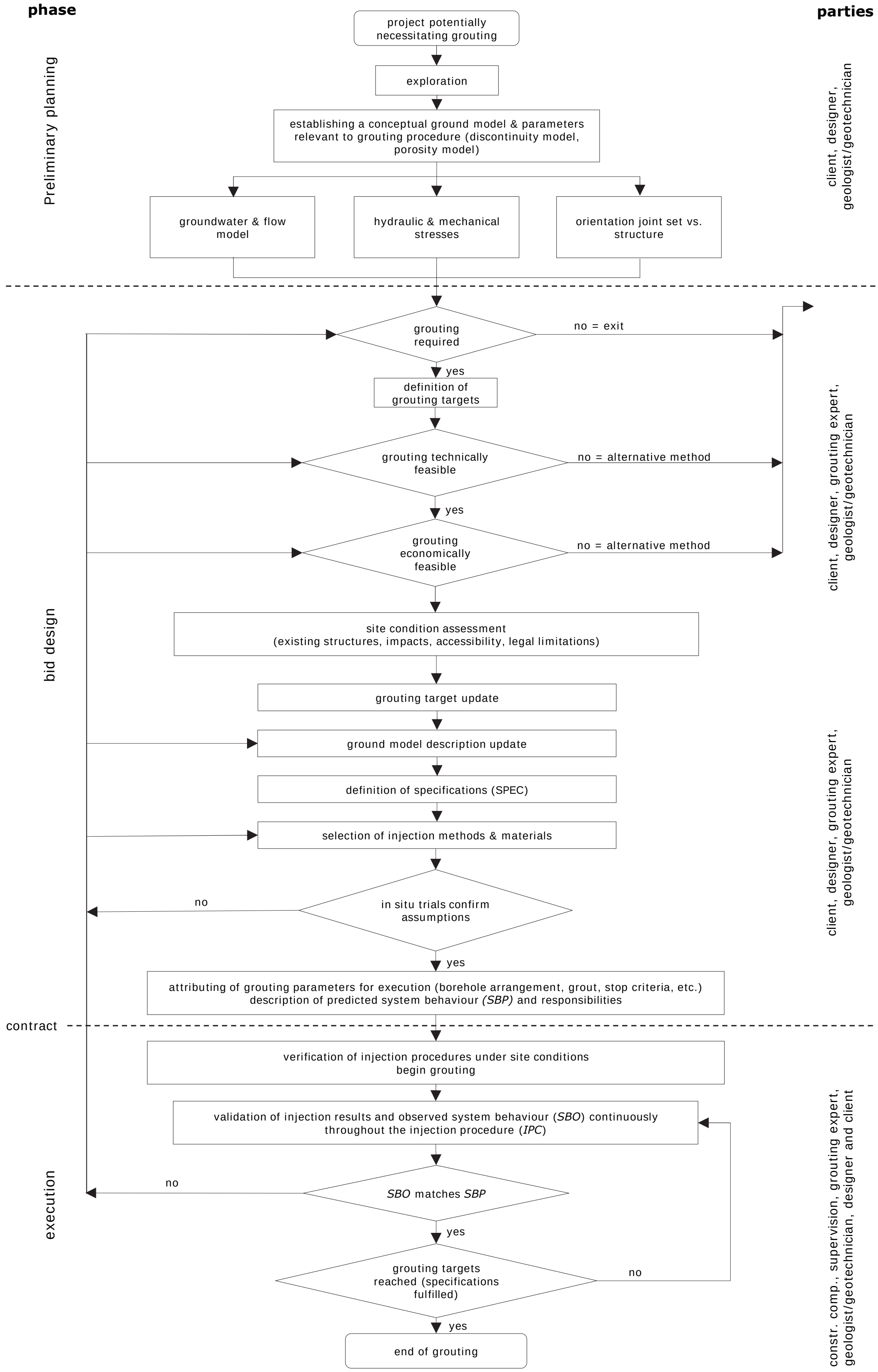


Figure 6. Flow chart; phases of a grouting procedure

5. SITE INVESTIGATION

Specifications mentioned in chapter 5 of the EN 12715 regarding geotechnical investigations should be considered geological & geotechnical investigations instead of just geotechnical in nature and treated as such. This requires an expanded scope of investigations and trials specific to grouting - in situ as well as in laboratory tests. Reports should cover all relevant information of engineering-geological description of the ground, geotechnical tests - and their protocols - as well as interpretations of data - in a clear and explicit manner, accompanied by graphs, illustrations and additional test reports. These interpretations may be used to consolidate empirical data (in situ and laboratory) with geological genesis and anthropogenic factors. Using the previous chapter's flow chart and this chapter's investigative methods should allow an early focus on grouting requirements.

5.1. General

5.1.1. Requirements regarding ground investigation and goals of the investigation

For general requirements concerning ground investigations reference is made to ÖNORM B 1997-2, ÖN EN ISO 14688 - parts 1 & 2, EN ISO 14689 - parts 1 & 2, ON B 4400 – parts 1 & 2, as well as relevant national and international guidelines and standards. Methods of exploration particularly suitable for design and execution of grouting procedures find special mention in this document (tables 2 & 3).

While planning any grouting procedure definite statements regarding ground (soil or solid rock) are necessary. Hydraulic parameters and information on void structure and connectivity should be considered to be paramount.

The extent and nature of geological-geotechnical investigations depends on project phase, type of structure and possible construction methods. Different types and parts of structures pose different requirements for grouting. A conceptual ground model plays a very important role in planning and satisfying injection targets. Site investigations and their results are generally needed in an early phase of the project in order to better identify grouting requirements and optimal concepts (see also figure 6).

5.1.2. Extent of site investigations

Investigations (method and extent) and their placement must be in accordance with regional and local, geological and tectonic parameters. Structural geological conditions (bulk density, joint sets, etc.) need to be considered when planning investigations, so that areas of particular importance for later injections can be localized and evaluated. It is recommended to begin by using comparatively cheap investigation methods and proceed step by step afterwards. Engineering geological mapping and the generation of a conceptual ground model of an appropriate scale should be among the first stages of the design.

It may also be of benefit to further investigate geological conditions in the region by consulting any of the following during preliminary surveys:

- existing geological maps, profiles and reports;
- existing site investigation reports in the vicinity;
- geologically and geotechnically relevant information from site investigations of similar or nearby projects and documentation thereof.

5.1.3. Exploration methods

Exploration methods have to serve the goal of ground characterization and assessment for the sake of determining grouting targets and the resulting grouting requirements.

This means that methods providing primarily geohydraulic data should be employed in addition to standardized procedures during site investigation, providing more appropriate data for the verification of grouting impact (see table 2 and table 3).

Table 2. Recommendations for various exploration parameters (unpublished Stadler, adapted)

Geotechnical Exploration Parameters

Soil				
	indispensable	required	recommended	helpful
Shear strength				X
Modulus of deformation				X
Grain size distribution	X			
Saturation				X
Relative densitiy			X	
Stratification	X			
Filtration characteristics			X	
Permeability k_f, hor/vert.	X			
Groundwater flow			X	
Virgin in situ stress				X
Porosity		X		

Rock				
	indispensable	required	recommended	helpful
Uniaxial strength			X	
Modulus of deformation		X		
Porperties of discontinuities	X			
Opening parameters	X			
Transmissivity profile	X			
Anisotropy of transmissivity			X	
Mineralogical Composition				X
(Lithological) stratification	X			
Porosity		X		
DRI Index				X
RQD Index				X
Weathering				X

When it comes to geological and geotechnical exploration methods we differentiate between field methods and laboratory tests.

Field methods should be employed at natural outcrops and artificial cuts**.** Mapping of existing natural outcrops form the base of every thorough geological and geotechnical ground excavation. Aerial as well as geomorphic imagery should also be considered. Samples for laboratory tests of course need to be taken following all applicable standards.

Artificial exploration such as drilling or digging/excavation as a form of "direct procedures", are mainly used to collect samples and conduct in situ tests.

Indirect procedures include geophysical methods such as seismics, resistivity measurements etc.

Laboratory tests cover disciplines such as (water) chemistry, mineralogy, geomechanics and geo-hydraulics.

Table 3 lists parameters and their suitable exploration methods.

Table 3. Field trials and laboratory tests to determine injection parameters

Field tests				
soil/hard rock	**method**	**parameters**	**technique**	**comments, limits**
soil/hard rock	geologic mapping/discontinuities/ fractures/joints	lithology, discontinuity characteristics, geological boundaries etc.	field survey supported by airborne/satellite surveying, (Stereo Photogrammetry, LiDAR, etc.)	evaluate 3D orientation with dip/dip direction of geological structures and thorough understanding and communication
soil/hard rock	resisitivity measurements	geological layer boundaries		snow, ground water flow
				influenced by water content
soil/hard rock	refraction seismic measurement	geological layer boundaries		low priced; not applicable for complex geology, limited survey depth
		groundwater level		
soil/hard rock	reflexion seismic measurement	geological layer boundaries		sophisticated, expensive, near surface area poorly measured
soil/hard rock	hybrid seismic measurements	geological layer boundaries		advantage of both refraction and reflection seismics combined
soil/hard rock	trial pits and shafts	geological layer boundaries, orientation		limited depth
		groundwater level		
		sampling		
		in situ tests		
hard rock	survey galleries	rock mass properties		sophisticated, expensive
		in situ tests		
		sampling		
soil/hard rock	drillings	geology/geological layer boundaries	core logging	
			televiewer, optical/acoustic borehole imaging	clean borehole
soil		hydraulic properties	slug/pulse test in the borehole	
soil/hard rock			water pressure tests	Karst, hydraulic conductivity too high
hard rock			water level, hydrographs	
hard rock			flow direction und velocity	
soil/hard rock		geomechanical properties	in situ stress tests	short time stable boreholes
soil			standard penetration tests	
soil/hard rock			drilling energy	
soil		drill core	soil mechanical survey	depends on sample quality
hard rock			rock mechanical survey	
soil/hard rock	soundings	geological layer boundaries	dynamic probing, CPT, drill stem test, drilling parameters	
soil		compactness	dynamic probing, CPT, drilling parameters	

Laboratory Test			
	relevance	**parameters**	**method**
soil	●	grain size distribution	sieve analysis
	○	grain density	pycnometer
	○	grain shape	visual inspection / microscope
	●	bulk density	vibrating table method, Proctor
	●	loose/dense packing	vibrating table method, Proctor
	○	water content	oven dry samples, air pycnometer
	○	friction angle, cohesion	shear test, triaxial test
	○	plasticity	compression testing, triaxial test
	●	permeability	tests with constant/changing hydraulic head
	●	pore volume	porosity test
	○	mineralogy	thin section, XRPD, clay mineral analysis
	○	determination of loss on ignition	determination of organic content
	○	abrasivity	LCPC test,abrasivity test, Los Angeles test
hard rock	○	density	density test
	●	porosity	pycnometer
	○	compressive strength	single axial compression test, triaxial test
	●	deformability	single axial compression test, triaxial test, Quellversuche
	○	shear strength	triaxial test
	●*/○	tensile strength	splitting tensile test
	○	permeability	permeability test with changing hydraulic head
	○	mineralogy	thin section, XRPD, clay mineral analysis
	○	abrasivity	Cherchar, NTNU

● property of significant importance

○ property of lesser importance

* for layered/schisted/laminated rocks

5.1.4. Investigation report requirements

The investigation report has to provide sufficient basis for the planning of the grouting procedure. Subsoil reports listing primarily geo-hydraulic data as well as methods and procedures used are absolutely essential.

Results must be interpreted and consolidated into a conceptual ground model. Additional geological – geotechnical cross-sections complementing the model and facilitating communication are always advised, with detailed individual results to be published in the appendix of the documents. Data from field trials, in situ and laboratory tests should always be clearly separated from their interpretations.

Clarity and comprehensibility must be emphasized throughout, in order to enable the efficient communication of the ground model between the various disciplines in a project team. The inclusion of schematics illustrating the anticipated distribution of the grout according to chapter 5.3 is definitely recommended.

The investigation report (in the sense of a geotechnical baseline report) also serves as reference if deviations from the ground model are being determined later.

5.2. Geo-hydraulic fundamentals

In the course of geotechnical grouting, water-binder mixtures of liquid or paste-like consistency are being injected under pressure into the ground. Illustrating geohydraulic conditions should, therefore, be considered crucial when establishing a ground model. This document will shed light on select topics, with fundamental principles easily accessible via specific technical literature.

The essential (and interrelated) geo-hydraulic parameters can be found in the ISRM "Report on Grouting" (1996):

Table 4. Correlation of geo-hydraulic parameters (ISRM, 1996)

parameter	value	T	K	k	measured in
Transmissivity	**T**	T	$K \cdot d$	$k \cdot \frac{d \cdot \gamma}{\eta}$	[m²/s]
Conductivity	**K**	$\frac{T}{d}$	K	$k \cdot \frac{\gamma}{\eta}$	[m/s]
Permeability	**k**	$\frac{T \cdot \eta}{\gamma \cdot d}$	$K \cdot \frac{\eta}{\gamma}$	k	[m²]

η: dynamic viscosity [mPA s]

d: thickness of the aquifers [m]

γ: specific weight of the fluid [kN/m³]

In order to understand the hydraulic processes in the ground it is necessary to consider the rheological differences of fluids (water and cement suspensions), especially the difference between Bingham fluids and Newtonian fluids.

Water (Medium for water pressure tests as well as Lugeon tests) is being classified as a Newtonian fluid, mostly due to its stress-independent viscosity and its directly proportional correlation of shear stress and shear rate (no yield point).

Bingham fluids (applicable for most particulate grouts and suspensions) differ from Newtonian fluids as they exhibit cohesion (yield point τ_0) which needs to be overcome in order to initiate flow. Shear stress commonly increases in Bingham fluids directly proportional to shear rate τ_0 once the yield point has been surpassed (see figure 7).

Liquids diverting from this linearity usually show pseudoplastic behavior (structural viscosity). Some rheopectic fluids (for example bentonite-silicate gels, suspensions with large amounts of solids) exhibit shear thinning with increasing shearing time and shear rate – other fluids dilate; they exhibit shear thickening behavior. Both phenomena are – to a certain extent – reversible once fluids return to their original state.

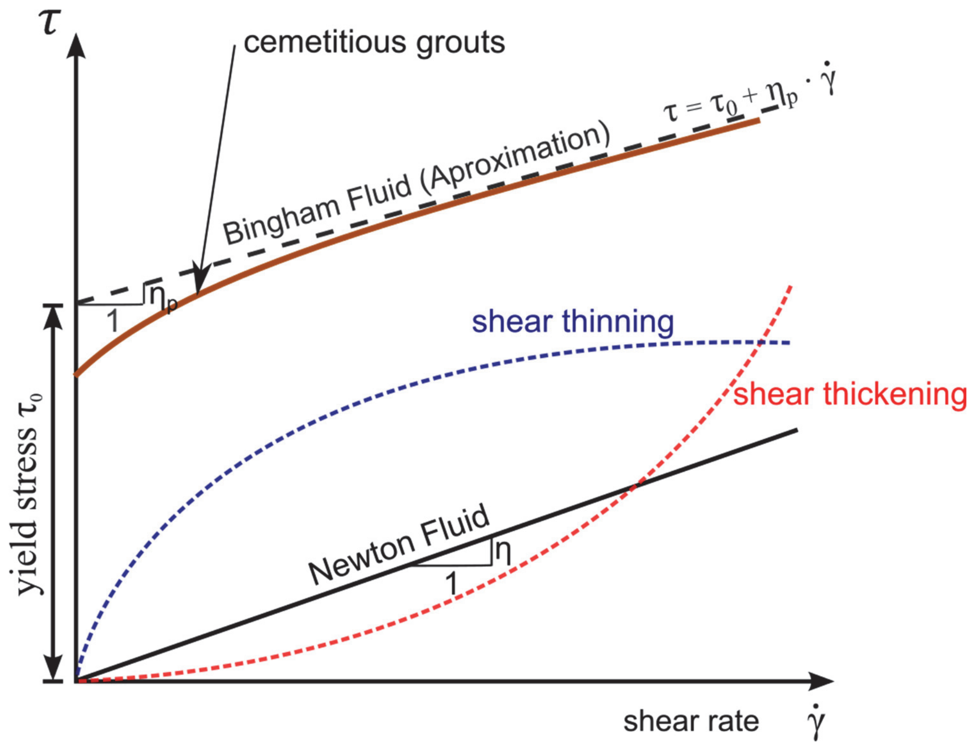


Figure 7. Flow behavior of different liquids (Kainrath, 2014)

Thixotropy

This term describes the changing, thinning behavior of a fluid under mechanical stress (shear thinning), while exhibiting an increase in viscosity or yield point in its idle state. The process is repeatable and reversible. Figure 8 illustrates the influence of thixotropy using a typical flow curve. Thixotropy occurs predominantly while using grouts with high clay contents (especially bentonite) or other additives and becomes a crucial factor should interruptions during the grouting itself occur - or if, for example, the suspension is being held in the Marsh cone for too long before measuring efflux time.

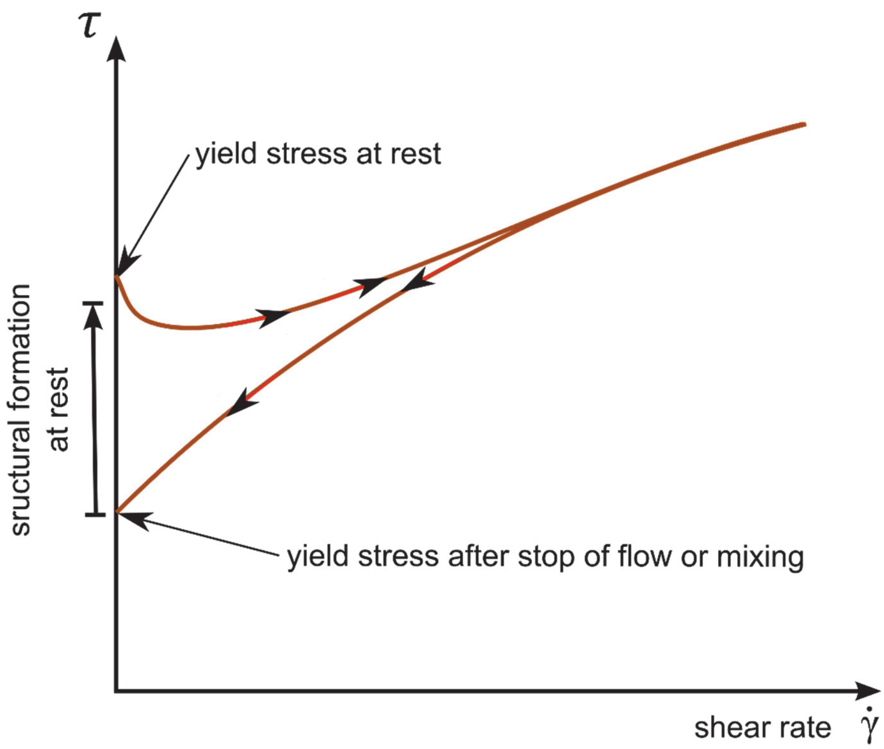


Figure 8. Flow curve of thixotropic liquids (unpublished Stadler, 2016)

5.2.1. Geo-hydraulics In soil

The hydraulic characteristics in soil are defined by its structure (grain shape, grain size, density). To describe the flow of water through ground Darcy's Law is commonly used. In it filter velocity (v_f) is the quotient of total discharge (Q) and the total cross-sectional area to flow (A). According to Darcy this velocity (v_f) is directly proportional to the hydraulic gradient (I). This gradient (I) itself is a result of the difference in water level (Δh) and the total length (L) over which the pressure drop is taking place. (k_f) is the coefficient of permeability of the ground. Figure 9 illustrates these correlations below:

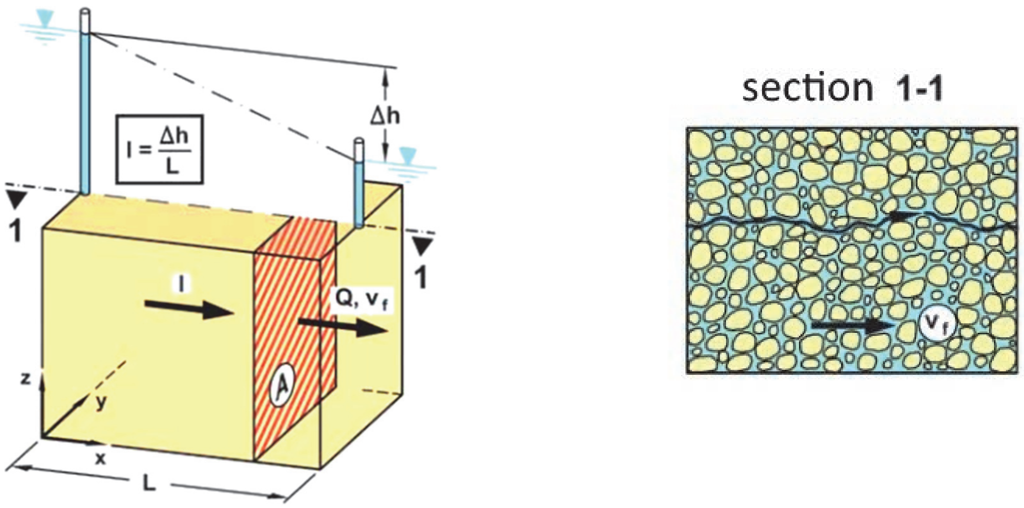


Figure 9. Abstraction of the soil-hydraulic model (Sommer, 2012)

$$v_f = \frac{Q}{A} = k_f \cdot l \quad (3)$$

5.2.2. Geo-hydraulics in solid rock

Hydraulic characteristics of solid rock in the sense of ducting water predominantly in fissures are determined by the geometry and configuration of joint planes and their hydraulic connectivity. For fault zones with characteristics of soil refer to chapter 5.2.1. Solid rock of significant porosity should be considered a mixed medium for both pore water and fissure water flow.

5.2.2.1. Discontinuities in solid rock

Discontinuities in a rock mass include joints (or fractures), foliation (or cleavage), bedding planes, faults or others, defined by parameters such as aperture, surface attributes (i.e. roughness), fillings, spacing, persistence and frequency. Depending on the genesis of rock there are different types of joints to be distinguished - and their orientation relative to the structure are of particular importance (figure 10).

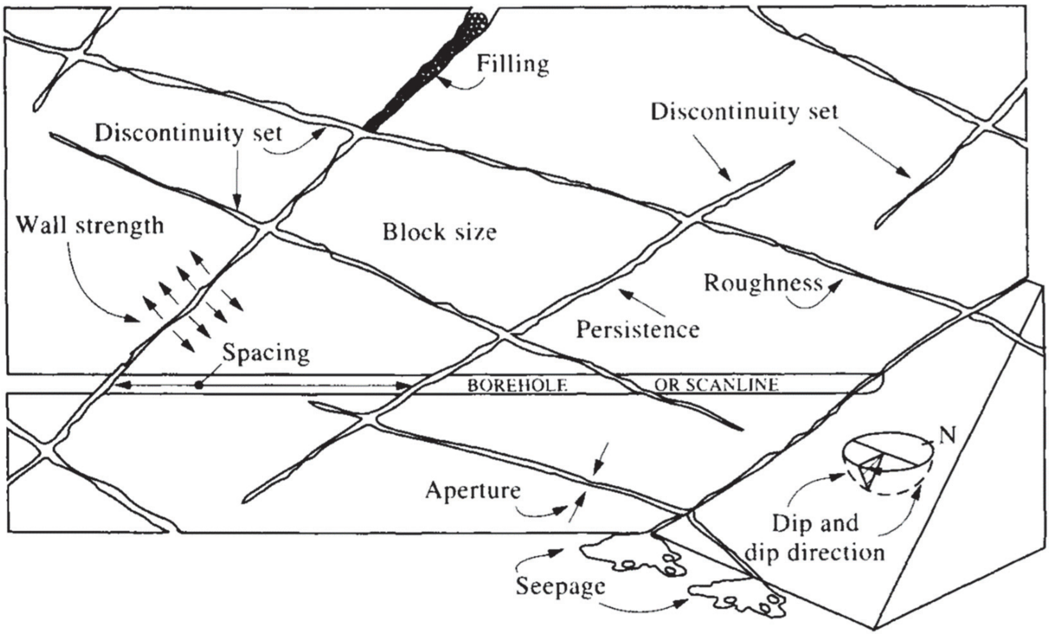


Figure 10. Discontinuity system illustrating spacing, aperture, roughness and intersection with a borehole. (Hudson, 1989)

5.2.2.2. Discontinuity hydraulics

According to Darcy any flow in a homogenous rock mass can be described with the filter velocity (v_f). It is the quotient of discharge (Q) and cross-sectional area to flow (A) (including both "impermeable" matrix and voids). Following this model, flow itself only takes place in spaces between discontinuity (= joints). Permeability of a given joint can be described as follows:

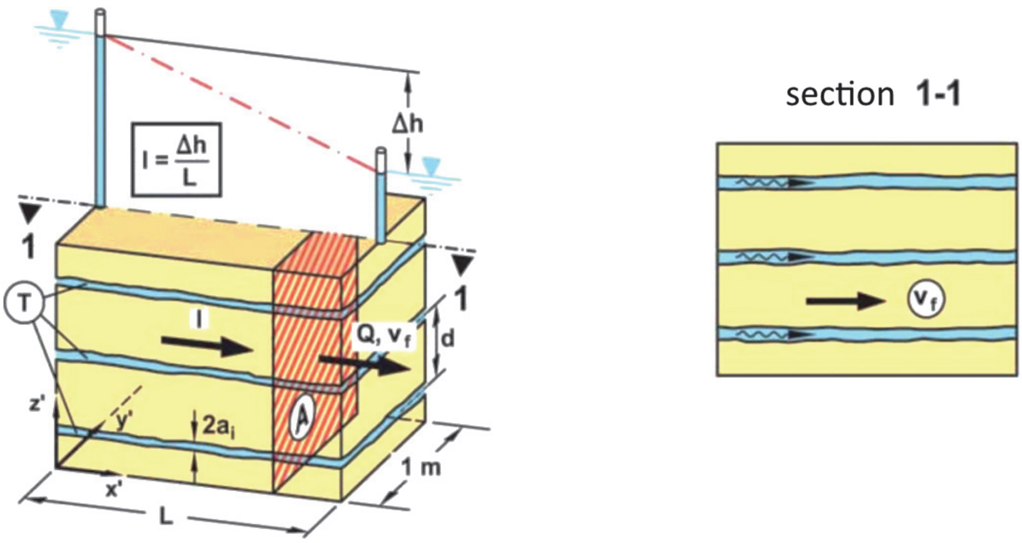


Figure 11. Abstraction of the hydraulic model in solid rock (Sommer, 2012)

$$v_f = \frac{Q}{A} = \frac{g(a_i)^2}{12v} \cdot \frac{2a_i}{d} \cdot l = k_t \cdot \frac{2a_i}{d} \cdot l = k_T \cdot l \quad (4)$$

g:	earth gravity	[m/s^2]
v:	kinematic viscosity	[m^2/s]
2_{ai}:	joint aperture	[m]
L:	distance	[m]
Q:	discharge	[m^3/s]
k_t:	coefficient of permeability	[m/s]
d:	mean joint aperture	[m]

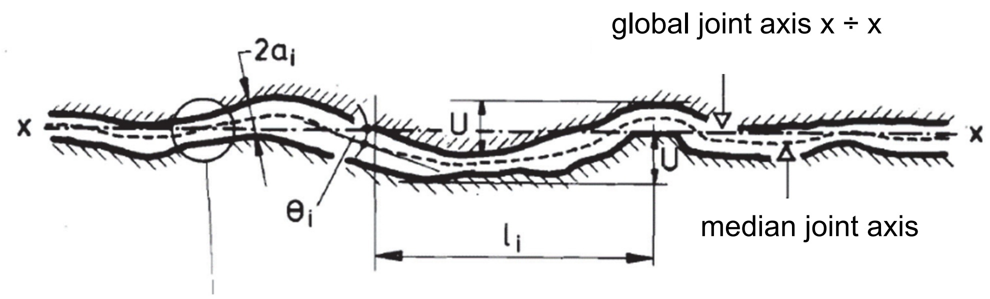


Figure 12. Illustration of a common joint (Louis, 1967)

In this simplified way the total discharge can be calculated by adding up the joint planes oriented parallel to the direction of flow –adding up all joint planes orthogonally intersecting the relevant cross-sectional area. For approximating flow of formation water in solid rock the Cubic Law should be used, which means that transmissivity is proportional to the third power of the hydraulic joint aperture, and flux directly proportional to the pressure gradient. Limitations due to turbulence may apply.

Due to their important influence on connectivity, anisotropic conditions in solid rock are particularly relevant in the context of injection.

Actual transmissivity (table 4) of a rock mass is usually being determined in situ by using the Lugeon test. The Lugeon value equals the amount of water (in L) per meter of test hole per minute at an injection pressure of 10 bars. In real life situations, however, different lengths of boreholes are being used, as well as different sets of pressures and different scenarios (single packer at the end of the borehole, or double packers over the span of an interval of a hole). In such cases the Lugeon value at 10 bars can be extrapolated linearly by using the test's last pressure stage.

Since such water pressure tests rarely proceed linearly, it might be prudent to analyze the values (flow/pressure, usually in diagram form) in regards to possible changes in geo-hydraulic conditions during the tests themselves – and interpret the data accordingly.

Important phenomena in the context of grouting are:

- Washout
- Clogging
- Turbulence
- Elastic joint widening (dilation)
- Hydrojacking & Hydrofracking

Extrapolation of low test pressures to the reference pressure of 10 bars should always be evaluated critically, especially in the case of non-linear appearance of testing stages. The Lugeon value only acquires its relevance to injection procedures once a plausible distribution of joint apertures has been established. The difference in rheology of water and suspensions needs to be considered when evaluating Lugeon-test results as well. The Lugeon value is oftentimes not sufficiently precise to arrive at a definite aperture distribution, it can, however, be used as a useful indicator of transmissivity before and after the grouting procedure.

5.3. Geomechanical fundamentals

During the project planning stage, the systemic interaction of the ground, planned structure and planned grouting procedures has to be explored fully. The possible change in mechanical and hydraulic characteristics in the ground caused by grouting or construction procedures is of major technical and economic significance.

In order to assess system behavior, the following items should be considered:

- Geomechanical attributes of the ground (e.g. soil parameters, rock parameters, rock-mass parameters, pore- or joint-interface water regime)
- Impact of construction (loading) and its effect on geomechanical behavior of the ground (elastic, plastic or time-dependent)
- Impact of grouting on the ground (e.g. changes in cohesion, deformation and permeability)

Applicable geomechanical fundamentals depend on the target of the grouting procedure and ground characteristics. In the context of guidelines for underground works, information published by the Austrian Society for Geomechanics (“Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation” available at www.oegg.at; ÖGG, 2010) contains parameters for the characterization of certain rock mass types, which should be of sufficient assistance in that regard.

The following schematics facilitate the illustration of possible grout travel. Schematics like these have to be part of the investigation report.

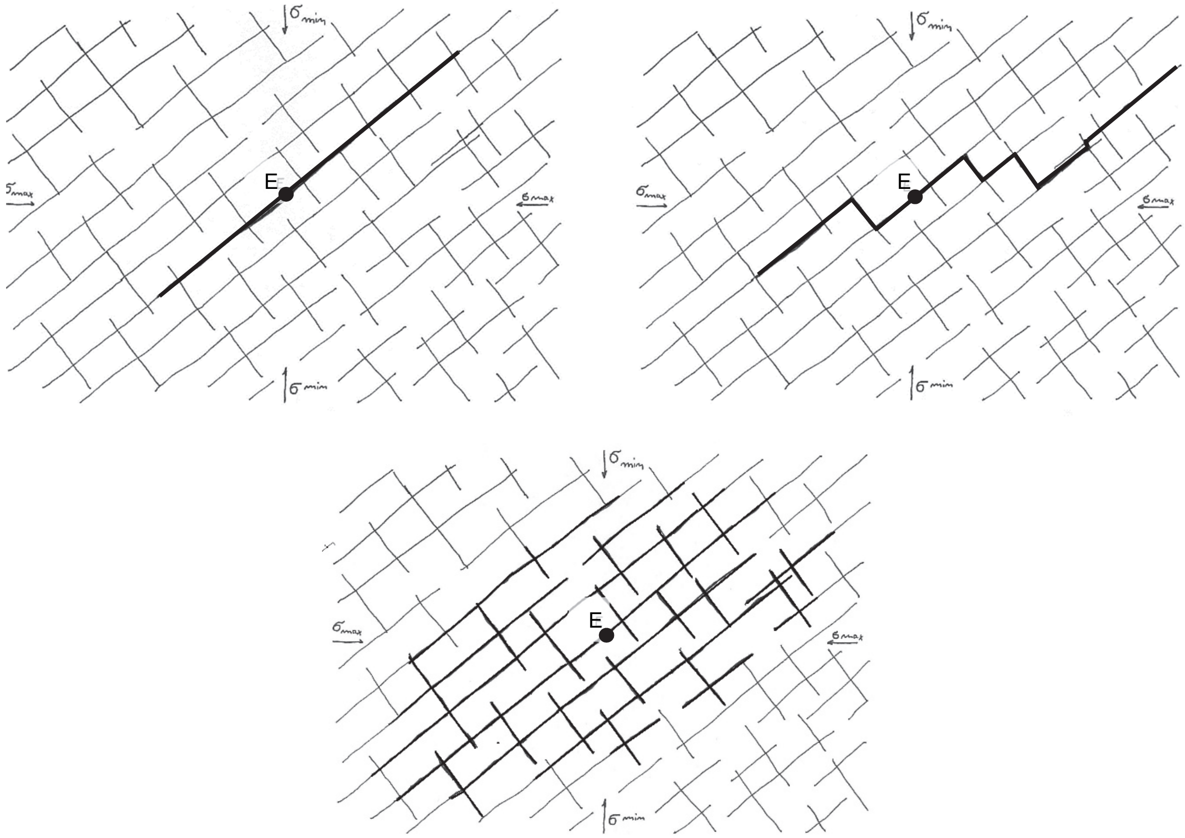


Figure 13. *Different distributions of grout emanating from entry (E), depending on joint plane characteristics and tension in rock mass (Ewert, 1985).*

5.4. Deduction of grouting-specific parameters

5.4.1. Information gained from exploratory drilling

Exploratory drilling already leads to additional data essential for the understanding of the ground model. Important data such as drilling parameters (specific energy, torque, thrust pressure or rotational speed) and the evaluation of drilling protocols (flushing loss, observations of the drill operator, etc.) have to be included into the analysis of ground characteristics. An energy profile along the borehole can assist in evaluating grain size distribution, density, intensity of jointing, fault zones or voids and complements all other geotechnical investigations in relation to geological profiles.

$$e = \frac{F}{A} + \frac{2\pi NT}{AR} \quad (5)$$

e:	Specific drill energy	[kJ/m³]
F:	Contact pressure (feed force)	[kN]
A:	Cross-sectional area of the hole	[m²]
N:	Revolutions	[RPM]
T:	Torque	[kNm]
R:	Drill rate	[m/s]

5.4.2. Hydraulic and mechanical parameters

Relevant information which can be gained from drilling includes:

- Joint aperture
- Characteristics of discontinuities (shape, roughness, filling, degree of separation)
- Number of joint planes per meter/borehole (intensity of jointing), categorized in relation to hydraulic relevance
- Position and orientation of joint planes

These criteria should be presented in their relation to the planned position of the structure, as well as their orientation relative to it.

Investigations into hydraulic parameters will only provide references to pore or joint constrictions, since only those tend to influence results of hydraulic in situ trials (hydraulic pressure and pump tests).

The geometric aperture of discontinuities and its intersections with the borehole differ from the significant hydraulic constriction insofar, as it determines filtration phenomena and grout entry losses.

Effective injection pressure usually causes elastic or plastic opening of joints (hydrojacking) in rock masses (or *claquages* in soil), which in turn promotes the permeation and distribution of the grout. In this context significant deviations from grout estimations can occur.

5.5. Injection trials on site and in the laboratory

Injection trials conducted in preparation for construction should be considered of exploratory nature and are highly recommended.

6. CONSTRUCTION MATERIALS AND PRODUCTS

6.1. General

There exists a plethora of construction materials and products for geotechnical injections, whose attributes are generally defined by their composition. Selection of grout, therefore, depends on grouting targets, parameters (soil or rock characteristics, hydrogeological conditions etc.) and injection-specific requirements. Selection and modification of the grout should be considered an iterative process, based on experience, trials and suspension test results.

6.2. Grouting materials

6.2.1. Hydraulic binders and cements

Hydraulic binders include cements and similar products usable in liquid suspensions for grouting. In general, the different grout classifications are:

6.2.1.1. Standard cements according to EN 197-1

According to EN 197-1 standard cements are being classified as follows:

Table 5. Classification according to compressive strength (Compressive strength of cements: EN 197-1)

strength class	compressive strength			
	initial strength		norm strength	
	2 days	7 days	28 days	
32.5 N	-	≥ 16.0	≥ 32.5	≤ 52.5
32.5 R	≥ 10.0	-		
42.5 N	≥ 10.0	-	≥ 42.5	≤ 62.5
42.5 R	≥ 20.0	-		
52.5 N	≥ 20.0	-	≥ 52.5	-
52.5 R	≥ 30.0	-		

N: normal

R: rapid

Table 6. Classification of standard cements according to composition

CEM I –	Portland cement
CEM II –	Portland-composite cement
CEM III –	Blastfurnace cement
CEM IV –	Puzzolanic cement
CEM V –	Composite cement

Physical parameters as found in EN 197-1 are valid for low water/binder ratios (~ 0.5 w/b). For injection procedures common ratios of w/b > 0.8 cause significant changes in those parameters.

CEM I contains as a main constituent pure cement clinker, whereas CEM II to CEM V contain higher percentages of other, different constituents. For grouting classes CEM I to CEM III should usually be used, with the stability of the suspension generally improving with higher clinker ratio and strength classes (higher fineness/blaine value).

6.2.1.2. Mixed binders (manufacturer-specific mixes)

Mixed binders constitute manufacturer-specific grouting mixes containing standard cements plus additives (fillers) are usually cheaper than standard cements. The physical and rheological attributes of suspensions containing mixed binders depend heavily on the composition of the binders themselves and need to be tested for suitability.

6.2.1.3. Microfine binders

Microfine binders are hydraulic binders of a maximum grain size of 95% passing at $d_{95} \leq 20$ µm. Instructions for use and testing can be found in „Merkblatt für Einpressarbeiten mit Feinstbindemittel in Lockergestein“ (Schulze, 1993).

6.2.2. Water

Drinking water should be used for mixing whenever possible. Water found on site from natural sources should be tested (especially for chloride and sulfide contents and organic compounds) before use. Surface water, groundwater, residual water require testing as well, especially on suspicion of containing damaging substances. Benchmarks for testing and evaluation of water for mixing purposes can be found in ÖNORM EN 1008. Where site water is to be used, mix trials with the actual components should be carried out in advance of the works to verify that target mix properties can be achieved.

6.2.3. Additives

Additives are materials added with the aim of modifying the suspension according to project requirements. These additives may be inert (fillers) or may exhibit pozzolanic characteristics (i.e. improve grout strength). Generally, additives are being added in order to improve rheological characteristics, or to improve the solid particle ratio of the suspension. The amount of additives is commonly significant enough to be a factor in volume calculations. A higher ratio of solids in the suspension, and therefore a higher density, increases durability and reduces permeability, an important factor when dealing with long-term hydraulic barriers. Optimal ratios need to be identified via suitability tests.

See also EN 12715 chapter 6.2.6.1:

> *„Calcareous or siliceous fillers, pulverised fuel ash (pfa), pozzolans and fly ash from thermal power plants or any inert or reactive components may be used in grouts, provided that they are chemically compatible with each other and satisfy immediate and long term environmental requirements.“*

See also EN 12715 chapter 6.2.3.1:

> *„Sand and fillers are commonly used in cement grouts or clay suspensions as bulking agents or as a means of varying the consistency of the grout, its resistance to wash-out, or its mechanical strength and deformability.“*

Possible applications of fillers in grouts are grouting of large voids or compaction grouting. Additives must not contain harmful particles, and the granulometry of sands and fillers used in the grout must be known.

6.2.4. Clays

In order to improve stability of cement suspensions, the addition of ground clay particles capable of swelling (bentonites) is common. They reduce sedimentation under gravity and bleeding under pressure. Depending on quality of bentonites added, hydration before introduction may be required to achieve maximum effect. This must be done in clean water free of cement since the ability of sodium bentonite to hydrate can be negatively influenced by calcium ions in the mixing water.
„The mineralogy, particle size, water content, and Atterberg liquid limit of the clay should be known.“ (EN 12715 chapter 6.2.2.)

6.2.5. Additives and admixtures

Additives may be introduced to the suspension in order to optimize its physical properties in accordance with project requirements. They can be added in liquid or powdery form to a limit of 5% of total cement mass (see also EN 934) and do not need to be accounted for in volume calculations. Additives can, among others, influence:

- Consistency (yield point, viscosity, thixotropy)
- Plasticity (maintaining fluid characteristics over duration of injection)
- Setting Time (decelerating or accelerating effect)
- Voids content
- Strength

Targeting one characteristic for improvement (e.g. fluidity) generally impacts other characteristics as well (e.g. compressive strength, aeration). In each case tests should be conducted to assess the suitability and amount of additives required. Relevant additives for grouting are classified into:

- Fluidifiers improve flow characteristics by reducing yield point and viscosity; they often act as a water reducing agent.
- Stabilizers (dispersing agents) reduce bleed, improve workability and prevent dilution in the case of contact with ground water.
- Accelerators reduce set time. They are usually being added to the grout whenever extensive spreading needs to be avoided (e.g. groundwater flow, set time increasing factors like sulfate, low temperature) or when rapid set is required.
- Inhibitors/retarders increase setting time.

6.3. Suspensions in grouting

Table 7 lists essential parameters for the classification of suspensions:

Table 7. Parameters for the classification of suspensions

Flow properties / Rheology	- yield point - viscosity - thixotropy
Density	- suspension density
Stability	- bleeding under pressure (pressure filtration) - sedimentation rate (bleed) - resistance to washout - dilution
Rigidity/ Development	- initial set - rapid set - final set
Durability	- resistance to chemical reactions - resistance to erosion - persistence

6.4. Sampling and testing

There are tests available for suitability (or aptitude) and quality control. The former are used to optimize attributes of suspensions in order to achieve grouting targets, with the latter providing quality control on site. The scope of suitability and aptitude tests should be determined by the designer after consultation with relevant experts. All rheological and physical parameters and the expected spread of test results needs to be considered. The extent of control tests, also specified by the designer, is limited to the control of previously stated benchmarks. Table 7 lists the most important criteria for both control and suitability tests.

6.4.1. Testing grouts in the laboratory

Grout characteristics are to be tested at an ambient temperature of 20 °C. Testing conditions (mixing sequence, temperature, time, speed/energy applied, mixing duration) should be kept constant; procedures as well as deviations need to be documented. Constituents of a mixture are to be weighed at a precision of 0.1 g and mixed in relevant sequence. High-speed mixers should be employed, and the temperature and chemistry of the water used should be identical to that present on site. Is no data available, then using 12 °C for mixing water is recommended. It is possible that interference by the chemistry of the water on site cannot be avoided, in which case all tests have to be conducted using water from the construction site.

*„If the conditions on site differ substantially from the laboratory conditions (especially the temperature) tests shall be conducted under the in situ conditions. The temperature development during testing shall be monitored.“ (*EN 12715 chapter 6.4.4)

6.4.2. Control testing on site

„The constituent materials of a grout mix as well as the mix itself shall regularly be sampled and tested to verify compliance with the design requirements.“ (EN 12715 chapter 6.4.1)

Sampling of already mixed suspensions should be done from the holding tank (or in case of longer pipe ranges at the borehole mouth) and not from the mixing tank. Time and place of sampling, age and composition of mixture need to be recorded. Rheological tests have to be conducted immediately after sampling. For retention samples (uniaxial compression strength) the use of a cylindrical sample container (or tube) with dimensions of 2:1 length/diameter is recommended. Storage of samples should use conditions similar to those of the ground in situ (temperature, humidity and water chemistry), but need to be documented in any case. Samples should be stored in water at room (ambient) temperature, with deviations from those conditions to be recorded as well. Agitation through transport should be avoided if possible, especially in the first few days. Samples should be trimmed to a ratio of 2:1 (height/diameter) -still in their tubular container - before tests are about to be carried out.

6.4.3. Testing

6.4.3.1. Manufacturer instructions and testing for product spec sheets

„Standardized testing methods (equipment, boundary conditions, analysis) shall be employed to allow comparison of the characteristics of the products provided by different suppliers.“ (EN 12715 chapter 6.4.2)

Manufacturer information for grouts should be, in the case of suspensions based on hydraulic binders, related to a w/b value of 1.0.

In addition to information (technical specifications and characteristics, and the complete data on granulometry and grain density) regarding the type of cement and additives to be used, a number of additional parameters must be indicated:

- In pure suspensions: density, Marsh time, sedimentation rate
- In stabilized suspensions (sedimentation rate < 5%): Percentage of admixture and product name of stabilizing agent, density, bleed und pressure, free water filtrate, yield point, viscosity (viscosity curve), Marsh time, initial set, compressive strength of the pure suspension after 28 days in cylinder

Table 8 lists empirical values for Portland cement suspensions:

Table 8. Empirical values for Portland cement suspensions

	method	unit	lower limit	upper limit	notes
filtrate	API-filter press	[ml]	40	110	DIN 4126; after 7.5 mins
Marsh-cone time	Marsh-cone	[s]	31	40	DIN 4126; at 1000ml
sedimentation rate	1000ml cup	[%]	1	5	DIN 4126; after 2h
initial set*		[min]	80	240	

*values may vary depending on method employed

6.4.3.2. Testing procedures and applications

Table 9 lists the most important parameters and possible suitability (aptitude) and control tests for suspensions. The types and amount of testings should be determined specifically for each project. Suitability tests in the laboratory aim to optimize and customize suspensions for the injection task at hand, while control tests on site serve to control chosen mixtures and quality assurance. The extent of the latter type of tests, therefore, should be expected to be significantly less and focused on simple testing procedures.

Table 9. Methods, suitability (aptitude) and control tests for suspensions

Parameters		Recommended Method	Eignungsprüfung	Kontrollprüfung
Composition	w	measuring cylinder, mud balance	yes	yes
Stability	sedimentation rate	measuring cylinder	yes (2/4/6h)	yes (2h)
		d = 6 cm, V = 1000 ml		
		sedimentation rate = Δh/h		
	filtrate	filter press[12]	yes	yes
Rheological Benchmark	yield point	viscosimeter (w. vane)[10]	yes	no[1]
		or		
		determination using Bingham flow curve		
		[EN 12715: fig. B1]		
		ball harp²	yes[2]	yes
	viscosity	flow curve[3]	yes	no[1]
		[EN 12715: fig. B1]		
		Marsh cone[4]	yes[5]	yes[5]
		1000ml, $d_{ischarge}$ = 4.75 mm		
Set	initial set[13]	viscosimeter (w. vane)[11]	yes[8, 9]	no
	early set	uniaxial compressive strength[6]	yes[7, 8]	no
	final set (28d)	uniaxial compressive strength[6, 7]	yes	yes

1 Possible exception: Whenever deviations from the original grout or changes in additives need to be meas-ured.

² Only for comparisons and control tests; large variation and lack of precision, especially if additives are being used. Adhesion tests (100-grit sandpaper) have proven especially apt for control tests under on site conditions. For aptitude tests and the determination of actual yield points, other tests should be used (vane, flow curve).

3 Viscosity test using a (rotary) cylindrical viscosimeter (coaxial layout). Using relative measurement systems is not recommended.

4 For a rough estimate of viscosity, and for control tests

5 Used only for relative measurements and comparative measurements during control tests

6 According to „Qualitätssicherung für Bodenvermörtelung“ or ÖNORM B 4415 for cylinders (h/d = 2:1) of the hardened grout (sedimentation rate in container/tube must be considered; fill level > sample level), storage of sample until test under water. Cut and alignment of sample faces, pathing controlled, feed at 1% of initial level, at ε<4% -> 0.2% of initial level; deviations from testing instructions are to be mentioned separately

7 Using retained samples stored in water

8 If required

9 If mixtures or additives are being used which can influence hydration significantly

10 Maximum shear stress is being used as yield point. See Kainrath (2014)

11 Intermittend test implementation. Measuring increase in shear stress over time. Initial set is assumed at τ = 100 Pa. See Kainrath (2014)

12 According to DIN 4127; filtration pressure of (7 ± 0.35) bar, filtrate volume after 7.5 minutes is being measured

13 In order to adhere to in situ conditions, the hardening test may follow temperature, humidity and properties of groundwater found on site

7. DESIGN CONSIDERATIONS

7.1. Preface

The design of grouting works is a multidisciplinary engineering challenge requiring extensive experience of all parties involved. The design of injections requires a great measure of adaptability, something that already needs to be considered during the design stages. This flexibility should be reflected and regulated explicitly in contracts so that it may be applied during execution. Following methods have proven successful:

- Planning of the grouting procedures with the use of simple models.
- Start parameters should be left variable in order to react to changing conditions.
- Risk analysis to better estimate possible scenarios, their extent and impact on design and bids.

7.2. Design fundamentals and targets

7.2.1. Design fundamentals

The design fundamentals for any grouting project are defined by grouting targets to be achieved and project conditions.

Main considerations revolve around the extent in which ground characteristics in the vicinity of the planned structures need to be altered – and whether this is possible via grouting at all. Targets usually consist of a change in ground characteristics beneficial for the project, be it hydrogeological or geomechanical changes, or a reduction in (or even compensation of) ground settlement. It might be of relevance for design targets, whether its effects are aimed at temporary or permanent changes.

The parameters defining the design are primarily determined by the ground (geology, hydrology), environmental limitations (allowed settlements, tolerable water ingress values, ecological factors) and site limitations (space, abutments counteracting grout forces).

“Preventive” grouting measures are meant to be executed before the actual main construction works are to start. In the case of tunneling, for example, this could mean a treatment of the ground from both above ground and underground before excavation begins. In such a case grouting trials are usually conducted during this phase as well. The aim of such “preventive” procedures is to reduce risks later, during execution of the main construction works.

“Intervention” grout injections are procedures which might have already been accounted for during risk analysis (albeit at low-risk), but still may have to be employed in the form of additional or special works (measures). In such cases the design cannot rely on standard explored conditions as would be the case for preventive measures. Pre-grouting trials might not be possible, neither.

In order to determine reach & distribution of grout, the geo-hydraulic fundamentals described in chapter 5, the rheological attributes of the grout itself, grouting parameters and grouting and intervention rules in context of drilling (cluster-pattern or row geometry of holes, depth, inclination and positioning of holes relative to each other) all have to be factored in.

Checklist fundamentals (complete list in appendix A.3.2):

- Grouting targets:
  - Sealing/reduction of water ingress
  - Altering geomechanical characteristics
  - Ground settlement compensation
  - Protection against erosion
- Groutability of the ground
- Suspension and technology used (see also chapters 6.2 and 7.3)
- Geology/geotechnical engineering (see chapters 5 and 7.3.2)
- Hydrogeology (see chapter 5.2)
- Injection parameters and environmental limitations
- Constraints of construction procedures
- Constraints of the construction site

7.2.2. Design goals

Differentiation of design goals for any grouting project mainly follows the respective design phases (figure 6).

The preliminary design study commonly entails the decision if, by which means and to what extent grouting procedures should be part of the overall design. Consequently, construction cost estimates, expected time to completion and risk analysis enter into subsequent design decisions. This requires a viable grouting concept based on the ground model, which needs to be able to provide answers pertaining to questions arising from the aspects named above.

Permit planning (environmental compliance planning) commonly lists all methods and measures as well as expected impacts based on exploratory results as available at the respective points in time. Grouting targets should also be formulated at this stage, but no later than finalization of the tender design.

Planning at this stage should be supplemented by a risk analysis in order to identify and elaborate on possible scenarios.

Tender design has to cover all planned grouting measures in all necessary detail to enable tenderers to submit their own designs, cost calculations and cost estimations. Later it must provide the contractor with all information needed for the actual construction, supervision and invoicing. In this phase of the project, the following must be designed for the most likely case (project scenario), and published accordingly;

- the grouting concept (grouts, grouting pattern, drill method, drill depth, diameter, injection phases, grouting trials, stop criteria, proof of success, etc.),
- a concept concerning plant and equipment, conditions of the construction site, construction phases (sequencing of construction steps) and material estimations (including invoicing concepts)

These need to be designed for the most likely case (project scenario), and published accordingly. To allow for alternate proposals of the contractor or adapting to changes caused by a change in conditions, this design phase should provide a rough framework, rather than a strict tender design. The iterative and interactive character of grouting procedures must never be ignored.

Implementation planning (execution) aims at adapting earlier conceptual design phases and intended monitoring to suit on site conditions.

Additional planning and design for grouting trials is necessary whenever preventive injections are envisaged, in order to verify or optimize designed grouting measures.

These interventional grouting measures need to be adjusted to actual site conditions and adapted to latest findings.

7.2.3. Groutability criteria for soil

For the estimation of the groutability of soil the following 3 criteria have proven to be most useful:

7.2.3.1. Analysis of grain size distribution

The limits of groutability for different grouts in relation to different grain size distributions is classically being determined by a discussion of the results of the so called "sieve analysis". Figure 14 illustrates three areas of possible applications. Results of the analysis of the soil in question should be within the marked areas of Figure 14. This criterion ignores, however, genesis of sedimentation, grain shape, bulk density and specific shapes of particle-size distribution curves.

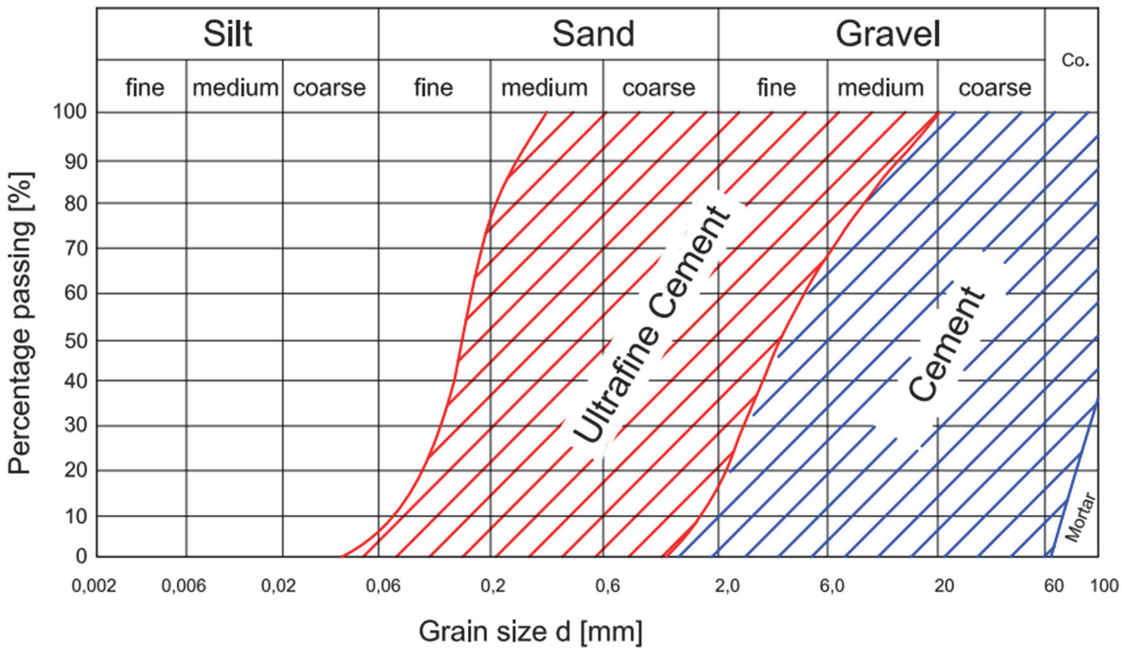


Figure 14. Applications of different grouts according to sieve analysis of the soil (unpublished Leitner, 2016)

7.2.3.2. D15/d85 ratio (N-criterion)

This value reflects the ratio of characteristic particle sizes in the soil and that of a given suspension. This "N-value" derives from the relation of D_{15} of soil to d_{85} of the suspension, and is a filter criterion used to describe empirical penetration limits of specific suspensions in soil.

N: D_{15}/d_{85}
D_{15}: Grain size of the soil at 15% filter pass
d_{85}: particle size in the suspension at 85% filter pass

Ranges of values published for estimating groutability on the basis of this N-value, by various authors, provide a rough assessment only, and are generally of conservative character. It should be noted that with the N-criterion only one value (D_{15}) of the particle-size distribution is being used for evaluation, which leads to limited observational value in the case of wide and intermittently-graded particle-size distributions.

Following N-criteria may be used to assume groutability of the soil:

Table 10. Benchmarks for groutability by author

Author	Groutability		
	possible	uncertain	not possible
Kutzner (1991)	N > 40	-	-
Mitchell (1970)	N > 24	24 < N < 11	N < 11
Sherard & Dunningan (1984)	N > 24	24 < N < 9	N < 9
Kravetz (1958)	N > 20	20 < N < 5	N < 5

For standard cements the following d_{85} values may be representative:

Table 11. Different cements and their particle size at 85% filter pass

CEM I 32.5	$d_{85} \sim 0.043$ mm
CEM I 42.5	$d_{85} \sim 0.025$ mm
CEM I 52.5	$d_{85} \sim 0.020$ mm
Ultrafine binders	$d_{85} < 0.016$ mm available up to 0.006 mm

For a more precise estimation of groutability, more complex procedures – like pore throat distribution – may be considered.

7.2.3.3. Pore throat distribution

This approach was formulated by Schulze (Schulze, 1993) and refined by Schuler and Brauns (Schuler and Brauns, 2000). Using a pore space model allows us to draw conclusions in regards to the effective pore diameters (pore throat diameters) of the soil, and thus of the groutability. This model uses, in contrast to the above N-criterion, the complete particle-size distribution and bulk density of the ground, providing a more precise and realistic approach.

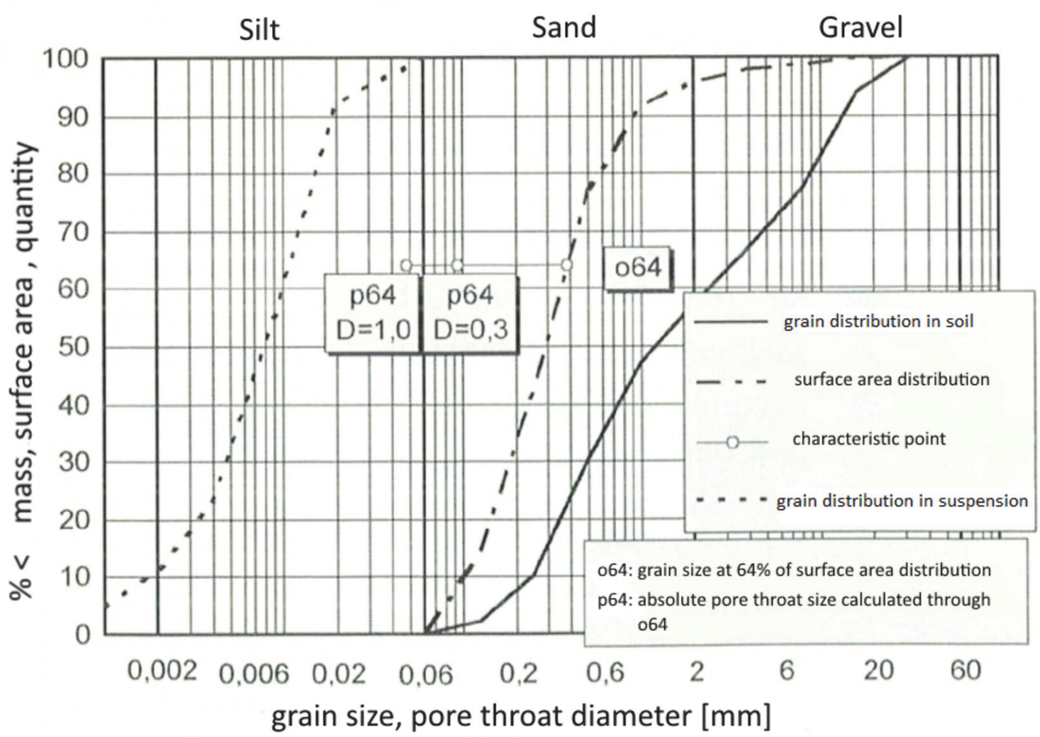


Figure 15. Pore throat distribution (Schuler and Brauns, 2000)

7.2.4. Criteria for the groutability of rock

Figure 16 helps estimate hydraulic joint apertures. Note that hydraulic apertures do not match the geometric (determined during geological investigations) joint apertures. Estimating joint apertures based on hydraulic in situ tests is also done with the intent of finding – in accordance with filter criteria stipulated previously - the largest usable particle size for grouts. Deformation of joints (widening) caused by effective injection pressure must once again be taken into consideration.

Figure 16 is to be read by entering the Lugeon value on the axis of abscissae of the left quadrant. Continuing up vertically until intersecting with one of the reference lines (isotropic/anisotropic), and then projected horizontally until intersecting with the chosen amount of joints per meter, either smooth or rough. This final intersection point, projected down to the axis of abscissae, provides the corresponding hydraulic joint aperture.

Calculations behind the graph - enhanced by discontinuity roughness – are based on the Cubic Law and assume the ideal case of parallel joint planes. Results, therefore, may only serve as approximations for (hydraulic) joint apertures.

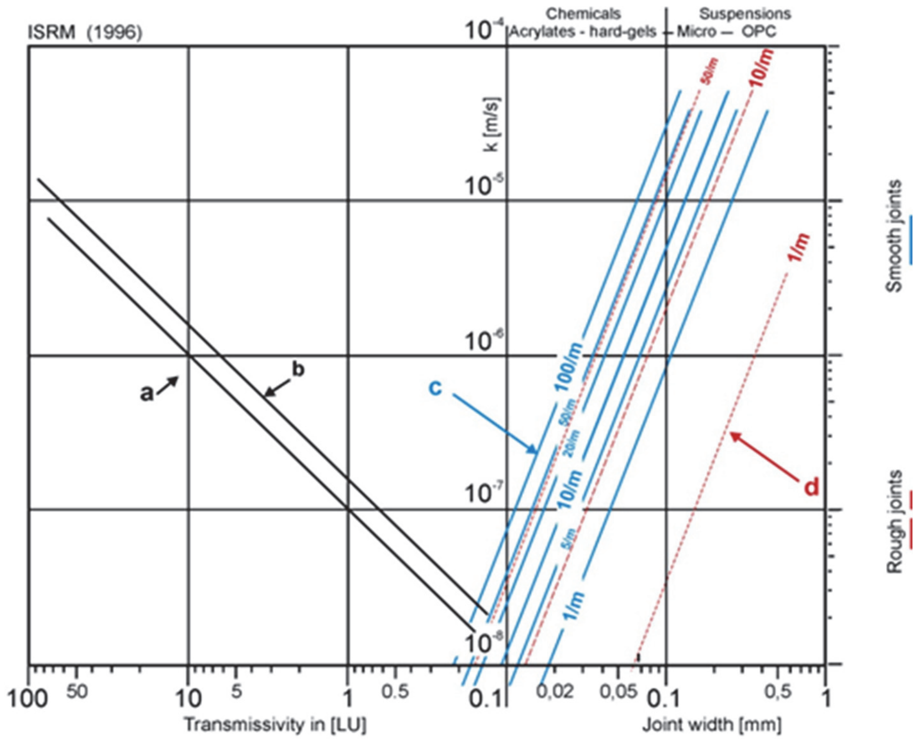


Figure 16. Transmissivity, conductivity and hydraulic joint - aperture (ISRM, 1996)

(a): isotropic conditions
(b): anisotropic conditions
(c): smooth joint planes
(d): rough joint planes

Grouting target and method are also to be defined according to prevailing permeabilities, which significantly influence actually achievable targets (see also table 12). At low initial values (e.g. k_f = 1E-08 m/s) grouting can actually increase permeability in some types of rock, due to new pathways caused by deformations.

Table 12. Empirical target values for permeability in rock (unpublished Stadler, 2016)

Virgin Lugeon kf [m/s]	**Incompetent rock** kf [m/s] achievable	**Competent rock** kf [m/s] achievable
1E-04	8E-09	5E-09
1E-05	5E-08	1E-08
1E-06	1E-07	6E-08
1E-07	3E-07	1E-07
1E-08	5E-07	3E-08

7.3. Grouting principles and methods

7.3.1. Grouting techniques

Table 13 lists the correlation between geotechnical parameters and possible grouting procedures.

For injections in soil, specific details of the particle-size distribution and virgin permeability are decisive when choosing grouts (ranging from chemical products like acrylate resins to mortars) and injection methods (lances, sleeve pipes, etc.). Transitions from effective pore penetration to *claquages* (see also hydrojacking) – and thus soil compaction due to displacement (especially in the case of fines) usually happen smoothly, with stop criteria being discussed in chapter 7.3.3.

Injections in rock also depend heavily on virgin transmissivity values (determined by Lugeon tests) for selecting the appropriate method. In rock however, a distinction must be made between a large number of joints with diffuse water flow characteristics and few, large, discrete joints of equal water flow. Stability of the ground and the borehole need to be factored in as well, since it's possible to either drill to the desired depth and begin grouting, or - as it might become necessary - to drill, inject and re-drill step by step in descending stages in order to complete the procedure. The use of multiple packer sleeve pipes (MPSP) for grouting in stages may also be recommended. Stop criteria consist of a number of different pressure and quantity limits (see also chapter 7.3.4).

7.3.1.1. Soil

Injection holes – supported by drill mud or casing – are usually being drilled at diameters between 76 mm and 140 mm. Project-specific borehole spacing depends on depth of holes, drilling accuracy and the reach of the suspension. Accuracy of drill set-up can be assumed at less than 10 cm. The annular space between borehole wall and sleeve pipe should be filled with low strength sleeve grout - filling the entire length of the annular space, starting bottom up – to avoid grout escaping/travelling in the annulus. Subsequent fracking of this seal mix surrounding the individual sleeves allows targeted grouting of separate stages and multiple re-injections. The use of double packers allows grouting of separate sleeves individually. Sleeve port grout pipes made out of steel or plastic usually come in diameters of ¾ of an inch to 2 inches, and with holes drilled through their walls are regular intervals of 33 cm to 100 cm. Injection lances can be used for special applications. Contrary to the procedures in solid rock discussed below, sleeve pipes can be used for multiple re-injections in several phases, and with different grouts. Borehole spacing ranges between 1 m and 3 m, depending on the k_f-value and results of trial injections.

Table 13. Overview over procedures and methods (Grundbautaschenbuch 6th edition, adapted)

Type	Soil				
	coarse			fine	
Grout ways	pore - penetration			displacement - deformation	
System		temporary			
	permanent			permanent	
Grout mixes				pastes	
	suspensions				
	chemical binders				
	synthetics				
Grouting parameters	limitation of quantity and pressure	grout limited quantities until resurgance or interconnections do occur		energy and displacement criteria	
Procedure	SP-Method	injection using lances	SEMA-Procedure	compaction	frac-grouting
Goal (Sealing or Compacting)	max. pore space filling	partial pore space filling		consolidation, cohesion, friction, uplift	

Type	Rock				
	stable	collapsable		unstable; tect. crushed	
Procedure	void filling (karst/fractured rock)			deformation; penetration	
System				occasionally temporary	
	permanent				
Grout mixes					pastes
	suspensions				
	Microfine binder and chemical grout products (e.g. acrylates/epoxy/plastics)				
Grouting parameters	split-spacing/ from inside outwards/ from outside inwards				
	pressure limitation/ GIN		GIN and saturation critera		
System	upstage	downstage	MPSP	SP-procedure	frac-grouting
Goal (Sealing or Compacting)	max. pore space filling			consolidation , sealing	

Annotations:	
temporary	Commonly used for < 2 years persistance
GIN	limiting grout volume by calculating the product of effective pressure and volume (see EN 12715, Grouting Intensity Number"GIN")
SP-Method	sleeve pipe method
Injection using lances	lances are being drilled or rammed into the ground, forming the injection path. This way entry points are spread along the area to be treated, injection is also possible through holes near the lance tip or through the bottom part of the pipe after withdrawal of the lance
SEMA-procedure	injection during the drilling procedure
Compaction	injection of pastes and mortars via pipes of 3" to 6" diameter. The mixture is being discharged from the open end of the pipe and only penetrates pores marginally
frac-grouting	fracturing by overcoming cohesion, potential tensile strength of the rock mass and load in the ground at the entry point
tect. crushed	crushed into small, jointed rock masses, consistency varies from grainy to very fine, sometimes comparable to mylonization
split-spacing	spacing bore holes (distance between bore holes) of subsequent stages halfway between existing holes of previous stages
outward	borehole clusters (tunnels, embankments, etc.) are filled beginning with the holes in the center
inward	boreholes are filled beginning with the holes furtherst from the center (care not to seal in groundwater by accident)
upstage	sequential filling of a borehole using packers
downstage	sequence of: drilling, placing packer, injecting, hardening, re-drilling, placing next packer deeper
MPSP	multiple-packer-sleeve-pipe
Saturation	degree of void filling achieved; detectable for example by observing change in pressures after stopping the pump (see EN 12715/[3], Transient Pressure Anaylsis "TPA")

7.3.1.2. Rock

Grout holes are usually being drilled without pipes using external hammer percussive drilling, or core drilling with diameters of 46 mm to HQ 96 mm or PQ 122 mm (in the case of double tube core barrels; 101 mm, 114 mm and 131 mm). Sections of unstable boreholes can be stabilized by top-down cementing and re-drilling. Commonly single packers are being used, and where the borehole wall is stable, injections are being executed ascending from toe of the hole to its mouth.

The distinct hydraulic differences compared to soil and the resulting flow paths of the suspension directly impact injection sequences. Design should consider the fact that suspension distribution will usually be limited to discrete joints of greater extent (5 m and more). Due to the possibility of grout bypassing packers, delayed grout set, overlapping of injection reach, grout travel into neighboring holes etc., drilling and injection procedures are alternating processes calling for continuous attention and design considerations. Distances between bore holes commonly decrease phase by phase (split spacing, see table 14), with primary, secondary and even tertiary holes and injection operations.

Table 14. *Guideline for borehole spacing* (unpublished Stadler, 2016)

Rock grouting

borehole spacing [a], borehole length [L], reach = a/2 [R]

Example application: linear curtain/blanket, target $K_f > 5 \times 10^{-8}$ m/s

- Starting from Virgin Lug		100 Lug	30 Lug	1 Lug
- resp. from Virgin K_f	10^{-4} m/s	10^{-5} m/s	10^{-6} m/s	10^{-7} m/s
- Primary	20.0 m	18.0 m	15.0 m	12.0 m
- Secondary	10.0 m	9.0 m	7.5 m	6.0 m
- Tertiary	5.0 m	4.5 m	3.8 m	3.0 m
- Quaternary	2.5 m	2.25 m	1.9 m	1.5 m

- Sedimentary rocks: increase [a]
- Karst: might have to reduce [a] (irresp. of Virgin-K_f)
- Crystalline rocks: [a] as indicated
- For consolidation blankets [a]/[L] varying between 0.8 and 1.5

7.3.2. Grout take and reach

Permeation is directly related to joint apertures, pore throat measurements and connectivity.

Reach and degree of penetration also depends on position of voids relative to bore hole, rheology of the grout, injection pressure, injection rate and duration of the injection procedure.

Based on Lombardi's theoretical considerations (Lombardi and Deere, 1993) the following correlations can be derived:

$$R_{max} = \frac{p_{max} \cdot t}{\tau_0} \quad (6)$$

$$V_{max} = \frac{2 \cdot \pi \cdot p_{max}^2 \cdot t^3}{\tau_0^2} \quad (7)$$

$$F_{max} = \frac{\pi \cdot p_{max}^3 \cdot t^2}{3 \cdot \tau_0^2} \quad (8)$$

τ_0: yield point
p_{max}: maximum pressure at entry point (void)
t: joint aperture
R_{max}: reach in an ideal, horizontally open joint
V_{max}: maximum amount of grout in an ideal, horizontally open joint
F_{max}: lifting force orthogonal to joint plane

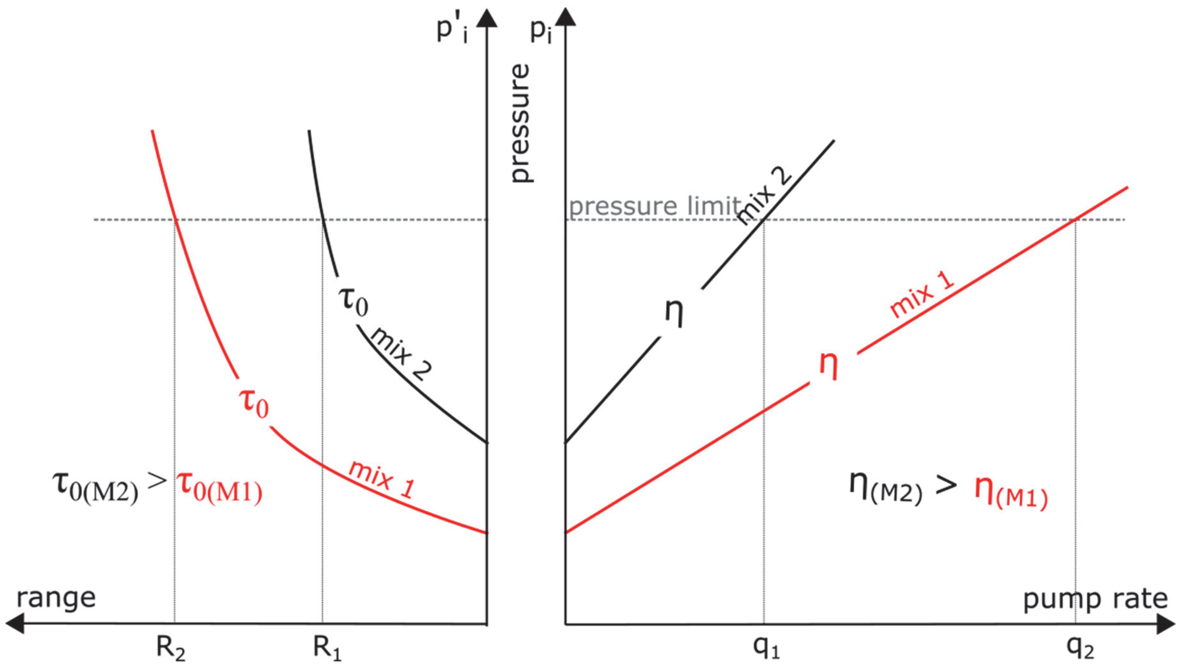


Figure 17. Interactive correlation between injection pressure, yield point, range and rate (Stadler, 2016)

In this schematic example (figure 17) the correlation of reach (R) (stagnation or injection radius), mixture and yield point (τ_0) or viscosity (η) and pump rate (q) can be seen for two different mixtures. Dependencies show the importance of injection pressure (p_i). A high injection pressure leads to higher reach; a low yield point at equal injection pressure leads to higher reach as well.

There is also a sixth parameter; pressure-related widening of a joint or fracture. This means that a chosen injection pressure can change reach, necessary pump time and grout volume.

Grouting design, therefore, requires either data concerning above parameters, acquired from test results during explorations, or suitable assumptions concerning the following items:

- Number, orientation and connectivity of discontinuities (joints, joint sets)
- Hydraulic and physical joint aperture and aperture distribution
- Deformation of rock mass under injection pressure

7.3.3. Stop criteria soil

For determining grout volumes and stop criteria in soil, the following four criteria have been proven very beneficial. They should be considered baseline and need to be specified for any project design accordingly. Illustrating these criteria using flow charts is recommended.

1. Injection stops after reaching planned volumes. Necessary volumes are being calculated with the help of effective porosity (17% to 25%) and tolerance factors for eventual losses, netting a design value of 23% to 30% of total ground volume. Actual grouting volumes for each stage must consider inhomogeneous ground conditions.
2. Injection stops once the maximum injection pressure at the borehole mouth has been reached. This pressure is usually 80% of the frac pressure previously determined by in situ frac tests. Usually these pressures range between 6 and 20 bars at injection rates of 5 to 15 l/min.
3. Injection stops if substantial uplift occurs, which can be measured using surface or down-hole control points. The respective reference points need to be outside the possible area of influence, and measurements must be frequent enough to enable a quick response. Deformation of the ground indicates the degree of saturation, or surpassing of deformation-safe pressure levels. Existing structures demand the utmost degree of care.
4. Seepage onto the surface, into sewers, channels or basements, etc. constitutes cause for an immediate termination of the injection process.

Rarely will dualistic criteria (e.g. GIN, limiting effective energy as used in rock) be used (chapter 7.3.4.4).

7.3.4. Stop criteria in rock

7.3.4.1. Apparent-Lugeon method

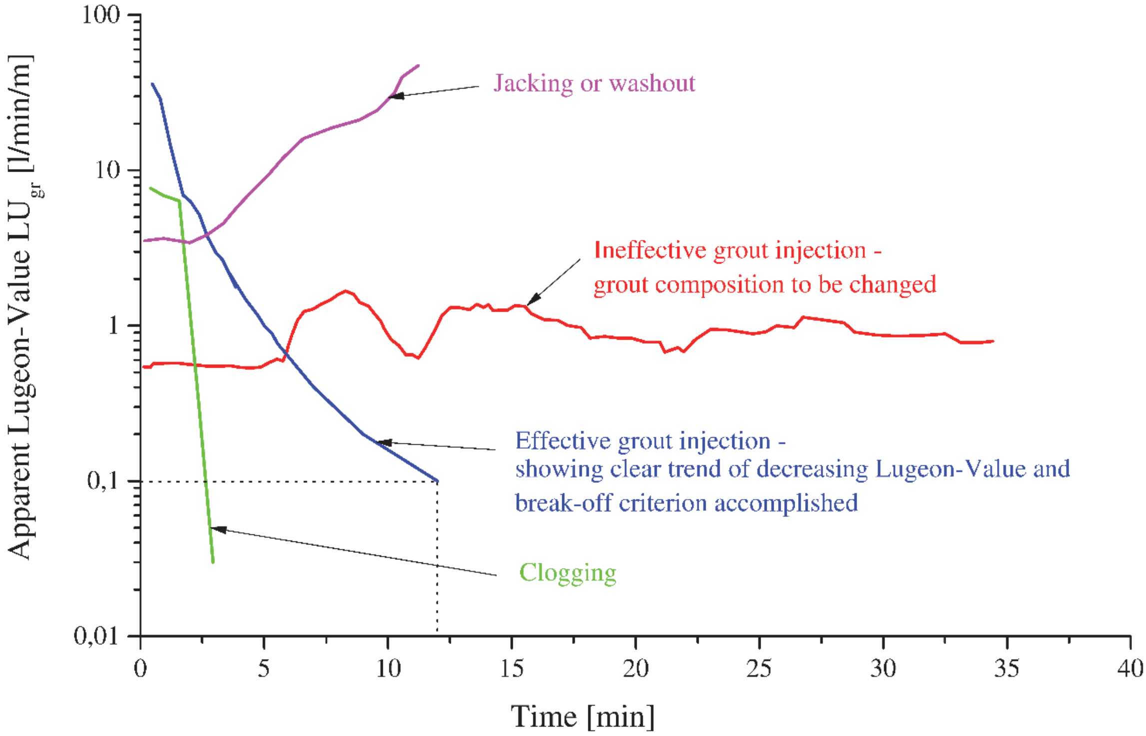


Figure 18. Possible gradients of the apparent-Lugeon value (Gabriel, 2016)

Rock grouting in the US uses the amenability theory under consideration of the apparent-Lugeon value. Rate, pressure and viscosity are being put into correlation with the Lugeon value (l/min/m borehole) using water and a test pressure of 10 bars as reference. The injection itself is being seen as a kind of continuous Lugeon test, replacing a Newtonian fluid (water) with a Bingham fluid (suspension). Flow rate, injection pump pressure during the injection and viscosity of the suspension are being used to calculate the apparent-Lugeon value, and this value is being put into correlation with the value of the initial Lugeon tests. This ratio is then being used to evaluate the suspension's aptitude for the given joint set, which means that the mixture is constantly being optimized. Suspensions are being chosen to be suitable for 75% of all joints, and grouting will be stopped once the apparent-Lugeon value has reached a particular limit. A disadvantage of this method is the fact that instead of dynamic viscosity (mPa∗s) the ratio of Marsh times is being used, which reflects only a fraction (~ 1/50th) of the true ratio. This definitely needs to be taken into account when attempting to interpret target values. Furthermore, this method ignores the effects of widening joint-apertures, and that information gained only reflects conditions in the first few decimeters around the borehole (limited by the permeability response in the immediate vicinity).

$$LU_{app} = LU_{gr} = \frac{q(l/min)}{1(l/min)} \times \frac{1(m)}{L_{stage}(m)} \times \frac{10(bar)}{P_{eff}(bar)} \times \frac{V_{Marsh}(\text{sec})}{28(sec)} \qquad (9)$$

LU_{app}:	apparent-Lugeon value	
V_{Marsh}:	Marsh time of the suspension	(sec)
L_{stage}:	Length of stage	(m)
P_{eff}:	effective pressure	(bar)
	(pressure at the injection pump minus hydrostatic counter-pressure)	
q:	flow	(l/min)

7.3.4.2. q/p – ratio

The apparent-Lugeon method is very similar to the significant-indicator-function of the q/p-specific rate development. In the latter, the rate [l/min] is being divided by the injection pressure at the pump [bar] and plotted along the Q-axis (grout volume), the result is the dotted line in this case. A ratio (rate/injection pressure) between 3 and 5 can be considered for the beginning of a stage with high permeability/acceptance, while a value of less than 0.2 indicates a - relative to viscosity and yield point of the mixture used – saturation of a given stage at the current injection pressure.

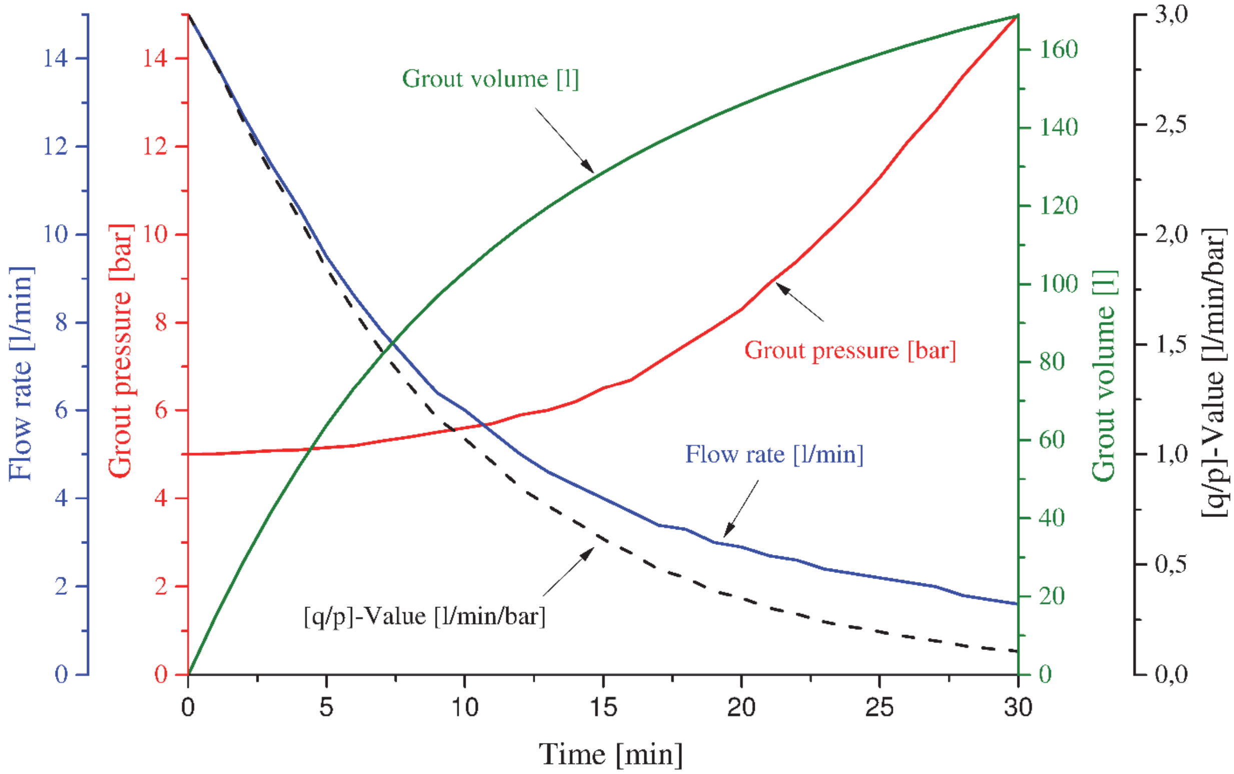


Figure 19. q/p - ratio (Gabriel, 2016; adapted after unpublished note, Stadler and Kutzner, 1991)

7.3.4.3. Real Time Grouting Control (RTGC)

Stille (2015) developed a method in Sweden, which used the results of an analysis of joint aperture distribution based on Lugeon tests, to calculate the reach of a grout for the largest and smallest joint. The application of the differential flow equations for Bingham fluids in a joint lead to the calculation of the theoretical pump time until completion. Injection is stopped as soon as the calculated reach in the smallest joint reaches a target value (minimal spread), or a limiting value in the largest joint (maximum spread). Necessary grout volumes can be calculated using the analysis of the joint aperture distribution. Grouting using the RTGC-Method usually happens pressure-controlled (no constant rate).

Critics of this method argue that the actual joint apertures are not being explored or estimated precisely enough, and that elastic aperture widening caused by the injection pressure (Swedish standard is 50 bars) is not being considered. This method is very much suited for homogeneous, competent solid rock (Scandinavia) but might be less suitable in inhomogeneous masses and in the case of anisotropies.

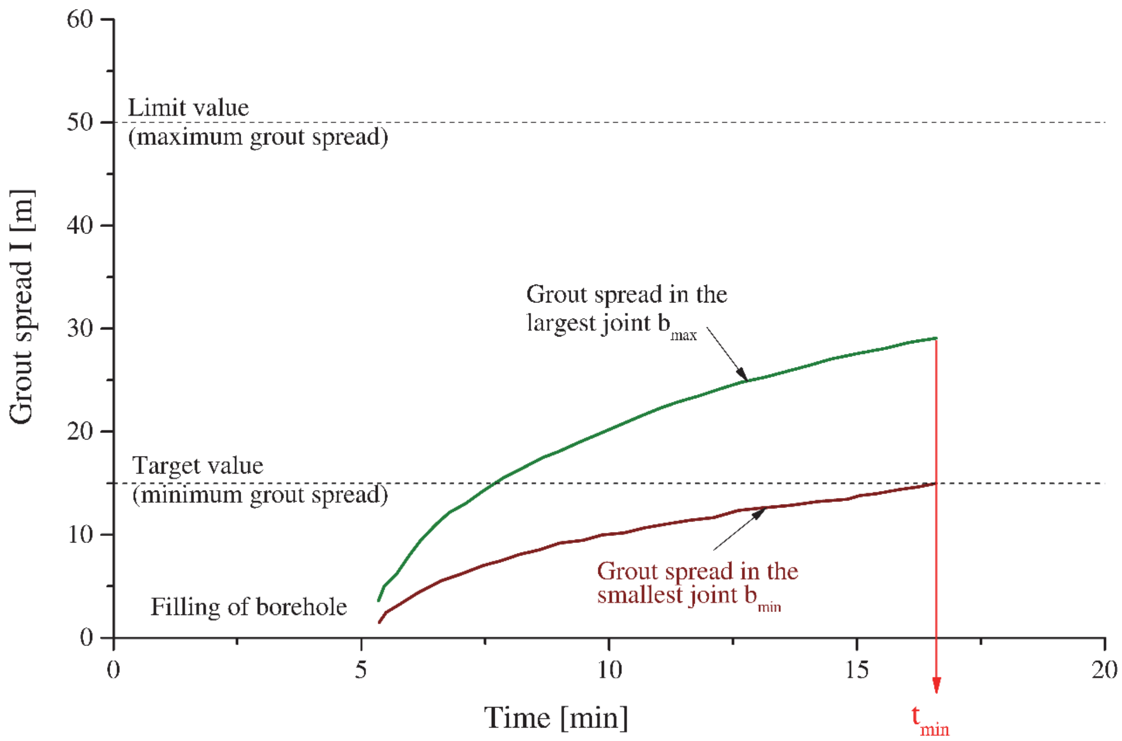


Figure 20. Example documentation for real time grouting control (RTGC) (Stille et al., 2015; – adapted by Gabriel, 2016)

7.3.4.4. Grouting Intensity Number (GIN)

The concept of limiting the energy of an injection per meter of borehole goes back to Lombardi (Lombardi et al., 1993) and is expressed by the Grouting Intensity Number (GIN). This "intensity" can be determined by multiplication of grout quantity (at a given point in time) by grouting pressure measured at the pump, per meter of borehole section and expressed as [bar∗l/m]). GIN-values between 500 (competent rock) and 2,500 (incompetent rock) are recommended. Despite this method owing much of its genius to its simplicity, a number of questions are being critically discussed among experts (in engineering geology): Why limit the energy to meters of borehole and not to the corresponding rock mass of the section in question? How exactly would one identify the difference between the energy necessary for a good grouting effect and a detrimental amount of energy for the relevant type of rock? Why do we use pump pressure for calculations, and not the effective pressure in the joint itself? Since effective injection pressure is representative of conditions inside the joint, it should be used (to better represent actually applied energy values) as input values for any calculation of the GIN-value.

Since the GIN-value limits the energy applied to the rock, any amount of grout used for gravity filling as a (pre-) grouting needs to be excluded from GIN calculations.

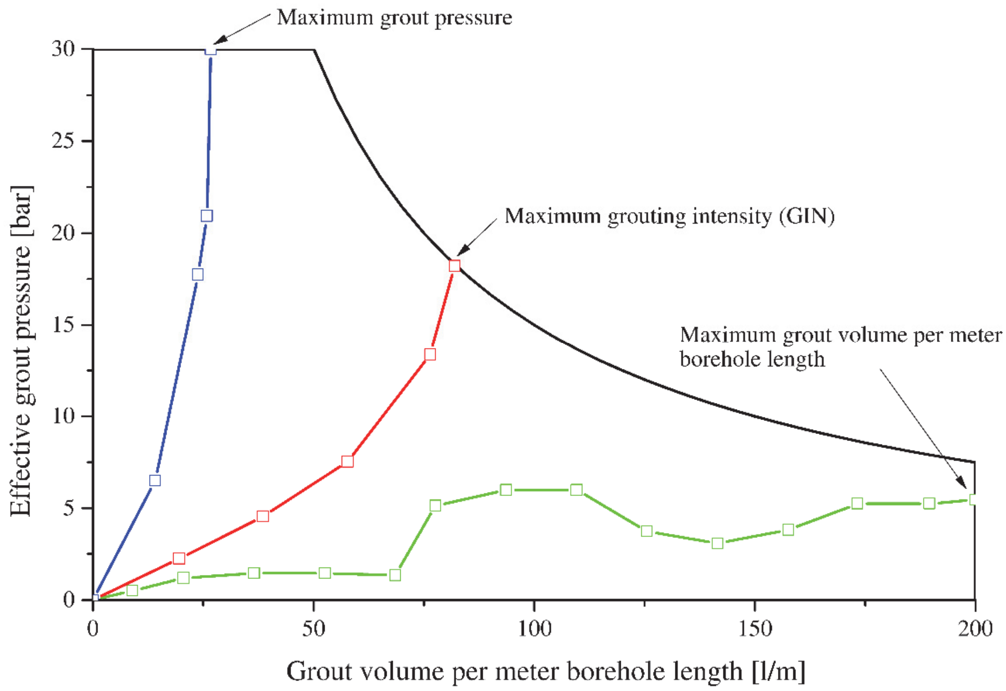


Figure 21. Example of an injection procedure using the GIN method (Gabriel, 2016)

7.3.4.5. Aperture Controlled Grouting (ACG)

Recommended by Carter (Carter et al., 2014) and used for more than 40 years, this method uses joint (fracture) analysis – similar to the RTGC method – and Lugeon tests to determine suitable suspensions in order to achieve a specific target q/p-value (see figure 22). During the injection procedure, pressure and amount of grout are constantly being monitored in order to interpret the ratio of injection rate to injection pressure. Using this method provides the possibility to optimize both suspension and injection rate during the procedure, to reach the target as rapidly as feasible, as well as preventing unwanted hydrojacking or hydrofracking from occurring (figure 23).

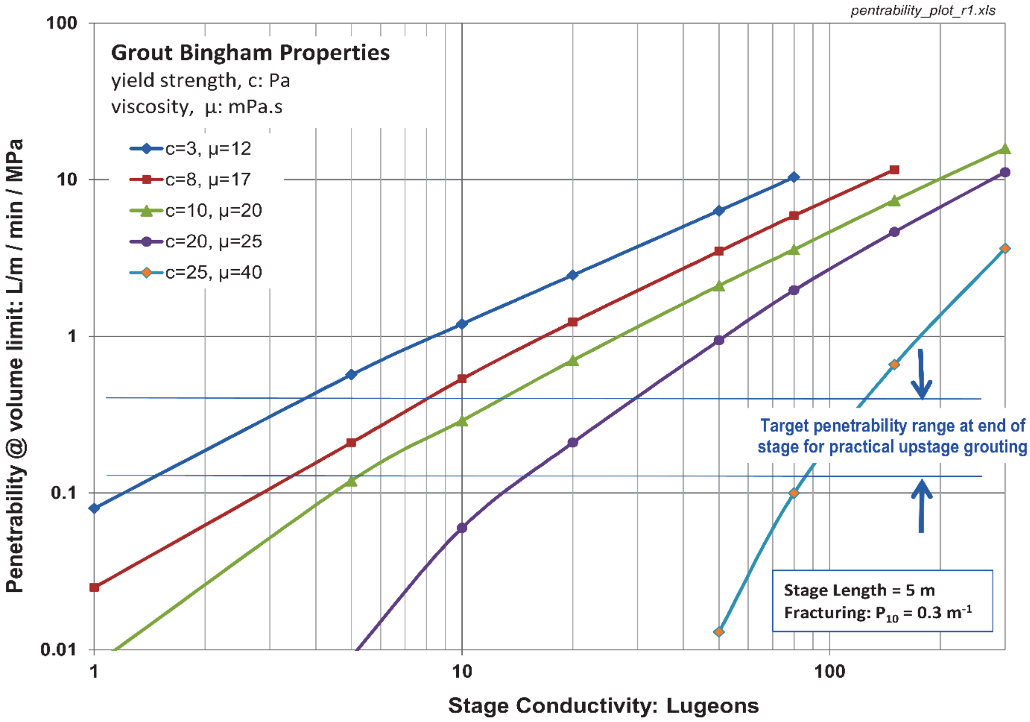


Figure 22. Assigning suspension mixes to permeabilities in different stages (Carter et al., 2014)

This method is a hybrid of some of the stop criteria approaches mentioned in chapter 7.3.4, which might be the reason for the lack of criticism brought forward by experts in the field – as long as on site monitoring can service the complex demands this method entails.

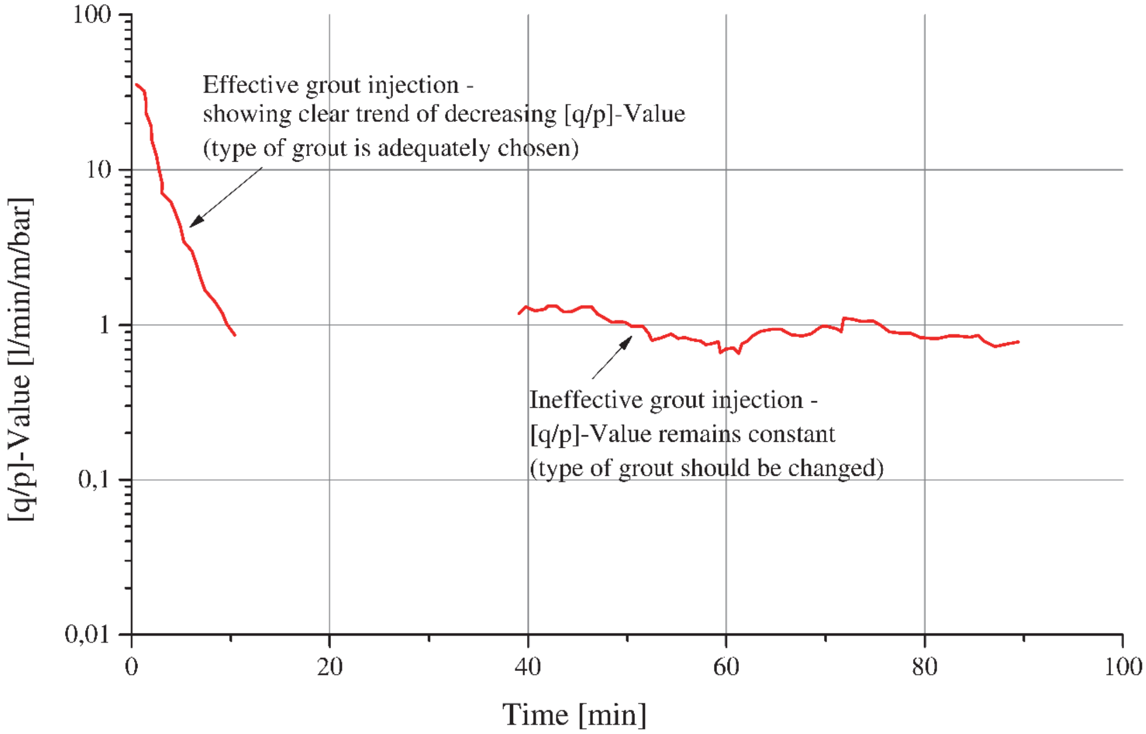


Figure 23. q/p - ratio over time (Gabriel, 2016; after Carter et al., 2014)

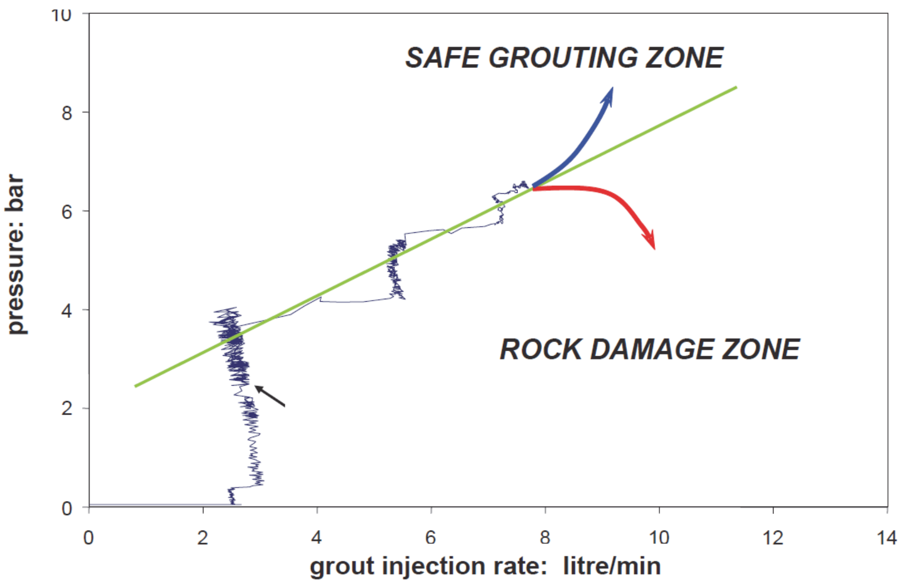


Figure 24. Illustration of an injection. The green line represents the border between safe grouting and damaging rock mass. (Bonin et al., 2012)

7.3.4.6. Transient Pressure Analysis (TPA)

Using pressure drop curves after pump stop (shut-in) not only allows estimating effective in situ pressures, but the shape of the curves (and their relative change over several iterations, see also figure 25) can also provide information about achieved saturation. When the same shut-in times are being applied (about 20s), the relative changes in pressures at [t+t20s] may - even plotting linear charts - denote a possible grout leak or clogging. Additionally, saturation, washout, erosions, fracking or tapering of joints may be indicated. Quantitative indications (using a log-log plot to illustrate the pressure drop curve) on relative permeability or the existence of open or closed boundaries can be detected more clearly using TPA than using other methods (Stadler, 1992; Pollard, 2009; EN 12715).

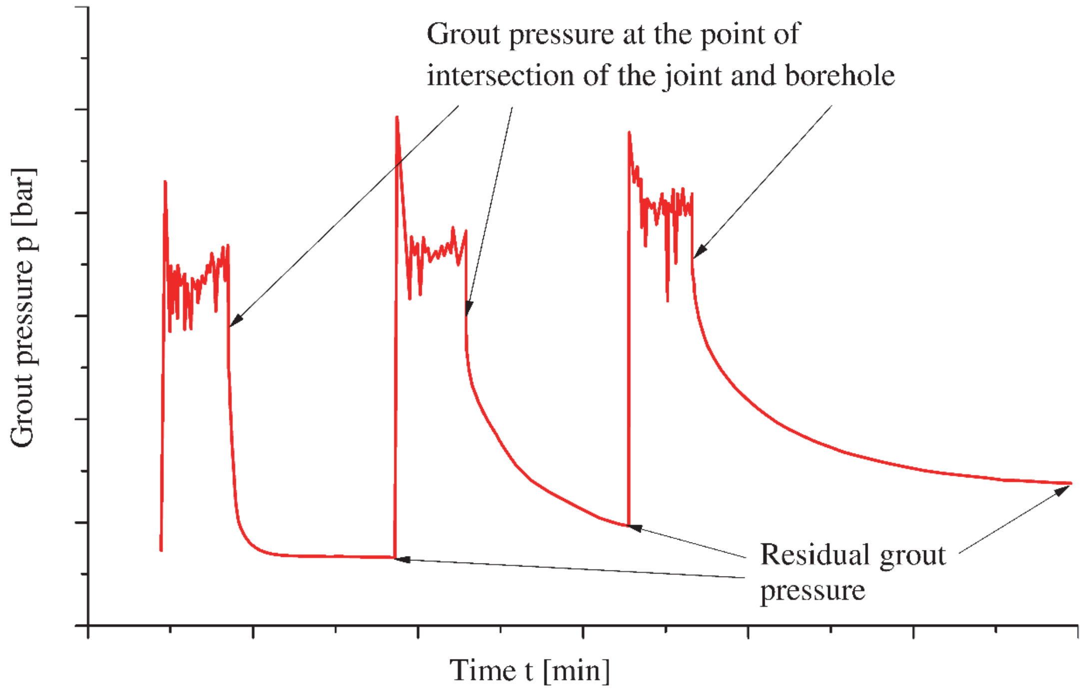
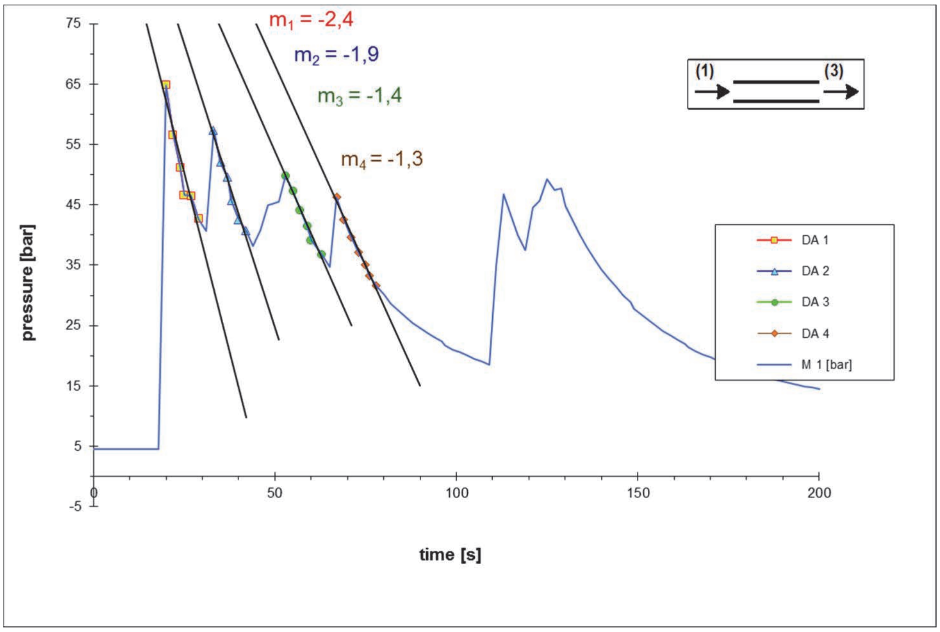


Figure 25. Schematic illustration of injection pump pressure and pressure drop curves (Stadler, 1992; adapted by Gabriel, 2016)

Viability of this method in the field has been proven during the course of projects like Kölnbrein Sperre, AT and Dounreay, UK. Due to the Bingham rheology of the grout it is not possible to derive absolute values for permeability, aperture widening and distance from borehole of a detected phenomenon. Interpretations of sufficient precision for the execution of grouting procedures, however, are definitely possible.

7.3.4.7. Pressure Sensitive Grouting *(PSG)*

Further development of TPA lead to trials proving that the gradient of a pressure drop curve, after stopping the pump, and the pressure at rest at the end of a pressure drop curve could be used to determine pressures and saturations in connected voids. Figure 26 shows the pressure gradient at the borehole mouth to the left with 4 distinct drops ($m_1 < m_4$) in pressure. The second chart shows pressures measured inside a joint during a test. The pressure gradient inside the joint approaches zero, indicating increasing saturation inside the join (M1 = borehole mouth, M8 = end of joint) from first pressure drop (DA 1) to the fourth drop (DA 4).



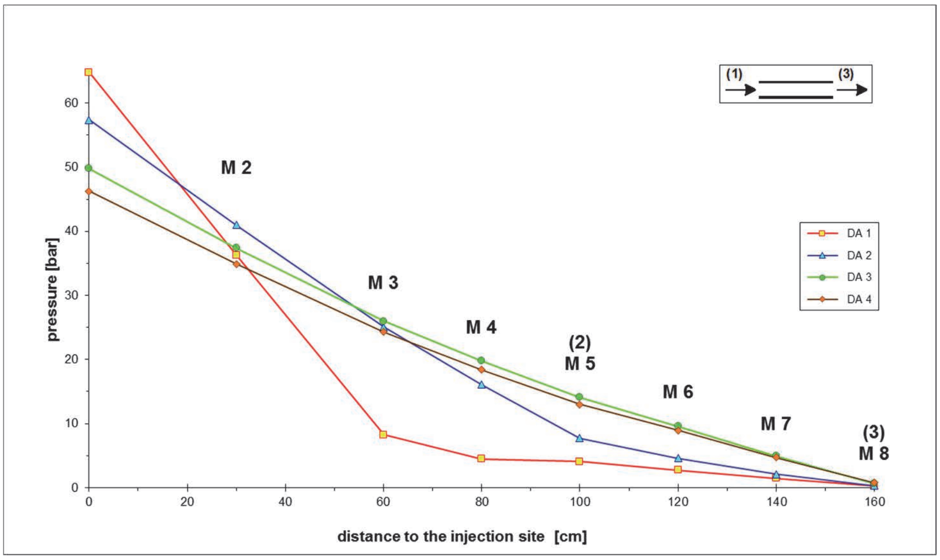


Figure 26. Pressure drops and corresponding pressure distribution in the joint (Reichl, 2000)

It is absolutely essential to stop any and all energy delivery from the pump after initiating a pressure drop. Changes of the gradients (c in figure 27) and pressure at rest (k in figure 27) – pressure drop to pressure drop – don't just indicate increased penetration of voids, but also a possible overload (jacking or even fracking) of the rock. Large voids can also be detected and treated efficiently (e.g. increase in injection rate). PSG can be used to inject every individual stage using the necessary grout volume and injection rate for an efficient and yet safe filling of voids while maintaining target distribution/reach. All four mentioned parameters (pressure drop gradient, pressure at rest [after defined interval, usually 20s], change in gradient between distinct pressure drops and the change in pressure at rest from drop to drop as seen in figure 27) allow the use of a fuzzy modeling for the pre-planning of grouting procedures.

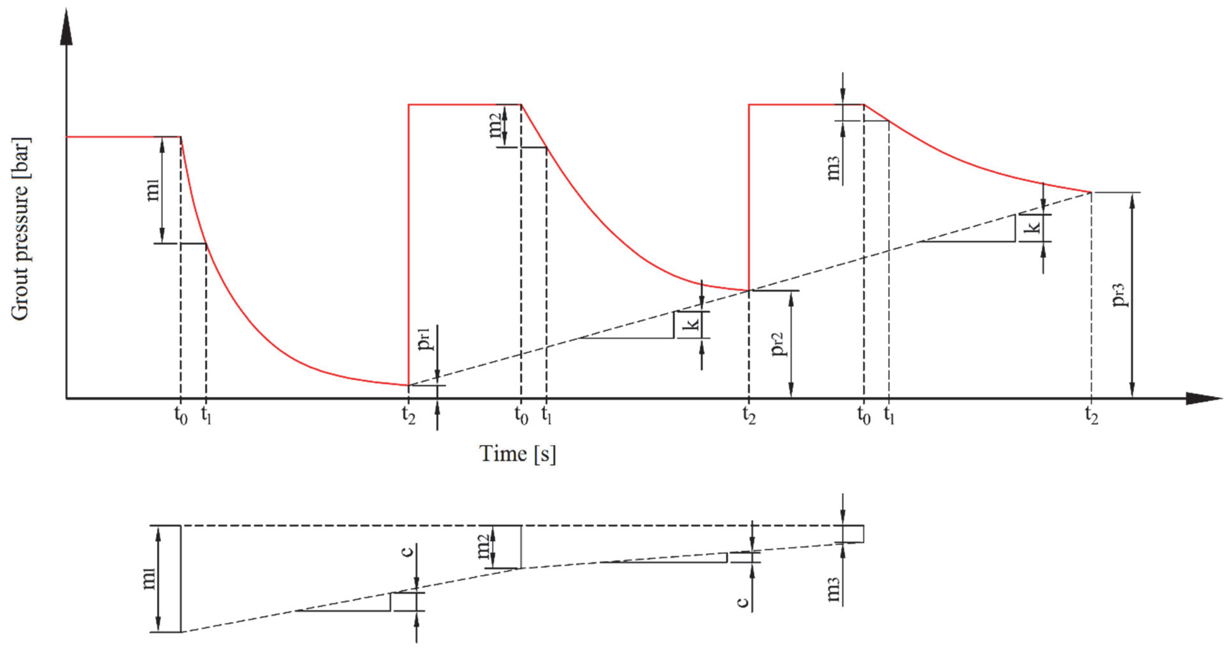


Figure 27. Parameters used to control injections using the PSG method (Reichl, 2000; adapted by Gabriel, 2016)

Injection of a stage is automatically terminated once design targets (adaptable at any time by the designer) have been reached (similar to the GIN-method) and does not require any additional, possibly ambiguous discussion on comparable stop criteria. This method has already been successfully used in several trial applications at the Semmering pilot tunnel.

7.3.4.8. Combining systems and methods

Evaluation methods described in chapters 7.3.4.1 to 7.3.4.7 are based on similar data sets (volume, rate, pressure, pressure at rest, etc.), which are nowadays recorded (mandatory) online on site and thus can be used for all of the abovementioned evaluations.

Combining the above criteria (RTGC, app. Lugeon, q/p ratio, GIN value, ACG, TPA/PSG) provides multiple levels of redundancy and safety/robustness in interpreting data in regards to achieved saturation. Target saturation, detrimental widening (jacking) and washout, grout run-off into open boundaries, achieving (reduced) target transmissivity and many other parameters can be estimated and interpreted just as easily. This combinatorial approach is highly recommended.

7.3.5. Monitoring and control criteria

The design must contain the following provision: during execution (grouting trials and actual injection) grouting data (findings from drilling, Lugeon tests in boreholes, pressure, volume, rate, pressure drop, actual suspension characteristics etc.) must constantly and consistently be evaluated by a grouting expert based on knowledge gained from exploration. Grouting parameters (pressure, rate, volume/stage, suspension characteristics and stop criteria) need to be adapted accordingly. This responsibility and function is comparable to that of the on-site geotechnical engineer in projects following the New Austrian tunneling method (NATM) (see ÖGG 2010 and ÖNORM B2203-1:2001).

7.4. Grout

See chapter 6: Materials and products

7.5. Grout placement

Chapter 7.5.4.1 of the EN 12715 mentions injection pressure, operating pressure and effective pressure. Since all three of these pressures can vary greatly, even effective pressure in relation to the pressure at the borehole mouth greatly varying from stage to stage, a clear distinction must be made both during design and execution. Pressure directly at the pump, pressure at the borehole mouth and the actually effective pressure in the voids need to be properly differentiated. Pressure at the pump and the borehole mouth both can be measured using a manometer. Effective pressure can be interpreted using the pressure drop (chapter 7.3.4.6) by installing a manometer between the pump's pressure valve (or any valve suitable as a shut-off device) and the void. The pump is then stopped and the valve shut off, ceasing any energy transfer by the pump with the effect that the interstitial pressure inside the void may be registered by the pressure gauge after a short time (usually between 20 s and 5 min). Shut- in times exceeding five minutes are only viable in the course of test injections. Note that waiting for more than 5 minutes can cause sedimentation and clogging if cement suspensions are being used. On site injections generally require only a few seconds to pass before receiving viable results.

Effective pressure is being determined by the rheology of the grout, the size and shape of entry points (geometry of borehole intersections with joints), and size and shape of accessed voids.

The boreholes (EN 12715, 7.5.2.7) must be checked for deviations. Grouting parameters (pressure, volume, rate) should be adapted to actual circumstances.

8. EXECUTION

8.1. Drilling

Drilling procedures mentioned in the EN 12715 are of varying precision. This can become rather important past borehole lengths of 30 m, or, for example, when drilling in horizontal clusters - as can be the case in compensation grouting. Vertical drilling, large diameters, low contact pressure and drill string optimization are all factors which can positively impact drilling precision.

Drilling parallel to joints or layers in the ground is not recommended due to poor grout distribution in voids.

Drilling diameters for sleeve pipes are usually between 100 mm and 150 mm. Drilling in rock should generally be done with smaller diameters (36 mm to 76 mm), leading to a beneficial change in grout volume required, since borehole volume in rock oftentimes exceeds void space volume significantly. Better flow rates and a reduced risk of sedimentation inside the borehole are additional benefits, leading to a reduced risk of premature setting in “dead zones”.

Water as flushing media is generally recommended, since it cleans joints and increases grout acceptance. Using pressurized air risks clogging of otherwise open joint geometry.

8.2. Grout preparation

Preparation of suspensions with a water/solids ratio larger than 0.4 can be done with commonly used pumps and mixers. Most important is the proper dispersion of solids in the mixing water by applying necessary shear forces. Intermittent, automatic introduction of constituents into the mixture commonly leads to highest precision rate (< 3%) regarding grout volume during metering.

Suitable mixers should manage one batch of cement suspension in less than 3 minutes (net mixing time of 60 s or more) to avoid a rise in temperature and aging of the suspension. Necessary energy for the preparation of cement suspensions commonly average around 550 KJ/m^3.

Fine and ultrafine binders require a separate discussion.

8.3. Pumping and delivery

The rule of one vent per pump should be maintained for the sake of quality.

Pressure- and rate-controlled pumps for volumes between 3 and 15 l/min and injection pressures between 3 and 35 bars are considered suitable for standard applications. Forcing open sleeve grouts and grouting of very fine joints may require higher pressure of up to 100 bars.

Measuring of pressures (including PTA curve after shut-in) along the injection path can be achieved using digital instruments at a precision of less than 5% of the regular measurements during normal operation. Parameters must be recorded consistently and continuously, independently of pump operations, and records must be accessible digitally (e.g. .csv file) and in paper form.

8.4. Annotations regarding grouting procedures

During planning of grouting procedures an assortment of correlations and interactions must be taken into consideration. It is not possible to account for all possible combinations of events during planning, this means that proper execution on site needs to be emphasized. Certain provisions, however, have proven useful in preparing for commonly occurring phenomena:

- Drilling with ongoing injections in the vicinity can lead to washout of grout by drill mud.
- Groundwater can be closed in by injections and threaten the success of the grouting procedure if a hole cluster is not being injected from the center outwards.
- Flushing of weathering material can – depending on clay contents – be of only limited success. Necessary speeds of turbulent flow are only rarely achieved, even when using pressurized air.
- Due to unpredictable joint aperture distribution in rock, it is often recommended to begin with homogenizing procedures before attempting the grouting procedure.
- Tectonic faults or similar phenomena require special attention when planning the sequence of grouting steps. Depending on the decomposition of the material in the inclusion (ranging from partially coherent fault rock to incoherent, loose material) penetration grouting or consolidation grouting might be advisable.
- Suspensions prepared for injection tend to form thin flow- threads and films when exposed to in situ temperatures (low hydration heat) and to also set rather slowly (in rare cases more than 24 hours, see also hardening test). Controls in situ need to be scheduled accordingly.
- Interactive adjusting of all necessary details, even with detailed instructions at hand, might be necessary at all times.
- Authorities for these interactive changes need to be clearly established (EN 12715 stipulates the involvement of the designer in this regard).

Table 15 might be helpful when planning quantities for rock grouting.

Based on assumptions regarding

- number of hydraulically active joints;
- run-off of grout into adjacent voids;
- the effect on grouting quantities with respect to joint dilation;

Table 15 lists typical values for transmissivity related to total grout volume.

The table also provides information regarding different injection phases (primary, secondary, etc.), their typical sequence – increasing saturation and decreasing acceptance – and progressively finer grouting materials.

Combined with common stop criteria (chapter 7.3.3 and chapter 7.3.4) a preliminary overview for required types and amounts of grout and the resulting construction times can be gained.

Table 15. Estimating material costs for rock grouting

[1]	**Virgin Lugeons**							**>100 Lug**	**50**	**30**	**15**	**<5 Lug**	reach radius [m]	run-off	wedge effect	Nos Frac/m³		
[2]	Starting Mix W/C 1.5:1 OPC; Starting Pressure Pi [bar] at 5 lit/min rate:							0-3	4-8	9-15	16-21	22-30	3.00	20%	2.0	a	b	c
[3]	Fissure width [µm]							300	250	180	120	60						
[4]	Virgin Porosity							0.27%	0.23%	0.16%	0.11%	0.05%				4	3	2
[5]	Porosity grout-volume							0.58%	0.48%	0.35%	0.23%	0.12%						
[6]	Theor. grout-volume m [lit]							**183**	**153**	**110**	**73**	**37**						
[7]	**Grouting target: < 1.0 Lug**	Break off criteria &/or change of Mix & Pressure																
[8]	**pi max < 80% "Jack-Pressure"**	**RTGC**	**appLug**	**TPA**	**GIN**	**q**	**∑eff Vol**	**371**	**309**	**223**	**149**	**74**	% of line [6]	runf-off				
[9]	P-Holes [lit/m]	to=6.ΔP.µg/To#2; tD=t/to; ID=I/Imax	Target Lugeon related to viscosity of mix and pressure		C=P20"TPA*Vol.inj; S-holes=80%ofP; T-holes=75%ofS; Q-holes =66%ofT	either < 3.0 lit/min	or when reaching Volume-Limit:	146	122	88	59	29	80%			OPC		
[10]	S-Holes [lit/m]							92	76	55	37	18	50%	25%		Microfine Cement		
[11]	T-Holes [lit/m]							67	56	40	27	13	55%	33%		Ultrafine Cement		
[12]	Q-Holes [lit/m]							66	55	40	27	13	66%	50%		Chemical Grout		

9. MONITORING, TESTS AND CONTROLS

9.1. Monitoring and controls

Type, extent and accuracy of monitoring should already be laid out during early planning phases and should be detailed and explained in the proposal. They heavily depend on general grouting targets and procedures used.

The presence of an expert consultant during the planning phase, proposal compiling and construction is recommended.

Authority of individual parties fall under the client's coordinational obligations. Suitable tools (i.e. flow charts) should be used to clear up individual competences, hierarchies and flow of information and documents.

Monitoring on site - independent of the party involved (client or contractor), the contract type or the chosen injection process – will always revolve around the execution of a specific project in accordance with project specifications.

On site monitoring mainly entails:

- Control of materials used
- Control of (measuring) tools used, i.e. calibrations and approval certificates of manometer and flow meter
- Control of suspensions used, including their attributes (viscosity, density, yield point, tipping time)
- Control of hole geometry
- Control of injection parameters and stop criteria (pressures, volume etc.)
- Control of the reliability of digital record keeping (comparison of handwritten notes on site to injection protocols)
- General observations; surface deformation, seepage, environmental impacts
- Compliance control
- Control of working hours and crew size

Should on site conditions deviate from those described in plan and proposal documents, then suitable changes in the procedure must be introduced.

The designer and expert need to be consulted. If needed the client must be contacted and make all necessary decisions.

The flow of information and responsibilities between client and contractor, as well as hierarchies, should be stipulated in the work orders.

Monitoring also means controlling the correct implementation of work orders.

All relevant drill and injection parameters must be saved electronically in an editable format. It's part of the duties of construction monitoring to control evaluation and illustration of recorded parameters. The same goes for injection protocols, which need to be compared with plan values – or adapted values. Compliance with stop criteria must also be monitored.

Reliability of data recording must be controlled using hand written notes (covering for example pressures, volume, etc.).

Proof of injection success, defined during planning and stipulated in agreements, will be verified by monitoring as well.

Success of treatment can usually only be proven indirectly, using methods such as the Lugeon-test, dynamic probing, pressure sounding, core drilling, widening of borehole sections, evaluation of grout volume used and the degree of stop criteria reached. Core drilling is usually not an option at this point. Determining cement ratios in samples of injected ground can be used to draw conclusions regarding ground mechanical and geophysical values. Observation of groundwater levels in a larger area can be used to determine the success of sealing treatments.

Feasibility and validity are the most important aspects when choosing a method to proof success of treatment.

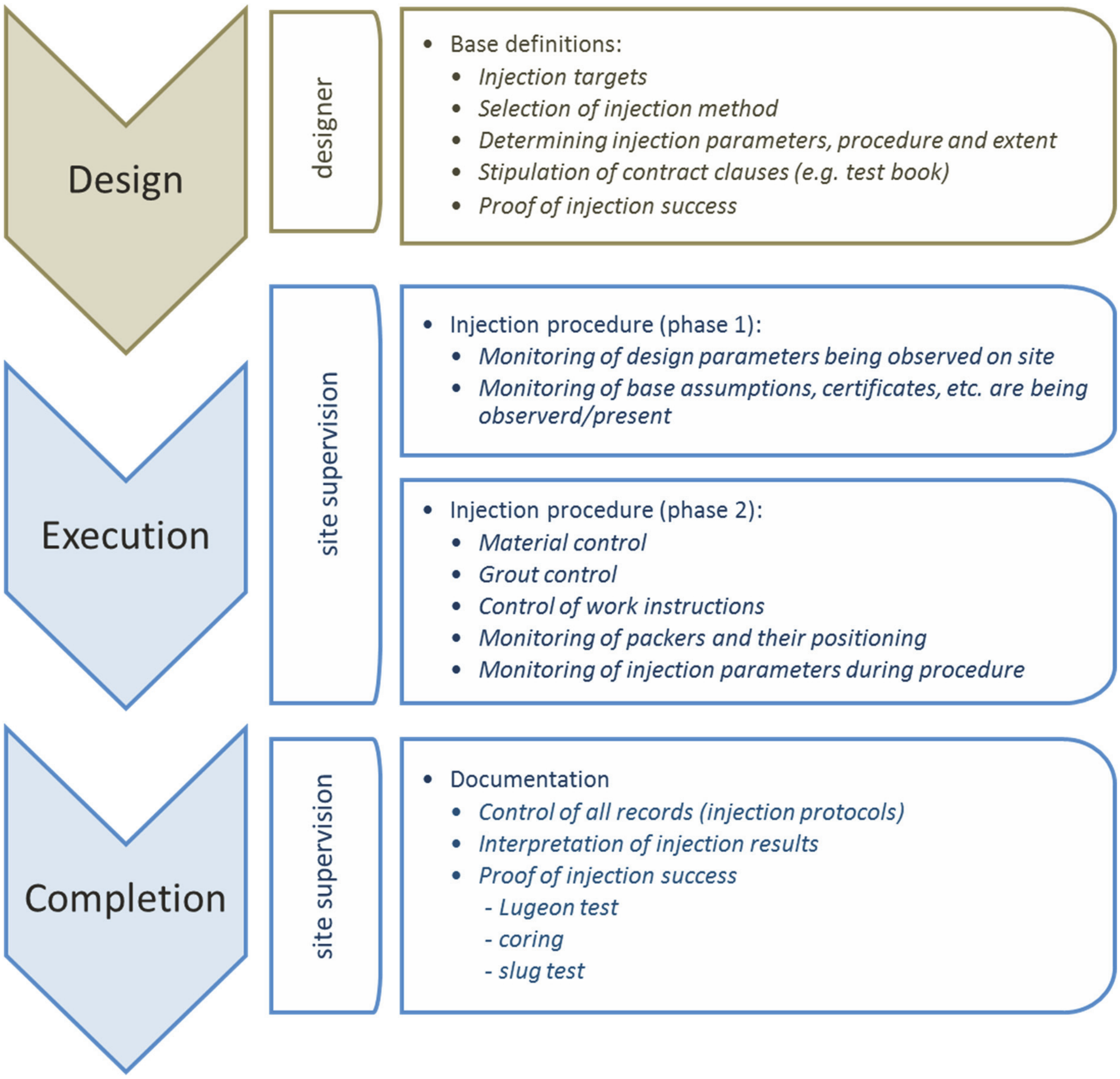


Figure 28. Illustration explaining the responsibilities of site supervision

10. WORKS DOCUMENTATION

In addition to points already mentioned in EN 12715, procedure instructions must contain guidelines for predictable occurrences during the course of trial injections and grouting procedures/programs. Deviations from planned behaviors and how to handle them must clearly be described as such and understood by all parties involved. Procedure instructions must also contain all information relevant to the various parties (from project lead to pump operator) and may contain flow charts. Responsibilities (expertise and authority would ideally be found in the same person) and communication channels must be considered as well.

Records must be evaluated and interpreted by experts (ideally on both client's and contractor's sides). Interpretations are the basis for agreement with or adaption of the procedure instructions. During initial and exploratory phases this evaluation and interpretation must be done daily, with the involvement of designer and geotechnical engineer or geologist.

The following injection parameters must be recorded digitally, and independently of pump operations:

- Pump (number)
- Type of suspension
- Borehole (name)
- Stage
- Pressure (Working pressure, even better pressure at borehole mouth)
- Rate [l/min] and
- Grout volume [l]

Together with a timestamp [date; hour:minute:second] this data should be sent to the client in an editable file format (e.g. .csv). Such records are indispensable for later evaluation of injection targets.

Surface leakage of ground water in boreholes needs to be documented; volume (l/s or min), pressure, temperature and if applicable pH-value and conductivity are to be recorded.

All data, especially grouting pressure (injection pressure at borehole mouth, even better: pressure at rest), grout volume and stop criteria (leakage, degree of stop criteria reached) have to be recorded and illustrated succinctly (three-dimensionally where applicable) and relative to the position of planned construction.

11. SPECIAL ASPECTS

No additions at this point.

12. COMPENSATION MODELS

Some aspects relevant to both productivity and costs cannot be described with sufficient precision during design phase, or comprehensively described without ambiguity when compiling specifications and schedules of rates. Among those aspects are the number and degree of utilization of pumps (and simultaneous use if applicable), also specific weight of suspensions, pumping rate and stop criteria during design. The type of compensation for grouting works should, therefore, always take a degree of uncertainty into account. All-inclusive (lump sum) pricing should, consequently, be considered an exception and an undue risk-transfer onto the contractor.

Existing guidelines recommend the following forms of compensation for construction works depending on type, extent, quality and circumstances of execution:

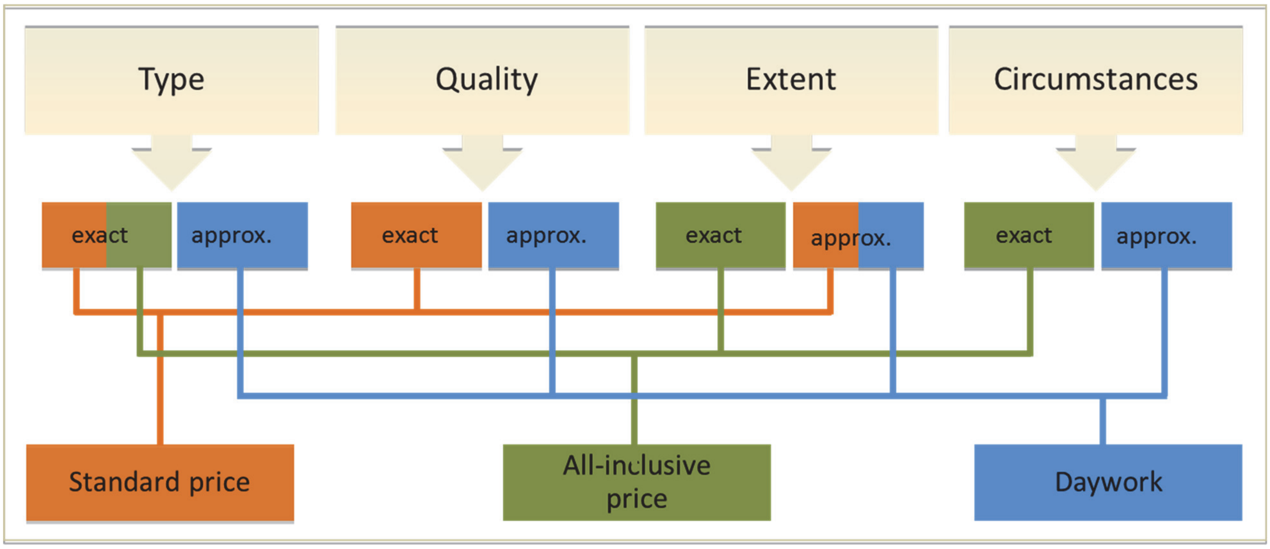


Figure 29. Selection of contract type depending on the quality of information available (Ganster, 2001)

When drafting contracts for grouting works the need for explicitly introducing time-related items becomes evident quite quickly, not the least since predictions concerning type, quality, extent and circumstances are commonly difficult to predict. Client decisions affecting execution must be considered also.

Depending on (increasing) depth and precision of exploratory measures employed or, (increasing) exertion of influence by the client on matters concerning execution, alternative compensation models may become viable. These models may range from all-inclusive pricing to daywork - compensation (including company markups).

Table 16. Contract type vs. information available (Regie = Daywork) (Stadler and Semprich, 2009)

	Influence on design →							
Source/ Titel		**LS**		**DIN 18301&09**	**ON 2270**	**"STILFOS"**	**Regie**	**DCRC**
Payable - Items	functional	/m^3 Ground /lm Tunnel	/lm Drilling /m^3 Ground /Test	/lm Drilling Pump-Hour /Test Materials	GSE; /Mo /lm Drilling Pump-Hour Materials /Test	GSE; /Mo Rental; /Mo. FieldPersonnel; /h Production; /Item Materials Energy, etc.	GSE; /Mo Rental; /Mo. FieldPersonnel; /h OperativeTimes Materials Energy, etc.	Directly-Attributable-Costs-Reimbursement-Contract; plus Fee for General Expenses
	←						*Intensity of exploration*	

The more a client influences construction and procedures and the less the depth and precision of investigation results, the larger the degree of uncertainty when it comes to estimating all relevant costs.

Compensation models thus range from

- problematic functional tendering or all-inclusive prices,
- standard unit-price definitions as found in DIN 18301 (and the former ON 2270), to
- production- and time-related compensation (working title “StilfOs”) or
- classic daywork
- to a direct cost reimbursement contract.

Kirsch and Bell (2011) propose a standardized service schedule (Schedule of Rates) consisting of a mixed approach (day work, standard unit-prices and all-inclusive prices = lump sum). Their suggestions are a solid reference point for both structure and amount of detail necessary (see also appendix A.3.1).

13. APPENDIX

APPENDIX A.2 (INFORMATIVE) Measurement of grout parameters

Appendix A.2.1: GIN value

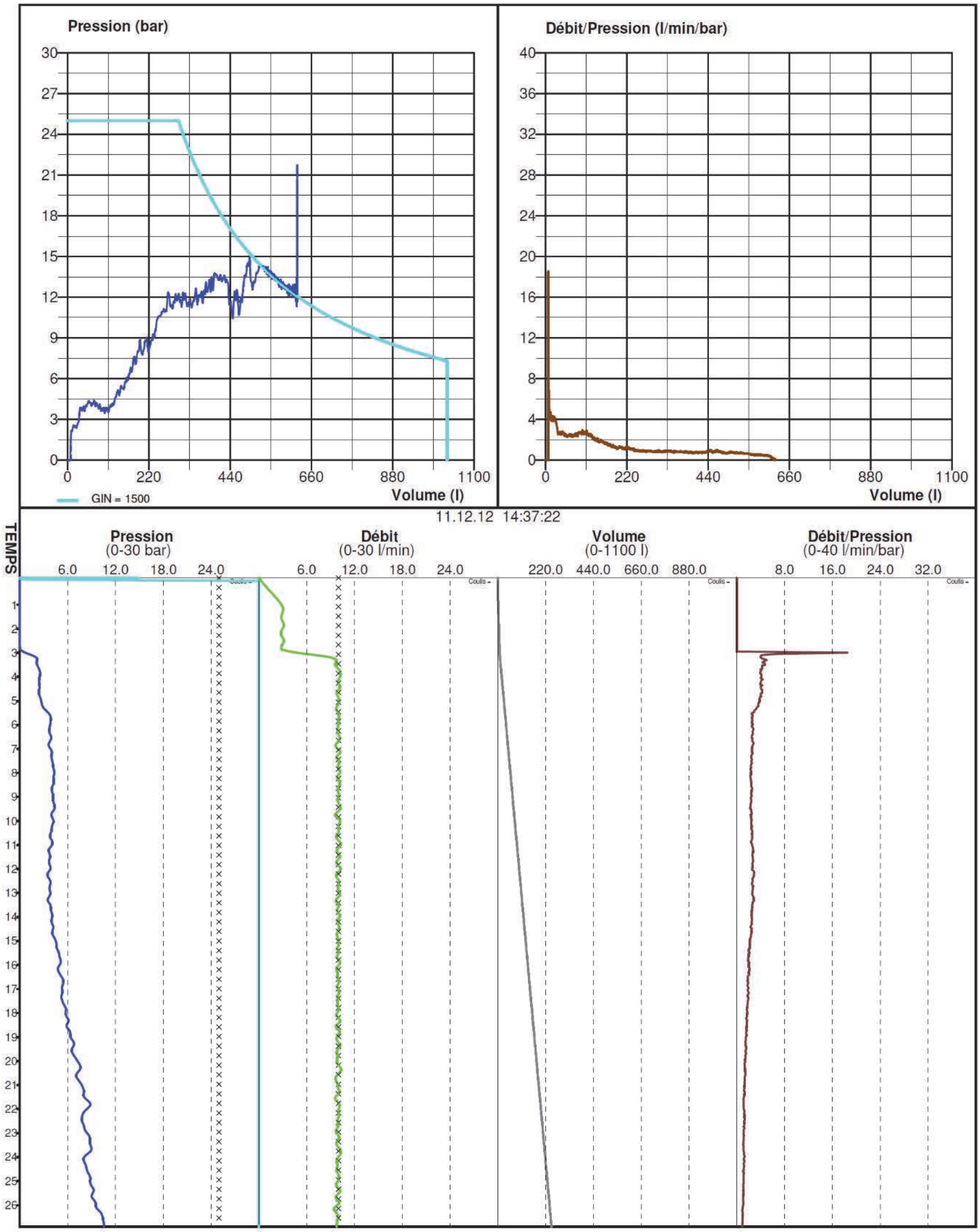
Appendix A.2.2: Pressure/volume ratio

APPENDIX A.3 (INFORMATIVE) Proposed service schedule

Appendix A.3.1: Proposed standard service schedule for grouting procedures

Appendix A.3.2: Design checklist

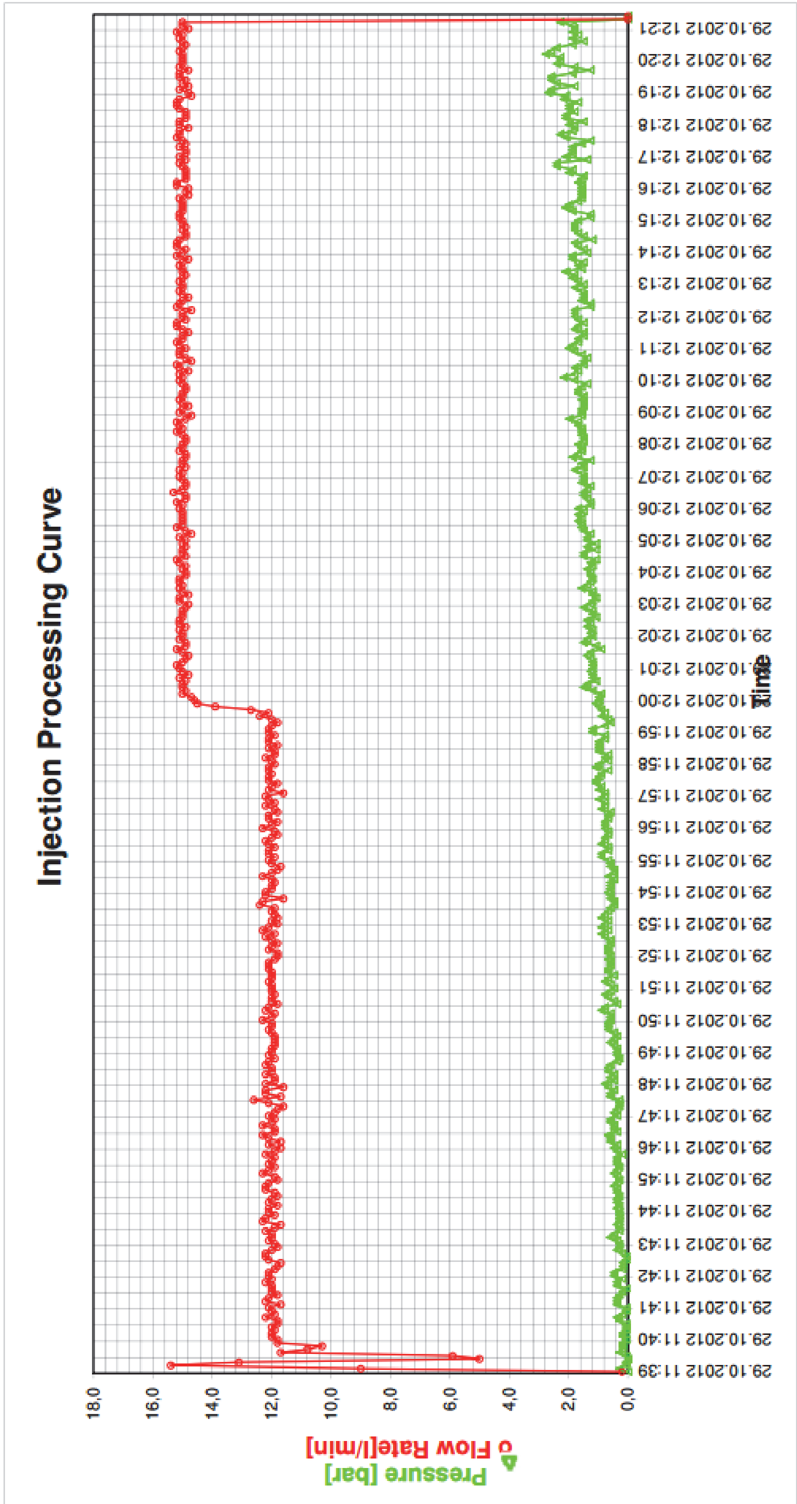
APPENDIX A.2.1: GIN VALUE BY LOMBARDI



APPENDIX A.2.2: PRESSURE/VOLUME RATIO

Grouting Diagram

Site Name:	Compensation Grouting York University						Device:	Hpi6	
Zone	Section	Sub-S.	Borehole	Sleeve	Step	Actual V	Target Volume	Start	End
S	Sh2	U	207B	1	1	574	574,00	29.10.2012 11:39:00	29.10.2012 12:21:17
Depth	Mixture	End Pressure		Average Pressure			Burst Pressure	Comments	Duration
15,66	1	1,8		0,9			2,3	OK	0:42:17



APPENDIX A.3.1: Proposed service schedule for grouting procedure

Item No	Group	Main	Sub	Unit	Quantity	Price	Item Price
1.01	Mobilization, site installlation, demobilization	General site installation	Offices, store, personnel W/Shop, vehicles, etc	LS			
1.02		Rigs & equipment	Mixing/batching plant	LS			
1.03			Drill rig (Type)	LS			
1.04			Grout pump (single, containerised)	LS			
1.05			Testing unit	LS			
1.06		Additional units	Type as above or other specified	LS			
1.091	Relocating rigs & equipment (Type)	Within project area	Per item 1.02-1.06	LS			
1.092		From site to site	Per item 1.02-1.06	LS			
2.01	Rental of equipment	General site installation		Cal. week			
2.02		Rigs & equipment	Per item (as above)	Cal. week			
3.0	Idle-/downtime (as specified)	Personnel (Category)	on site	Man hour			
4.00	Setup & rigging drill over hole						
4.01		incl displacing rig >2.5m		no.			
4.02		without displacement of rig		no.			
5.00	Drilling for coring or grouting, in all types of ground, all directions and inclinations, collaring <2,0m above working area						
5.01		Coring 75-115mm					
5.011			0-15m	m			
5.012			15-30m	m			
5.013			30-60m	m			
5.014			Extra over for casing	m			
5.02		Roto-Percussion drilling 56 bis 76mm					
5.021			0-6m	m			
5.022			6-12m	m			
5.023			12-20m	m			
5.03		Over burden drilling 115 to 133mm (in loose ground)					
5.031			0-15m	m			
5.032			15-30m	m			
6.01	Supply, install and sheath grout sleeve pipes (tubes a manchettes)	MS 2" dia, port distance 66cm		m			
6.02	ditto in HDPE			m			
6.03	Supply, maintain, position and remove	Packers: all dia, all depths					
6.031		Single packer		no.			
6.032		Double packer		no.			
6.033		MPSP-inflatable packer		no.			
6.034		Circulation-packer incl return line		no.			
6.035		Inflatable double-packer for tubes a manschettes					
7.0	Operating grout pump, incl weighing, batching, storing, ducting of grout mixes of all kind, operating grout pump under pressure, electronic data acquisiton	Documentation of pressure, rate and quantity as per EN 12715 requirement					
7.01		Hour operation of one only (first) pump		h			
7.02		Hour operation of a second pump at same site location, simultaneously with operating the first pump		h			
7.03		Hour operatione of a third pump at same site location, simultaneously with operating the first and second pump		h			
8.0	Material for grout mix						
8.01		OPC (Blaine >3.900cm²/g)		to			
8.02		UFC (D_{80} < 12µm)		to			
8.03		Sodium-Bentonite		to			
8.04		Calcium-Betonite		to			
8.05		Sodiumsilicate (liquid, 38° Bé)		kg			
8.06		PU (single shot)		kg			
8.07		PU (two-component mix)		kg			
8.09		Acrylate-(asper tenderers proposal)		kg			
9.0	Borehole test	Water pressure test in rock (Lugeon), permeability test in loose ground (Lefranc), incl all pumps, ducts, packers and data recording/documentation, all depth		no.			
Total, net				Currency			

APPENDIX A.3.2: DESIGN CHECKLIST

The checklist contains absolutely essential items.

In order to plan grouting procedures, either quantifiable exploration data covering all important aspects needs to be provided, or reproducible deductions need to have been made.

Success of treatment can usually only be proven indirectly, using methods such as the Lugeon-test, dynamic probing, pressure sounding, core drilling and widening of borehole sections, evaluation of grout volume used and the degree of stop criteria reached. Gaining usable samples from injected bodies is only rarely possible.

Feasibility and validity are the most important aspects when choosing a method to prove success of treatment.

<u>Checklist Design:</u>

- Grouting targets:
  - temporary or permanent
  - sealing / reduction of water ingress
  - change of geomechanical characteristics
  - subsidence compensation
- Proof of treatment
  - methods and procedures
- Topography:
  - depth of host medium
  - primary stress ratios
- Geology/geotechnical aspects (see chapters 5.1, 5.3 and 5.4):
  - rock classification according to the guideline for the geotechnical design of underground structures with conventional excavation (ÖGG, 2010)
  - deformation of the ground, joint/fracture characteristics under pressure
  - schematics illustrating anticipated grout distribution (chapter 5.3)
- Hydrogeology (chapter 5.2):
  - ground model including: water and/or suspension permeability in rock; number, orientation and connection of discontinuities, hydraulic and geometric apertures, deformation of rock mass under pressure
  - ground model including permeability profile in soil
  - water flow
  - groundwater pressure
  - permeability, transmissivity, Lugeon value
  - groundwater flow velocity during injection
  - water chemistry
  - environmental factors
  - groutability/penetrability of the ground (Newton liquids vs. Bingham liquids)

- Drillability of the ground:
  - possible drill systems and speeds
  - recording of parameters during drilling
  - borehole stability
- Injection parameters:
  - working injection pressure, effective injection pressure
  - injection rate, maximum volume/stage
  - stop criteria
  - rule set
  - grout (e.g. binders, resins, foams)
  - determination of rheological suspension mixes
  - drilling scheme, injection sequence
- Boundaries and limitations:
  - statutes and limitations concerning grouting and environment; allowable products and impacts (temporary/permanent)
  - construction method; above ground, underground, during which stage, e.g. excavation
  - Infrastructure, space constraints, temperature, waste disposal

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