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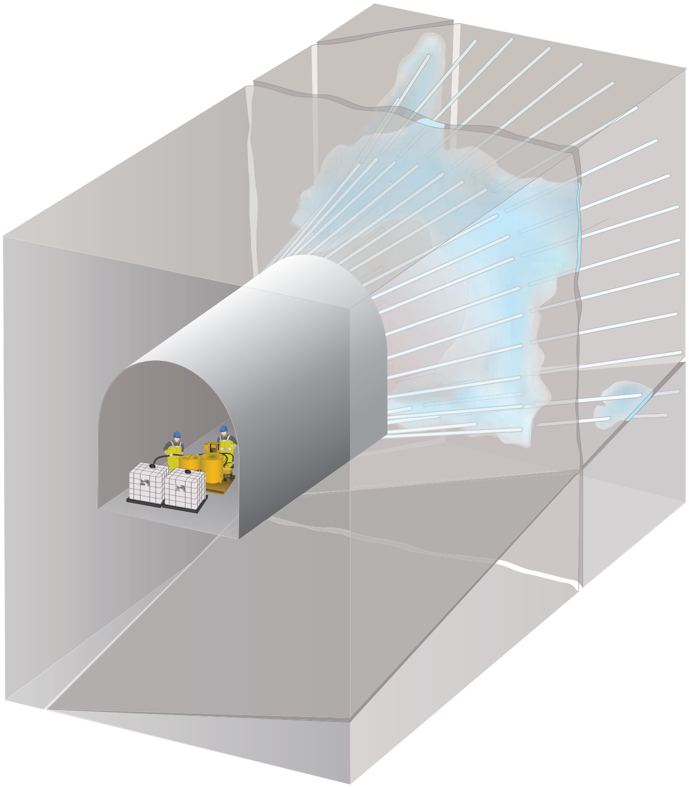

GUIDE TO GROUTING WITH SILICA SOL

– for sealing in hard rock

Johan Funehag

BeFo Report 118

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Karin Holmgren, Chalmers University of Technology

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GUIDE TO GROUTING WITH SILICA SOL
- for sealing in hard rock

Handledning för injektering med silica sol
- för tätning i hårt berg

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In memory of Professor Gunnar Gustafson

This guide is founded on, and a result of, the driving force of an incredible person and his capacity to understand problems. Gunnar Gustafson had a rare entrepreneurial spirit that allowed us to constantly reach out and apply the results of our research.

His death is a great source of sorrow for the industry but his energy and inspiration will remain within us for a long time to come.

Foreword

Grouting research has been part of the BeFo programme for 30 years and is an important part of Scandinavian rock construction. Carefully executed grouting is a cheaper alternative to sealed lining. Stricter stipulations regarding low ingression levels are pushing up the cost of grouting, making cost calculation more difficult. Grouting largely takes place in conjunction with rock extraction. The lifespan of the grout is affected by the groundwater, possible stress movements, the materials used and the design that is adopted. Many of these factors can be influenced and there is a demand for greater predictability and a better financial outcome for grouting. Grout that fails to harden or flows back could result in erosion of the grout and deterioration in the quality of the work. Strength is linked to groundwater pressure and fan geometry in the grouting design. The threshold for how watertight the rock can be made without lining is being raised constantly. Research in recent years has led to a new type of grout, silica sol, which when used correctly offers excellent functionality. It was introduced onto the Swedish market as a grout for hard rock in 2002 and since then it has been used in several tunnels. The grout is suitable as a complement to traditional cement grouting in order to meet strict water ingression stipulations in tunnels. The aim of this current project is to provide a guide to grouting with silica sol. The guide is aimed at contractors, consultants and clients. The purpose is threefold: to provide a design and implementation tool for industry, to address the problems that could arise and to present measures that can be taken to rectify such problems. The guide summarises the research that has been conducted in this area, in particular at Chalmers University of Technology, as well as the projects in which the University has been involved.

The reference group that contributed to the project comprised Gunnar Gustafson, Chalmers University of Technology, Bjarne Liljestrand, STRABAG, Magnus Zetterlund, Vattenfall, Kenneth Rosell, Swedish Transport Administration, Hans-Olov Hognestad, BASF, Inger Jansson, Eka, and Mikael Hellsten, BeFo.

Stockholm, October 2012

Per Tengborg

Sammanfattning

Föreliggande rapport är en redogörelse av kunskapsläget vid dags datum i hur man bör injektera med silica sol i hårt berg. Den innefattar både resultatet av flera teoretiska studier samt erfarenheter från ett antal genomförda projekt där silica sol använts som injekteringsmedel. Rapporten kan ses som en handledning ämnad för beställare, konsulter and entreprenörer i hur man utför en silica sol injektering. Den beskriver projekteringstegen, utförandet samt hur styrning på plats görs. En del som tidigare inte rapporterats så ofta är de problem som kan uppstå vid en injektering and är i denna rapport framlyfta för att åskådliggöra vilka val entreprenören måste göra.

På senare tid har kraven på täthet vid tunnelbyggande skärpts väsentligt. De täthetskrav som ställs, ibland mindre än någon liter per minut and 100 meter tunnel, samt beställarens egna funktionskrav på dropp and dylikt har medfört att konventionell förinjektering med cementbaserade injekteringsmedel kan bli otillräcklig. Om en hydraulisk sprickvidd ner till ex 30 µm måste tätas innebär detta att ett annat injekteringsmedel än cement behöver användas alternativt kompletteras.

Ett miljömässigt bra alternativt injekteringsmedel som klarar de högre täthetskraven jämfört med de traditionella cementbaserade injekteringsmedlen är kolloidalt kisel, dvs. silica sol. Silica sol är en kolloidal lösning av silikapartiklar i vatten. När silica sol blandas med exempelvis vanligt koksalt startar en reaktion and partiklarna bildar bindningar mellan sig. Silica sol har ett helt annat beteende jämfört med cement. Forskningen har, liksom för konventionell cementinjektering, visat att sprickvidden, injekteringstrycket and tiden har stor inverkan på injekteringsresultatet men för silica solen har dessutom geltiden stor betydelse för utförandet and resultatet. De praktiska fördelarna med silica sol, förutom inträngningsförmågan, är uppenbara när det kommer till att styra injekteringsmedlets geltid. Med silica sol kan geltiden styras and därmed injekteringstiden per hål från några minuter till flera timmar, om så är önskvärt.

Den styrbara and snabba viskositetstillväxten kopplas till inträngningslängden via den hydrauliska sprickvidden, injekteringsövertryck and geltid på silica solen. Med vetskap om vilken minsta sprickvidd som behöver tätas för att klara inläckagekravet kan en härledbar injekteringsdesign upprättas där den använda injekteringstiden kan förutsägas.

För att injekteringen skall bli så effektiv som möjligt bör utrustning and genomförande anpassas. I de hittills genomförda projekten har en traditionell cementinjekteringsutrustning använts med framgång. De problem som observerats under en silica sol injektering beror på stora injekteringsvolymer, återslag eller ytläckage. När sådana problem uppstår måste designen uppdateras. Denna handledning ger förslag till sådana uppdateringar, i huvudsak bestående av förändringar i tryck eller geltid.

Nyckelord: Design, handledning, berg, tunnel, injektering, silica sol

Summary

This report is a summary of current knowledge of how grouting in hard rock with silica sol should be performed. It includes results from several theoretical studies and experience from different tunnel projects where silica sol has been used. The report can be regarded as a guide for clients, consultants and contractors to what silica sol grouting means in practice. It describes the design stages and execution and how the work can be directed and controlled on site. Problems encountered during grouting is an area that has not been particularly well reported in the past. These problems are highlighted in this report to show all the choices the contractor needs to make.

In recent decades, the stipulations regarding ingression of water into tunnels have become stricter. The stipulations, sometimes less than one litre per minute per hundred metres of tunnel, together with the client's demands regarding functionality for the permitted number of drips, have meant that at times traditional cement grouting has not been adequate. If, for instance, a hydraulic aperture of a fracture down to 30 µm needs to be sealed to meet the stipulations, a grout other than a cement grout needs to be used or used as a supplement.

An environmentally sound alternative that meets the strict stipulations regarding water ingression is colloidal silica, i.e. silica sol. Silica sol is a colloidal mixture of silica particles in water. When silica sol is mixed with, for instance, ordinary table salt (sodium chloride, NaCl) a reaction starts and bonding between the particles commences. Silica sol behaves in a totally different way to cement grouts. Research has shown – as is also the case for cement grouting – that the fracture aperture, the grouting pressure and grouting time all have a specific role to play in the grouting result. In addition, the gel time for silica sol has an impact on both the execution and result. The practical advantages of silica sol, apart from excellent penetrability, are obvious when it comes to controllable gel times, controllable penetration lengths and grouting time. The controllable gel time and the rapid increase in viscosity are linked directly to the penetration lengths via hydraulic aperture, grouting pressure and gel time. With knowledge of the minimum fracture aperture that needs to be sealed, a deducible grouting design can be computed where the grouting time taken can be predicted.

To achieve efficient grouting, the equipment and execution need to be adapted. In the projects carried out so far, traditional grouting equipment for cement grouts has been used successfully. The problems encountered during grouting with silica sol are large grouting volumes, backflows or surface leakages. The challenge lies in the fact that the proposed design cannot be adhered to and updates needs to be made. In this guide, suggestions are made on how to update the design, basically consisting of changes in pressure and gel times.

Keywords: Design, guide, tunnel, hard rock, grouting, silica sol

Nomenclature

Description	Designation	Unit
Penetration length	I	M
Maximum penetration length	I_{max}	m
Relative penetration length	I_D	-
Estimated conductivity, ungrouted	K_0	m/s
Estimated conductivity, grouted	K_{inj}	m/s
Section length	L	m
Inflow	Q	m^3/s
Transmissivity, ungrouted	T_0	m^2/s
Transmissivity, grouted	T_{inj}	m^2/s
Fracture aperture	b	µm
Fracture aperture, dimensioned	$b_{dim,}$ b_{crit}	µm
Hydraulic fracture aperture	b_{hyd}	µm
Rock cover	d	m
Earth's acceleration	g	m/s^2
Ingression before grouting	q	m^3/s, m
Tunnel radius	r_t	m
Borehole radius	r_w	m
Time, dimensionless	t_D	-
Time, relative grouting time	t_0	s
Gel time	T_G	min
Gel induction time	t_G	s, min
Thickness of grouted zone	t	m
Hydraulic gradient	dh/dr	-
Density, rock	ρ_b	kg/m^3
Density, water	ρ_w	kg/m^3
Grouting overpressure	Δp	Pa
Groundwater pressure	Δh	Pa
Flow limit, grout	τ_0	Pa
Skin factor	ξ	-
Viscosity, water	μ	Pas
Initial viscosity, silica sol	μ_0	Pas

Contents

1 Background

Water ingression stipulations in conjunction with tunnel construction have become considerably stricter in recent years. The underlying reasons are stricter environmental requirements coupled with the realisation that lowering the groundwater level around the tunnels frequently results in damage to buildings. The water ingression stipulations, at times less than a litre or so per minute per 100 metres of tunnel, as well as the client's own functional drip stipulation and other requirements, have meant that conventional pre-grouting using cement-based grout could prove insufficient. A method developed at Chalmers University of Technology (Gustafson et al, 2004) shows how a pre-grouting design can be produced that is predictable in terms of result and resources. The design is based on the hydraulic fracture apertures along the tunnel and that the tunnel water ingression stipulation is predetermined. By sealing all fractures down to a certain fixed hydraulic fracture, the ingression stipulation can be achieved. If a hydraulic fracture aperture down to 30 µm needs to be achieved, cement-based grout would need to be replaced or supplemented by grouts that meet the strict ingression requirements. This could involve sealing a borehole with a high ingression with cement and sealing boreholes with a low ingression with the alternative grout. The ingression thresholds are unique to each tunnel and depend on a number of factors, including groundwater pressure and the distribution of the fracture apertures. This guide will deal mainly with how grouting using silica sol should be performed and how the basic design is prepared where the decision reached is that silica sol must be used to satisfy the ingression stipulation.

An environmentally sound alternative that meets the strict stipulations regarding water ingression is colloidal silica, i.e. silica sol. Silica sol is a colloidal solution of silica particles in water. When silica sol is mixed, for example, with sodium chloride (ordinary table salt), this causes a reaction and the particles form compounds. The relationship between the mixture of silica particles and saline solution governs how quickly silica sol gels. The mechanism behind the gelling and how the particles bind to each other is not understood entirely. How the gelling affects the penetration length in rock fractures is described in this report.

As silica sol behaves totally differently compared with cement, the grouting process ought to be adapted specifically to silica sol. Research has shown – as is also the case for cement grouting – that the fracture aperture, the grouting pressure and grouting time all have a specific role to play in the grouting result although for silica sol the gel time is also of major significance to performance and result.

1.1 Aim of this guide

The aim of this guide is to describe the guidelines that are currently available with regard to designing, planning and executing grouting using silica sol. This involves the gel times and grouting pressure that need to be used in relation to the required penetration length and the apertures of the fractures. The resource and equipment requirements also need to be examined as well as carrying out, in practice, batch pumping and grouting and the equipment required for this process. It also includes a description of how continuous pumping takes place as well as the key features necessary to control the process.

We can expect silica sol or a similar grout to be used in the future as a complement to cement-based grout. It is therefore imperative that the industry complies with the recommendations that have been issued and that have been developed to date and that there should be an exchange of experience from one project to another.

Colloidal silica has yet to be tested in conjunction with large flows in crystalline rock and consequently this area is not covered in this guide. The guide generally covers rock with fine fractures, defined here as rock with hydraulic fracture apertures of less than around 200 µm.

The guide is divided into three sections. Part 1 is a description of silica sol; Part 2 deals with the execution; Part 3 covers design and planning. Different sections are suitable for the different parties in a project, e.g. client, contractor and planner.

2 The material

2.1 What is colloidal silica?

Colloidal silica is the collective name for stable solutions of particles made up of amorphous silica dioxide, SiO_2, which is dispersed in water. The size of the particles can be up to around 500 nm. Silica sol is a subset of colloidal silica where the particle concentration and particle size have been limited. A common silica concentration is approximately 40% (the largest volume that can be obtained as a stable solution) and the particles are approximately 20 nanometres in diameter. They are stabilised in the water solution with the aid of cations (Na_2O). The production of silica sol is often based on sodium silicate through dilution with water and an acid or a base. The solution then passes an ion exchange material where the sodium content falls dramatically. At this stage, a silicic acid sol is obtained comprising monomer silicate ions that are further modified (build up particles) in a reactor into a desired product where the pH, temperature and pressure can be changed. The way the process or polymerisation can be controlled towards achieving a desired product is presented in Figure 2-1 below.

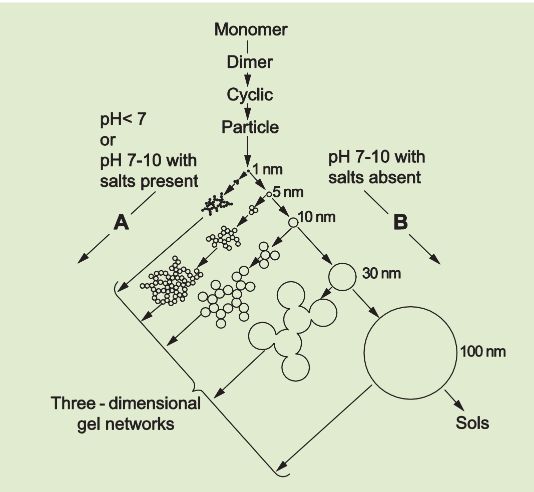

Figure 2-1. Polymerisation of silica sol. In an acid solution, or with salts present, the particles form a gel (A). In an alkaline solution, the particles grow in size but fall in number (B). From Iler (1979).

A monomer molecule, SiO_4-tetrahedron, begins to react and is bound to other molecules, producing a dimer, i.e. a molecule with two similar units. Further binding produces a cyclical chain and the result is a particle. Once the particles have been formed, there are two ways to obtain the desired product. In the event of a surplus of monomers, a pH lower than 7 or a pH of 7-10 with no salts present, the particles grow in size. If salts are present and the pH is 7-10, the particles will aggregate and form a gel. This final process (A) is used when we use it as a grout, i.e. we add a saline solution. The volume of added saline solution governs the gel time – the more salt that is added the shorter the gel time. The initial product can thus be determined, which in simple terms means the size of the particles that are desired. A smaller particle size produces a higher specific surface and is thus more reactive. Normally, a particle size of 16-20 nm is used where the particle size distribution ('fan curve'), varies depending on the product. It should be borne in mind that the natural condition of silica sol is a gelled state and the processes that take place to keep it liquid are controlled. This means that the grout has a 'use-by date', at which point the properties deviate significantly from the original properties. The 'use-by date' is set by the manufacturer and must always be checked before the product is used.

The practical advantages of silica sol, apart from the penetration capacity, are obvious when it comes to controlling the gelling time of the grout. The technique for conventional grouting, i.e. the pressure and grout that should be used and how the stop criteria are designed, is normally based on past experience. Furthermore, the planned time for grouting has not been known. With silica sol, the gel time can be controlled and the grouting time per hole can vary from a few minutes to several hours if preferred. The gel time also controls the penetration length in that a short gel time produces a short penetration length and vice versa. In certain cases, the aim is to limit the penetration length to minimise usage and wastage in conjunction, for example, with surface leakage and post-grouting situations. Figure 2-2 shows how the viscosity growth appears for different mixing ratios with the saline solution. Initially, silica sol has a consistently low viscosity (approximately 10 mPas, water = 1 mPas). After a certain period of time, the viscosity increases substantially and silica sol sets to a firm gel.

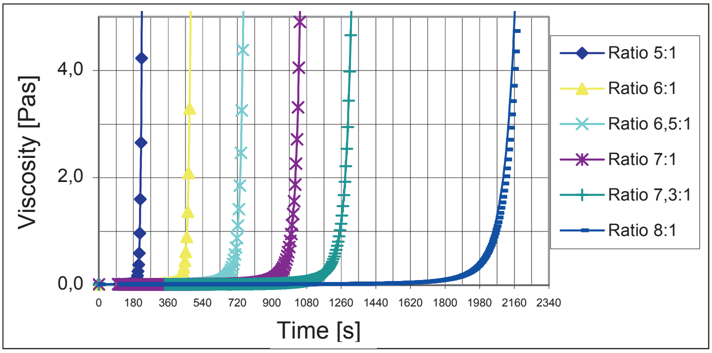

Figure 2-2. Viscosity curves for a silica salt product at different mixing ratios (based on weight) for the saline solution at a temperature of 8°C.

2.2 Available products

The commercial products made from silica sol that are available in Sweden are mainly Meyco MP320 and Meyco MP320T. At an early stage in the development of silica sol there was also Meyco MP320C, which is free of biocides (anti-mould agent) as well as silica sols intended for research purposes, such as 'Eka Gel Exp 36' and 'Cembinder U22', which are identical to Meyco MP320C but under another name.

Meyco MP320 is at present the most common product and is manufactured in Sweden. MP320T is manufactured mainly in Germany and the difference between these MP320s is that the particle content is only 30% compared to the Swedish level of 35-40%. Nowadays, there is also Meyco MP325, which has an even lower silicon content, 15%.

2.3 Silica sol, penetration and sealing properties

Properties in silica sol related to grouting:

- Penetrability into small fractures
- Flow properties/rheology, i.e. viscosity and gel time
- Gelling
- Longevity
- Sealing/*in situ* permeability

The penetrability capacity depends largely on the particle size. As the silica sol particles are small, 5-100 nm, the penetrability is initially good even in the smallest of fractures. The good penetrability decreases as soon as the particles begin to form larger networks in conjunction with gelling. Consequently, grouting should commence immediately after mixing the saline solution, which starts the gelling, in order to retain good penetrability.

The flow properties, the rheology, describe the flow properties for a fluid, in this case the grout. Silica sol behaves in the same way as a 'Newtonian fluid' for large parts of the flow process and for a Newtonian fluid the viscosity is the only material parameter that describes the flow properties of the fluid. By comparison, a cement grout is normally described as a 'Bingham fluid'

As soon as the gelling starts, the grout will acquire the properties of a Bingham fluid, i.e. with the material parameters viscosity and flow limit. The exact border between a Newtonian fluid and a Bingham fluid is difficult to determine and is basically a question of definition. In practical terms, it is not of major importance. Figure 2-3 below illustrates the difference between a Bingham fluid and a Newtonian fluid.

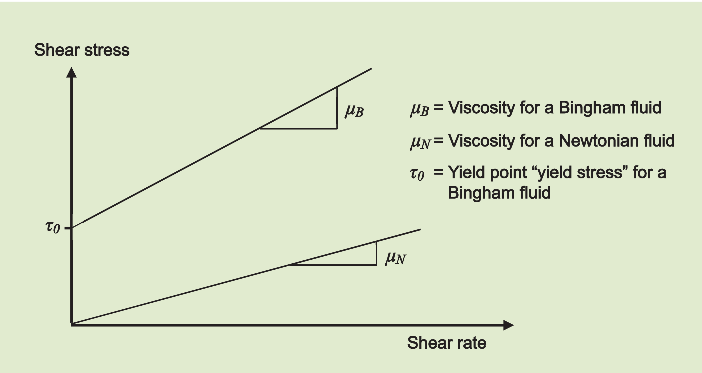

Figure 2-3. A schematic graph to illustrate a Newtonian fluid and a Bingham fluid as well as their rheological difference.

The difference between a Newtonian fluid of the silica sol type and a Bingham fluid of the cement type is that the Newtonian fluid comes into motion immediately the shearing force is exerted. In the case of a Bingham fluid, the exerted shearing speed must be greater than the shearing stress of the grout, known as the flow limit. In the same way, once the shearing force falls below the flow limit, the material stops. For a Newtonian fluid, the material always moves as long as the shearing stress is acting on the liquid. The gradient of the curve in Figure 2-3 is the viscosity. A material with a high viscosity flows more sluggishly or slowly than a fluid with a lower viscosity at the same exerted shearing speed. For a gelling liquid, the mobilised shearing stresses along the penetration length are balanced by the exerted pressure. Finally, the shearing stresses along the penetration length will be equal to the pressure and the liquid will stop. Such a penetration curve is shown in Figure 2-4 below.

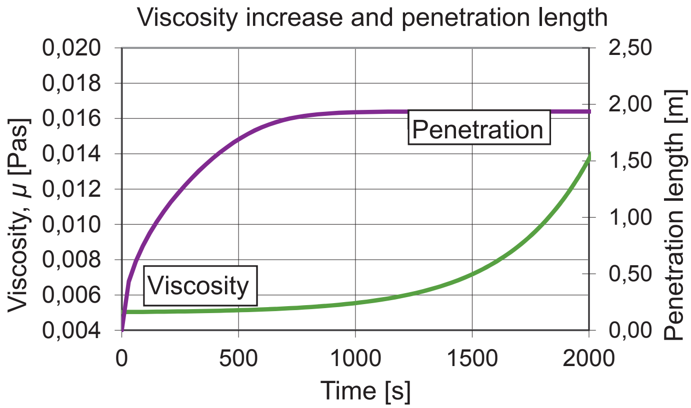

Figure 2-4. The penetration of silica sol over time. This figure also includes the viscosity increase.

As the figure shows, the penetration speed is initially rapid and as the penetration length increases, the speed decreases. Finally, the mobilised shearing stresses (a product of both the penetration length and the increase in viscosity) are so high that the penetration ceases. The penetration length can thus be controlled with the aid of exerted pressure and selected viscosity increase. Rapid gelling produces a short penetration length and vice versa. It is this ratio that must be borne in mind in the grouting design and this is covered extensively in this guide.

2.3.1 Selected concepts

Gel time, T_G = the time from when the silica sol and saline solution are mixed until it has gelled. The mixture is considered to have gelled when a beaker filled with the mixture can be turned 90° without the liquid flowing. Unit: minutes.

Initial viscosity, μ_0 = viscosity of the mixture directly after mixing. This is determined using a rheometer. Unit: Pas

Gel induction time, t_G = the time it takes for the viscosity to double in relation to the initial viscosity.

Pressure, p, and overpressure, Δp – the pressure at the grouting pump is the same as the exerted overpressure plus groundwater pressure.

Grouting time – the time the pressure remains at the packer and until the pump is turned off and the packer is closed. Unit: minutes

Effective grouting time – the effective grouting time commences when the packer is open, the design pressure is achieved and lasts for as long as the design pressure is maintained. For definitions, see Figure 2-5 below.

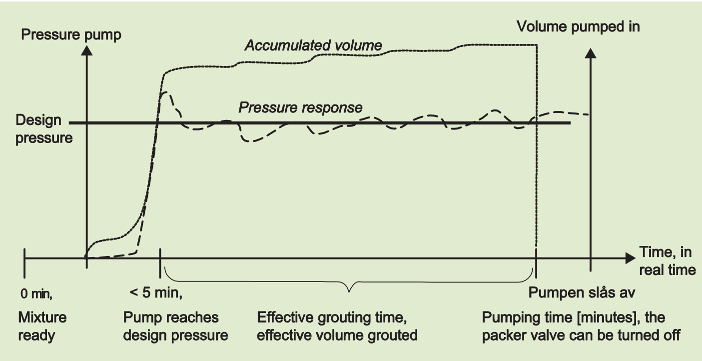

Figure 2-5. Illustration of the grouting time generally and the effective grouting time and pumping time specifically.

2.3.2 Gel induction time and penetration length

The gel time, gel induction time and viscosity in relation to the time is shown in Figure 2-6 below.

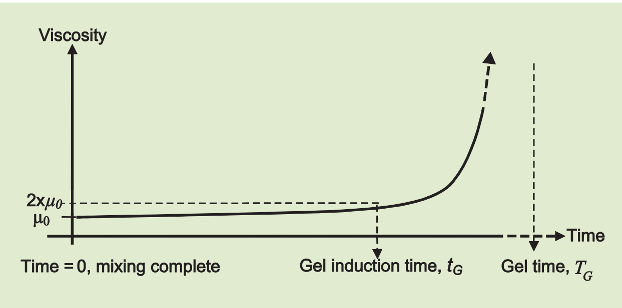

Figure 2-6. Schematic illustration of the terms 'gel induction time' and 'gel time'.

The penetration into a fracture is linked to the viscosity curve, which shows that the penetration achieves almost the maximum length before the gel time is reached (Figure 2-7).

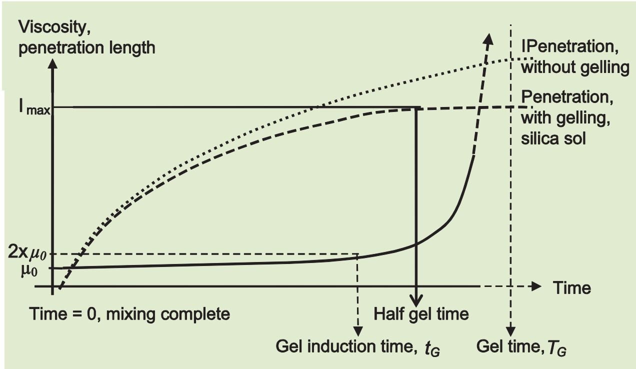

Figure 2-7. Penetration in relation to viscosity. The unbroken line is the viscosity curve for a silica sol. The broken line is the penetration for silica sol and for comparison purposes the dotted line is for a non-gelling silica sol (consistently low viscosity).

In the laboratory, many tests are being carried out to determine how the penetration of gelling liquid takes place. As a rule of thumb, it can be said that the maximum possible penetration, I_{max} is achieved at half the gel time, T_G. The liquid at this point is still very free-flowing. If no gelling had taken place, penetration would have continued indefinitely as long as the driving force was active. The viscosity only governs the penetration speed; a low-viscosity liquid has a short penetration and vice versa. The gelling results in a visible stop in the penetration and an increase in strength. The time the pressure must be exerted, over half the gel time, depends on the hydrogeological conditions, the hydraulic gradient and the risk of erosion of the grout. In deep tunnels, approximately 150-500 metres, the risk of erosion is greater and the grouting time must be longer than half the gel time, whilst in shallow tunnels, less than 100 metres, and if the hydraulic gradient is low, the risk of erosion is lower and the grouting time can be shorter, i.e. half the gel time.

The maximum penetration length for a two-dimensional flow (2-D) with silica sol, $I_{max,\ 2\text{-}D}$, is calculated as (Gustafson and Funehag, 2008a and 2008b)

$$I_{\max,2-D} = 0.45 \cdot b \cdot \sqrt{\frac{\Delta p t_G}{6\mu_0}} \qquad (2\text{-}1)$$

where b is the hydraulic fracture aperture, Δp is the exerted overpressure, t_G is the gel induction time and μ_0 is the initial viscosity in silica sol. The gel induction time is the time it takes for the initial viscosity to double. After the gel induction time, the increase in viscosity is rapid and the penetration capacity decreases dramatically. A rule of thumb is that the gel induction time is one-third of the gel time /Funehag, 2007/. The gel induction time must not be confused with the gel time.

The strength of silica sol can generally be determined by the particle size (specific surface), size distribution and particle content. The same properties also control the gel time of silica sol. In very simple terms, it can be said that the strength increases in a product with a higher particle content. However, higher strength for a product with a low particle content could be achieved if compensation is made in the form of a broader particle distribution, i.e. a mixture of particle sizes. However, it has not been possible to verify this approach completely through literature studies, due in part to the lack of information about material properties and to the fact that several products have not been compared with each other in the same study.

In situ permeability describes how permeable the grout is in reality. Water ingression should naturally be lower than the desired permeability of the rock that is to be sealed. Silica sol has properties that bind the water in the solution network. Indirect tests carried out on the material Eka gel Exp 36 reveal a hydraulic conductivity, K, of approximately 10^{-10}-10^{-11} m/s (Butron et al, 2007). The tested product had an average particle size of 16 nm with a weight ratio of 35%.

2.4 Silica sol, other properties

Other aspects, apart from the pure grouting properties, that could be of importance to how grouting with silica sol ought to be executed are as follows.

- **Mechanical**

A silica soil generally has low mechanical strength compared, for example, to cement. Studies (Axelsson, 2009) show that immediately after gelling, a shear strength of 60-80 Pa is achieved. The strength then increases rapidly. During the six months the shear strength was measured, the rate of increase had not fallen. Approximate values for measured shear strengths after six months' ageing (Butron et.al 2007 and Axelsson, 2006), are approximately 45-60 kPa. These values apply to test beakers that only contain silica sol.

There are studies (including Yonekura 1997, Persoff et.al 1999) where different types of sand were injected with silica sol and they had totally different strength after six months – up to around 500 kPa.

- **Shrinking, syneresis**

What was known previously, see for example Andersson (1998), is that silicates, and in particular sodium silicate, revealed substantial shrinkage. It should be noted that silica sol is not sodium silicate as the proportion of the base (Na_2O) is considerably lower and it comprises particles and not silicate chains. Silica sol shrinks under dry conditions. At a relative humidity of 98%, the shrinkage is very little or non-existent and at 100% RH or in indirect contact with water, there is no shrinkage (based on long-term tests, lasting more than six years, at Eka Chemicals in Bohus). After drying and shrinkage, silica sol cannot revert to a gel phase and instead the shrunken specimen will break down if water is added. In addition, observations from a laboratory test at Chalmers University of Technology show that the flow through a silica sol core can decrease and cease completely after a certain period of time. This could be an indication of a certain swelling effect but in that case the test specimens have not dried out.

- **Longevity**

Longevity is a question that has still not been answered fully. Theoretical studies at the Division of GeoEngineering at Chalmers University of Technology (material not yet published) show that silica sol is durable as long as the colloidal SiO_2 is present in the groundwater. This applies generally to all water in crystalline rock apart from meltwater, e.g. in mountain ranges. In Japan, silica sol is considered to be durable and it is the only grout, apart from cement grout, that is permitted for use when sealing tunnels. Professor Yonekura has published several articles in this area where (Yonekura 1997) is a reference article. It should be pointed out that research is being conducted in this area to acquire an understanding of the mechanical degradation mechanisms for grout.

- **Environmental and health aspects**

No demonstrable negative health effects have been reported. It should be borne in mind, however, that silica sol is slightly alkaline (pH 9-10) and it could cause irritation if it were to come into contact with the skin and eyes.

The use of colloidal particles in society is on the increase. It is common in paints, drinks, cosmetics and so on, and the long-term environmental effects of its use have not yet been investigated although there are suspicions that it could render watercourses turbid.

- **Storage and shelf life**

Silica sol also contains water, which means that it must not freeze or be exposed to major temperature changes. The recommended storage temperature is 5-35 degrees Celsius. High temperatures could speed up microbiological growth and reduce long-term stability. At normal storage temperatures, the long-term stability is guaranteed for at least 18 months for Meyco MP320 and MP320T. If stored for longer, the viscosity and the specific surface area ought to be checked, which for the most part can be carried out by the supplier.

- **Examples of requirements regarding material information that can be stipulated in a construction document**
  - Silicon content
  - Particle size, specific surface area
  - Strength during gelling
  - Strength after a certain period of time following conclusion of grouting
  - Type of accelerator, NaCl or CaCl, and the concentration

3 Execution of silica sol grouting

Execution is preceded by a grouting design or plan. The design involves proposed geometries for a grouting fan, the grout that is to be used, the pressure and times that are suitable as a starting point and the checks that need to be made to ensure the result. The equipment is stated indirectly in the form of a demand specification, which is obtained by knowing what pressure and times will be necessary. Appendix A contains an example of a grouting design, which is linked to a later chapter on execution. The essence of such a design is summarised in what is known as a design window, see Figure 3-1.

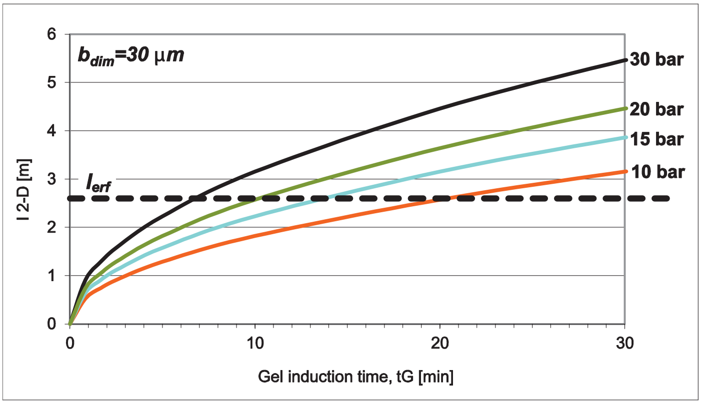

Figure 3-1. Penetration lengths for a dimensioning hydraulic fracture width, 30 µm, as a function of the grouting overpressure and gel induction time. The required penetration length of 2.63 m is shown as a horizontal, broken line.

Figure 3-1 illustrates that when choosing different pressures and times (gel induction time), different penetration lengths are obtained in a hydraulic fracture aperture of 30 µm. The penetration lengths govern the choice of borehole distance, c-distance, between the boreholes in the fan and the gel induction time, thus governing how long each borehole needs to be pumped. Furthermore, the pressure is selected to avoid the risk of lifting the rock or causing breakage, resulting in a need for more grout than is necessary. At the same time, the pressure must not be too low, as this would result in long grouting times to achieve a sufficient penetration length.

3.1 Suitable equipment currently available

At present, all mobile equipment produced for cement grouting also works for silica sol. It must be borne in mind that silica sol does not have any ‘lubricating’ effect on the equipment in the way that cement does. Routine inspection of the pumps and other equipment therefore needs to be carried out more regularly than is the case with cement grouting.

Silica sol for grouting comes in the form of two liquid solutions, one with silica sol and one with a saline solution. They are normally supplied in 1 m^3 plastic tanks with steel cages although there are smaller containers. Both the solutions are pumped over to the grouting equipment using barrel pumps. These must be powerful, at least 30 l/min (preferably with a flow meter) to avoid the mixing becoming a ‘bottleneck’. There are two alternatives for weighing silica sol. The silica sol can be weighed in the agitator or directly in the mixer. In both cases there must be a measurement system for either volume or weight. The agitator measures the weight relatively accurately for large batches – more than 50 l. For smaller batches, the accuracy ought to be checked and the margin of error should not exceed 5%.

Figure 3-2. 1m³ container with silica sol and a saline solution from a project in one of the Telia tunnels.

The weighing system for the mixer often comprises just one load cell and is only there to show whether there is material in the mixer or not. The level of accuracy is thus insufficient for automated recipe weighing. The mixer can be supplemented with up to three load cells, which can also compensate for the equipment not standing completely horizontally. If the barrel pumps have a more exact flow meter, the pumps can be used to pump up the correct volume into the mixer. On slightly more advanced barrel pumps, they can be set to always pump a certain volume before switching off. These electronic control systems, on and off switches, are already fitted to newer grouting equipment. The correct volume of saline solution can be pumped in the same way, using barrel pumps or scales. It should be borne in mind that the volume of saline solution is normally one-quarter to one-fifth of the volume of silica sol, which means that the measurement accuracy range is lower than for the silica sol. The saline solution can also be weighed using what are mostly separate additive arrangements, used mainly for different additives for cement. Automated dosage and mixing are preferable to save time when mixing.

Summary of the equipment list:

- Grouting pump, capacity requirement 50 l/min, 100 bar, with a maximum variation in pressure of 1 bar. Flow measurement and logging in real time are required.
- A flow meter that can measure small flows, < 0.1 l/min, accurately. The minimum flow that is to be measured must be linked to the design fracture aperture that is to be sealed. See also Part III, Planning and design theory. By measuring the flow, the pump can also be switched off if the flow is less than the stated flow and by doing so time can be saved when grouting. At present, however, the flow meters available on the grouting equipment are far too inaccurate. They measure very poorly, even at 4-6 l/min.
- Mixing container, weighing container
- Weighing system, weighing of salt and silica
- Barrel pumps, powerful, >30 l/min, and automated to close when the correct weight of silica has been fed in or fitted with a flow meter.

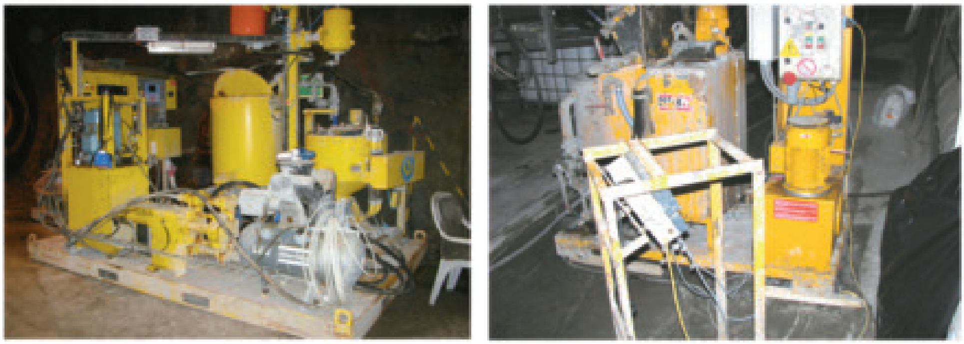

Figure 3-3. Example of grouting rigs. The photograph to the left is from the research facility at Äspö. The photograph to the right is from a project in the Telia tunnels.

3.2 Manning/organisational requirements

In the case of a 'standard set-up', two people are required at the grouting rig, one responsible for the grout and mixing and one responsible for pumping and other equipment. Another person could be necessary at the mixing point depending on the distance between the grouting equipment and the tunnel front as well as the number of grouting holes. For grouting to be 'successful', the team must have the necessary training and/or experience of grouting and the mixing procedure as well as the specific skills required. If this is not the case, expert staff are required on site when grouting commences in order to be involved in producing the recipe and to demonstrate the procedure and answer any questions.

3.3 Drilling and clearing of holes

Drilling holes for silica sol grouting takes place in the conventional way, i.e. all boreholes for the fan in question are drilled according to a drilling plan, normally with the same dimensions and equipment used for cement grouting.

Silica sol does not require any further clearance in the hole as opposed to the high-pressure flushing that is normally required in conjunction with cement grouting.

In the case of small inflows into the boreholes, where silica sol is also of greatest use, the boreholes ought to be drained of water before grouting. The expectation is that the volume will be so low that the water in the borehole can dilute the silica sol. In the case of large flows, the water, or the undiluted silica sol, are forced out into the apertures and the subsequent injected volume gels as expected. In the case of small inflows into boreholes, particularly holes on a downward incline, air ought to be removed from these holes. This is done, for example, with the aid of a vacuum pump connected to the hole before grouting commences, see description in Section 4.1.2.

Figure 3-4. Vacuum pump from a sealing project in the Telia tunnels.

3.4 Hydraulic tests in grouting holes

In the design for silica sol, criteria are normally given for when it is technically justified to use silica sol. Furthermore, the mixing conditions and batch volumes are obtained based on results from hydraulic tests in the grouting holes. Consequently, hydraulic tests should be carried out in the grouting holes before grouting commences.

Normally, there are two hydraulic tests in the boreholes, traditional water loss measurements and ingression measurements, see Figure 3-5 below.

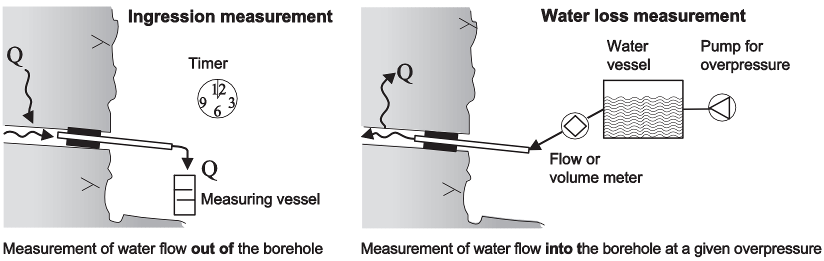

Figure 3-5. Illustration of ingression measurement and water loss measurement with related measuring equipment.

Water loss measurement means that water is forced/injected into the borehole through a packer at a set overpressure, 2-4 bar, for a set period of time, 1-3 minutes. The water flow reading is taken during the final minute and when the pressure has been stabilised. Inflow measurement means that the flow from the borehole is measured, i.e. water that flows naturally into the borehole. Normally, a stable groundwater level is required, at least a 40-metre water column, for the tests to be conducted quickly and efficiently. The analysis of the test results is determined by how long measurement can take place, from a few drops over a period of 10 minutes or a large flow over a period of 10 seconds. Both or just one of the tests must be carried out and the groundwater pressure must be measured in conjunction with the tests.

Hydraulic tests ought to be carried out in all the boreholes in a grouting fan. If the main purpose is to describe the properties of the rock and adapt the grouting design, all boreholes must be tested one at a time with the other boreholes closed. For a hole-by-hole grouting design, hydraulic tests are the obvious choice. A common misconception is that hydraulic tests are carried out mainly to find boreholes that are linked and, using this information, carry out grouting more efficiently. Increasing efficiency using this process, at least with silica sol, has been called into question and measures could be taking during grouting instead, see Section 3.5.3.

As the flow is low when silica sol has been used, the measuring equipment must be adapted to this. Conventional equipment for measuring water loss is not adapted. An example of measurement accuracy using adapted equipment is around 0.002 l/min, which is equivalent to $K = 4\times10^{-10}$ m/s as a measurement limit. The equivalent level of accuracy for conventional equipment is at best around 0.1 l/min, which is equivalent to $K = 2\times10^{-8}$ m/s as a measurement limit.

3.5 Batch grouting

3.5.1 Preparations

Each recipe is tested beforehand to check the gel time using the mixing equipment and temperature in question. Pre-testing can be carried out in the laboratory, where the viscosity curves and the specific quality measurements can also be produced: initial viscosity, gel induction time and gel time. Pre-testing in the field is thus simpler, as the recipe is checked only against the gel time.

The table (Table 3-1) shows an example of gel times for different mixing ratios of silica sol and salt at a temperature of 10 degrees. The density is assumed to be 1.2 kg/litre for silica sol and 1 kg/litre for the saline solution. The mixing ratio is stated in both volume and weight percentages.

Table 3-1. Examples of gel times, T_G, for different mixing ratios at a temperature of 10°C. The table shows the size of a batch measured either in weight or in volume.

Ratio			**Weights**			
Weight ratio	**Volume ratio**	**T_G (10°C)**	**Kg sol**	**Kg saline solution**	**Per kg sol**	**Kg saline solution**
4:1	3.3:1	22.5 min	100	25	1	0.25
4.5:1	3.75:1	30 min	102.6	22.8	1	0.22
5:1	4.2:1	38 min	105	21	1	0.2

Ratio			**Volumes**			
Weight ratio	**Volume ratio**	**T_G (10°C)**	**Litres, sol**	**Litres, saline solution**	**Per litre sol**	**Litres, saline solution**
4:1	3.3:1	22.5 min	83.3	25	1	0.3
4.5:1	3.75:1	30 min	85.5	22.8	1	0.27
5:1	4.2:1	38 min	87.5	21	1	0.24

The final two columns can be used as a starting point to multiply the size based on a selected batch size.

The gel time is strongly dependent on the temperature. As a rule of thumb, halving the temperature (°C) produces a doubling of the gel time. The above mixing ratios (weight ratios) result in the table below, which shows how the gel time varies according to temperature (Table 3-2). It should be noted that the temperature that the mixing ratio should be prepared for is the temperature in the rock and this is what determines the pumping time. If the ambient air temperature is higher than in the mixture, the silica sol will rapidly assume the ambient temperature in the rock during grouting of the small rock fractures.

Table 3-2. Examples of how the gel times, T_G, can vary depending on the temperature of the different mixing ratios shown in Table 3-1.

Weight ratio	5:1	Weight ratio	4.5:1	Weight ratio	4:1
Temp [°C]	Gel time, T_G [min]	Temp [°C]	Gel time, T_G [min]	Temp [°C]	Gel time, T_G [min]
5	43	5	35	5	27.5
10	38	10	30	10	22.5
15	33	15	25	15	17.5
20	28	20	20	20	12.5
25	23	25	15	25	7.5

3.5.2 Mixing and equipment

The most common mixing method to date in a number of projects has been what is termed batch grouting. Batch grouting means that a prescribed volume of silica sol is mixed for grouting a hole and then the whole or part of the batch is injected into the hole. The prescribed volume that needs to be mixed for a batch normally depends on the results of the hydraulic tests, see Section 6.2.2, as an initial estimate as well as the volume in hoses and grouting holes. A normal batch is approximately 200-250 kg.

When it is approaching the end, the next batch is mixed. The remaining volume must not be used for the next grouting hole due to gelling, see also Chapter 3.6, Development of the mixing procedure and equipment.

Batch mixing makes it easy to control the gel time. The mixing of silica sol and salt is done in the mixer on a conventional grouting platform. The mixture of silica sol and a saline solution is best done as close to the pump as possible, ideally in the mixer, which reduces the number of components that need to be cleaned.

The silica sol is weighed directly in the mixing container at the same time as the saline solution is weighed out in an additive tank. When the silica sol has been weighed, the saline solution is added automatically when the mixer is running. When the salt has been added, the mixer is allowed to run for 20-30 seconds depending on the power of the mixer. After this time, the gelling process for the mixture commences. A beaker sample is taken from the mixer immediately after mixing to check the gel time.

The pump is started, the hoses are filled with the grout and grouting can commence. During grouting, mixing is carried out in the mixer. The beaker test is labelled and checked regularly until gelling has been noted (a stable mixture has been obtained when the beaker can be tipped 90°), see Figure 3-6 below.

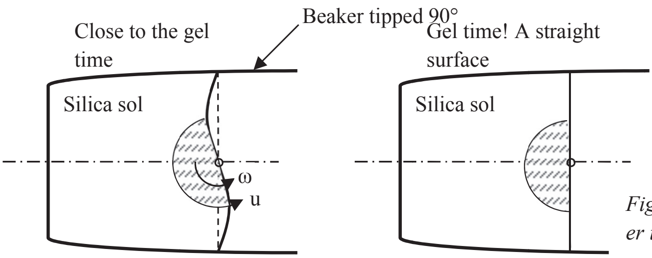

Figure 3-6. Illustration of the beaker test to determine the gel time.

When the gel time has been achieved, a straight surface is obtained but not necessarily entirely vertical (depending on the beaker used, the sample could slip from the surface). A further tip to see whether the sample has gelled is by feeling the surface of the sample with your fingertip. If your finger makes an impression on the surface of the sample without it sticking to your fingers this is a further indication that the gel time has been reached.

3.5.3 Grouting

Examples of the work process in conjunction with silica sol grouting are shown below.

1) Setting out of boreholes.
2) Drilling of a grouting fan.
3) Possible checking of the setting out, orientation and measurement of straightness.
4) All boreholes are flushed clean of sludge cuttings. Measurement of water loss can possibly be carried out at the same time if equipment is available and if possible connected holes can be identified.
5) Packer. The packer is fitted 1-1.5 metres into the borehole.
6) Hydraulic tests: Natural ingression, including dripping, are measured in all boreholes. In those holes where there is an ingression, e.g. >2 l/min, the groundwater pressure should also be measured.
    a) The results of the tests can be evaluated before choosing the mixture. Among other things, the batch volume for each hole is determined. This can be done on site.
    b) The results are used to update the procedure for the next fan and to evaluate the results.
7) Grouting commences in the lowest located grouting holes and is moved in a zigzag fashion up into the fan as grouting takes place.
8) Mixing according to the mixing procedure, Section 3.5.
9) Hoses are filled with the mixture – the hose is connected to a closed packer.
10) The design pressure must be achieved as quickly as possible and can be controlled with the flow, i.e. maximum flow initially.
11) Grouting continues until the grouting time has been reached and the mixture, pressure and flow are checked regularly. In the event of possible unexpected observations, action can be taken as stated in Section 4. If a connected hole is discovered, see below.

12) When the grouting time has been reached, grouting is concluded. The remaining mixture is pumped into the waste container and the equipment, including the hoses, are flushed clean.
13) A new mixture is prepared and the procedure is repeated until the final grouting holes with silica sol have been completed.
14) The waiting time after grouting in a concluded fan before the packers are dismantled is:
    - silica sol: at least three hours for shallow tunnels but this is project-specific and should be dealt with as part of the whole rock extraction cycle.
15) Compile the results recorded from the grouting.
16) Plugging and/or surface grouting (0-1.5 m into the hole) of all boreholes with cement/silica sol. This is done if a leaking borehole is discovered.

Connected holes

If it is discovered during the grouting process that grout is flowing out of one or several other boreholes, these are known as connected boreholes. In order to discover connected boreholes, it would be appropriate for the packers in the holes that are presumed to be connected to be kept open during grouting. When a connected hole is discovered, the hole being grouted is injected according to the design (stop criteria below). For connected holes, there are two alternatives: 1) Close the packer and clean out the hole later; 2) Allow it to flow until the hole being grouted has been finished and then grout the connected hole.

Step 1, closed packers

1) All packers to the connected holes are closed. This is suitable when several holes are connected.
2) When the current grouting hole has been grouted completely, all connected boreholes are cleaned.
3) Moving from below and upwards in a zigzag fashion, the connected holes are grouted according to the design.
4) If further connected holes are noted, these must also be treated as such.
5) The other remaining boreholes are then grouted normally.

Step two, the packers are allowed to flow

1) The connected holes are kept open and allowed to flow until the current grouting hole is completed. This is appropriate if there are only a few connected holes or if the flows of grout from these holes are small.
2) The connected holes are then grouted from the bottom and in a zigzag fashion upwards according to the design.
3) If further connected holes are noted, they must also be treated as such.

3.5.4 Stop criteria

The main stop criterion for silica sol is the time criterion. When half the gel time has been reached, no further penetration takes place, i.e. the maximum penetration length has been reached, although the pressure must be maintained until the necessary shearing strength for the gel has been achieved. The necessary shearing strength depends on the erosion risk; the greater the risk, the longer the grouting time. In simple terms, the risk of erosion is greater for tunnels that are deeper than 100 metres and less for tunnels that are not as deep. The risk of erosion is reduced by a large overlap between grouting fans and/or grouting of what are termed front holes.

In the following list, the stop criteria are listed in chronological order, i.e. the first point should be the focus but if this does not work the next point could work as a stop criterion. In the case of volume criterion X below, the volume pumped in must be adapted to the expected volume during grouting, see Section 6.2.3. Initially, the volume pumped in can be set at 1.5 to 2 times the expected grouting volume although adjusted subsequently based on the result. The maximum volume is the highest accepted volume and ought to be adapted in the light of the risk of reaching the surface or nearby facilities but also what can be regarded as an acceptable time to seal a borehole.

1) Grouting continues until the time for the stated design pressure has been reached
2) When a batch is finished, a new batch is mixed and must be pumped for the full period of time.
3) In the case of a total pumped volume of X litres, a quicker batch is mixed (equivalent to approximately half the gel time compared with the earlier batch) and this is also pumped for at least two-thirds of the gel time. Gel times shorter than 10 minutes are difficult to handle and are not recommended.
4) In the case of a total volume of more than X litres, grouting with silica sol is discontinued and the borehole is finally grouted with cement.
5) In the event of a sealed borehole and a plunger that has come to a standstill (movement of less than 1 mm/min) pumping can be discontinued.

3.5.5 Checks on grouting material

In conjunction with normal batch pumping, the gel time can be checked easily using beaker samples as an ongoing sampling process. In the first fans, a beaker sample is taken of each batch mixed. When repeatability is achieved, the testing can become less frequent, with checks carried out on every third to fifth batch. Checks made during grouting of silica sol, as well as the equipment, are shown in Table 3-3 below.

Table 3-3. Properties of the silica sol that are checked in the field as well as checking equipment.

Property	Equipment
Gel time	Disposable plastic beaker
Temperature	Thermometer

The temperature is measured easily and directly in the mixer and is used as a possible indication of changed gel times during the course of the work. This is particularly important with new deliveries of silica sol and in the event of temperature changes in the weather, e.g. changes throughout the day and throughout the year. The sampling process is shown below.

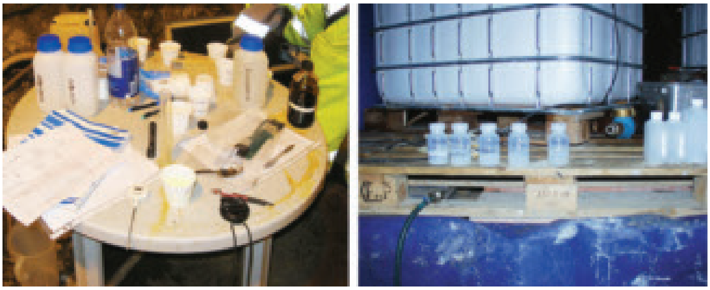

Figure 3-7. Pre-sampling in the field. The images are taken from a trial at Hallandsås.

Apart from the temperature of the silica sol, the temperature of the rock can be measured, e.g. the temperature of water flowing from the borehole. The rock temperature can differ, particularly at the entrance to the tunnel compared with some distance into the tunnel.

In conjunction with new deliveries, a request can be made to the supplier for a more detailed analysis of the silica sol, such as the concentration of the base (Na_2O), the specific surface area, the viscosity and the silicon concentration.

3.5.6 Checks following conclusion of grouting

Silica sol as a grouting material in hard rock is still relatively new and long-term experience of this material is limited. The first grouting trials in hard rock in Sweden were carried out as late as 2002 (Axelsson and Nilsson, 2002). As knowledge of silica sol is relatively new, careful documentation of the observations is important. The observations can then be compiled and passed on for follow-up by the client.

Observations and notes that could provide further knowledge and development are as follows:

In the boreholes following grouting	Preconditions
Gelled plug	Dry boreholes
Running or the plug is forced out	Groundwater pressure, gel times
Leaking boreholes	The leak before and after grouting

Below is a brief description of the observations

- Has the silica sol gelled in the boreholes or not?

Sometimes, it is noted that the borehole plug has 'moved out' when the packer has been removed. The reasons for this have not been investigated fully although there are a number of factors, such as a dry hole from the beginning (trapped air that forces the plug out), dilution of the silica sol, which reduces the strength (another form of pumping could be necessary). The borehole had not been pumped for a sufficiently long period of time, perhaps due to surface leakage or a connected hole.

A hole that shows a fully formed plug following blasting is shown below.

Figure 3-8. A good silica sol plug in a borehole. Image from Hallandsås.

- Leaking borehole

The borehole is leaking despite the fact that it has been grouted. It should be noted whether the leak is superficial or whether it is dripping from the actual borehole plug. One course of action could be to place the packer more superficially or plug the hole using an appropriate grout, such as stiff cement or polyurethane, and using an appropriate grouting technique. The following is very important in this context. The silica sol has been chosen as a grout mainly due to the low level of ingression and thus small fracture apertures. This means that it is difficult to achieve 100% sealing as the penetration length is more limited in even smaller fractures than what the design seeks to achieve. The result could be that certain boreholes leak but they should leak less than they did before grouting. If the channel flows are brought into the framework of what can be achieved, it will be even more difficult to demonstrate that sealing can be achieved. Certain channels will be sealed with grout although certain channels will not have been hit by the borehole and consequently they will not have been sealed. It should be noted, however, that a leaking borehole does not immediately mean that the fracture has not been sealed. An image illustrating a leaking borehole and an image showing a plug that is in the process of coming out are shown in Figure 3.9.

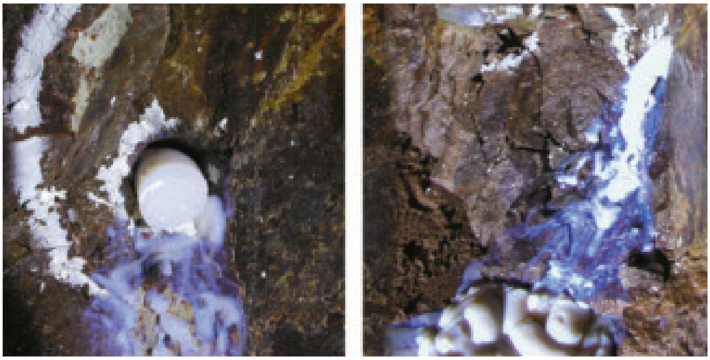

Figure 3-9. Illustration of less successful grouting of a borehole. The silica sol plug is in the process of coming out of the borehole and to the right the whole of the plug has come out in sections and fallen to the ground. The images are taken from the Törnskog Tunnel.

3.6 Checking rock sealing

Following grouting, the sealing result can be checked by drilling an inspection hole. Hydraulic tests in the grouting holes and in the inspection holes are compared. If the figure, for example, for the specific flow *Q/dh* of the hydraulic tests in the inspection holes, is lower than the figure for the grouting holes, the grouting has been effective. The degree of effectiveness can be put in relationship to the desired results, often measured as water ingression per metre of tunnel. As scale effects and running the hydraulic tests could have a major impact, inflow into a borehole cannot be compared directly with the desired inflow into tunnels. A recommendation is to compare the hydraulic fracture aperture, see Appendix A, that needs to be sealed in order to meet the ingression requirement and then use the median figure of the specific flow for all inspection holes. The median figure can be recalculated as a hydraulic fracture aperture, which is then compared with the fracture aperture for the unsealed rock (the flow into the grouting boreholes). The sealing factor that can be evaluated should be at least in the region of 50 or more for the grouting to be considered successful (compare this with the equation for calculating ingression into a tunnel in Section 5.2.1). It should be noted that the inspection holes only provide an estimate of how successful the grouting has been.

Follow-up. If ingression into the tunnel is measured in weirs, the flow ought to be measured over a long time period, several years or more. If a drip survey is conducted – to fit geomembranes for example – drip characterisation ought to be carried out several times over a long period. The weir results together with the drip survey data form a good basis for assessing the longevity of a grouting material. However, it is important that the drip survey is conducted systematically and with a time log, and that all drips are noted over a fixed section.

3.7 Development of the mixing process and equipment

There is considerable potential to achieve time-efficient grouting with silica sol. The controllable gel time is a development that is very positive from a material point of view. The waste generated in conjunction with batch grouting is at present necessary but could very well be minimised. Linking usage to water loss could be the first step towards reducing waste.

A major development possibility is abandoning the traditional piston pumps in favour, for example, of cogwheel pumps or several piston pumps connected in parallel (similar to a high-pressure washer) that can generate stable flows and stable pressures.

One condition, however, is that controllable gel times are retained, which at present can be made possible by two pumps being connected in parallel, with one pumping silica sol and the other pumping the saline solution. Both pumps work at the same pressure and are fitted with check valves. The mixing is carried out at the packer nozzle with a built-in spiral or with a mechanical mixer (it is not certain whether the latter is available on the market). To obtain a controllable gel time, the pump for the saline solution can be fitted with a control valve that supplies a small amount of saline solution on commencement of grouting before gradually increasing (alternatively, control the salt content). The regulation of such a pump ought to reproduce the desired viscosity curve.

A process with more imminent potential is grouting using a continuous batch. Instead of pouring out the excess material from a previous grouting batch, it is mixed with a new batch – see principle in Figure 3-10. See also Appendix A. This is possible if the batch has not gelled and the remaining amount is not too large in relation to the next batch. An attentive grouter can control this process although it still requires manual weighing of the volumes. If this procedure is used, it would be advisable to permit gel times with a variation of 5 minutes (designed gel time ± 5 minutes). The grouting time is then always set according to the longest gel time. This has been tested in two projects – in the Törnskog Tunnel and in post-grouting in Gothenburg (Funehag and Gustafson, 2005 and Janson et al. 2010). The method was formulated during the course of the work, where at least 30% of the remaining volume could be mixed with a new batch. A proportion higher than 40% of the excess batch should not to be used as the higher viscosity of the new, combined mixture has a direct effect on the penetration length. To determine the proportion of the excess batch that can be used when it is mixed, this must be tested in the laboratory.

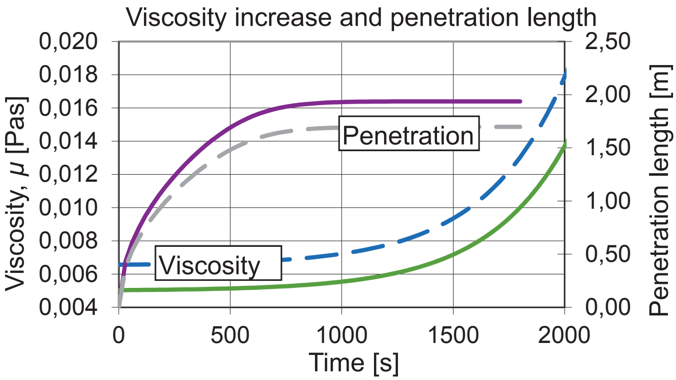

Figure 3-10. Example of how the viscosity and penetration are affected when an old batch is mixed with a new batch. The unbroken line is a new mixture and the broken line is an old mixture combined with a new batch, which results in a slightly higher viscosity.

In the case of continuous mixing, extra attention must be given to the mixing conditions and the gel times that are obtained. When the older mixture is mixed with a new mixture, this will increase the salt content or the silica sol content in the added mixture. A common occurrence is that a borehole has been grouted with a longer gel time, e.g. 38 minutes, whilst the next borehole is grouted with a gel time of 30 minutes. The normal mixing ratio is pre-set for 38 minutes and without changing the pre-set parameters the next mixture is prepared with a higher saline solution content, in this case a further 2.2 kg. If a longer gel time is desired, more silica sol is added. The table below shows four examples of such a mixture (Table 3-4). This only applies, however, when the batch has been newly mixed. If the mixture has begun to gel, it is recommended that it be discarded and the equipment cleaned.

Table 3-4. Adjustment of the mixing ratios.

Normal mixing ratio	**Gel time**	**Target gel time**	**Expected ratio**	**Weight ratio for a normal mixture**	
Weight	**min**	**Min**		**105 kg sol**	**21 kg salt**
5.0:1	38	30	4.5:1	-	+2.2 extra
5.0:1	38	22.5	4.0:1	-	+5 extra
4.0:1	30	30	4.5:1	+12.5 extra	-
4.0:1	30	38	5.0:1	+25 extra	-

4 Problems and actions in conjunction with grouting

4.1 Basic impact of the rock on grouting

When grouting takes place there is often one ‘problem’ or another. The nature of the problem is linked to how the rock is arranged. A common problem often reported from the tunnel front is surface leakage or backflow.

When silica sol is used, surface leakage often starts as a small spray of milky liquid from the rock. Gradually, the pressure rises, increasing the volume of ingression, but falls when the silica sol begins to gel. In purely practical terms, this is considered a problem although theoretically it does not affect the result, i.e. on condition that the pressure rises and reaches the design pressure. If surface leakage results in a high material usage (large volumes) the grouting technique should be adjusted but only if the design pressure is not achieved or if the grouting time is not achieved before a new mixture needs to be prepared.

4.1.1. Possible reasons for dilution

A problem linked to the grouting fan design is that there is water in some of the holes – the downwardly inclined boreholes.

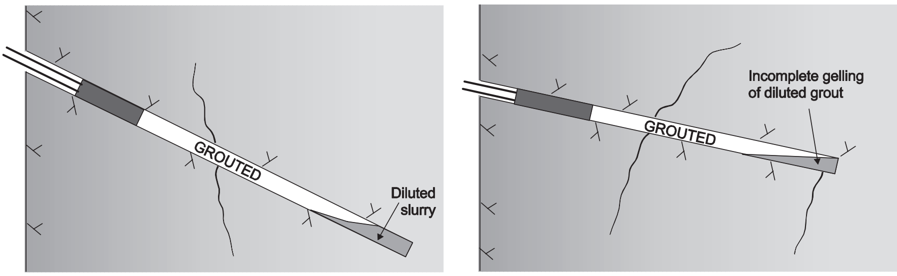

Figure 4-1. Boreholes directed downwards. The left-hand image shows a borehole where there is water remaining. The water is mixed with silica sol into a non-hardening ‘slurry’. The right-hand image shows a borehole where water is preventing a fracture from being sealed.

Some of the silica sol is mixed with the water that remains in the borehole ar becomes ‘slurry’. The gelled silica sol that is in contact with the slurry is slowly eroded. Gradually, the remaining gelled sol in the borehole has an insufficient contact surface with the rock, the shearing forces become less thar the pressure exerted and result is that the gel slides out. Visually, the hole fir appears to leak quite large volumes of water but as soon as the pressure falls back, this ceases and the flow reaches equilibrium.

To avoid this problem, it is important that the water in the borehole is pumpe out thoroughly before grouting commences.

Another problem that could also occur in upwardly inclined holes is that the silica sol does not gel. The left-hand image in Figure 4-2 shows a reason for this.

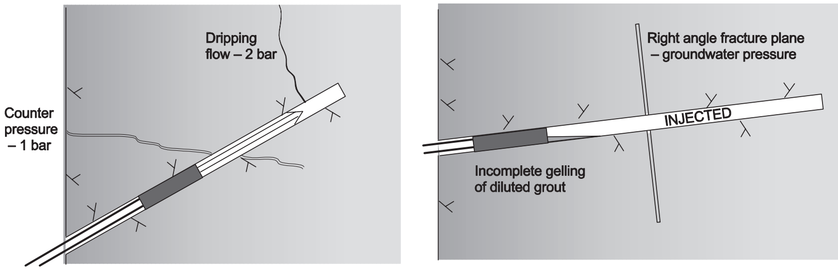

Figure 4-2. Upwardly inclined boreholes. The left-hand image illustrates the problem of dripping boreholes in conjunction with low pumping pressure. The right-hand image shows an injected borehole with a small wedge where gelling has not taken place because of diluted grout. Otherwise, it is a perfect hit on a right angle fracture plane with full penetration.

The problem in the left-hand image in Figure 4.2 is superficial fractures that cause a fall in pressure in the borehole. This can be likened to tests carried out at the Äspö Research Tunnel TASS (Funehag and Emmelin, 2010). Trapped air and water are forced out of the borehole during grouting using a hose lowered down through the packer. The idea was that the hose should allow complete filling of the borehole although the result instead was that the silica sol never hardened, which could be due to turbulent flow (the hose through the packer was in contact with atmospheric pressure) which caused a remixing of silica sol and inflow of water. Similarly, it could be a fracture that causes a pressure difference between the borehole and the tunnel. The simplest solution to this is that the packer is fitted lower down in the hole, thus bypassing the fracture that is releasing the pressure. An alternative is to reduce the flow and the pressure to fill the borehole more slowly and then return to the design pressure.

The right-hand image shows that, despite vacuum pumping, water is still entering the borehole even though the borehole is upwardly inclined. During grouting, the water entering the borehole dilutes the silica sol. Generally, the volumes are only small and do not affect the result. One way of preventing borehole problems is to categorise boreholes based on anticipated problems. Boreholes that fall into this ‘multi-action’ category could be a source of concern in that it will take more time and certainly a higher volume of grout to rectify the problems. The table on the next page (Table 4-1) contains a proposal that has been tested to predict ‘problem holes’. However, it can be said that a number of the measures are already being taken automatically by the contractor and the table should be regarded more as a way of highlighting the problems facing the grouter.

Table 4-1. Prediction of boreholes that cause problems for the grouter.

Step 1. Categorisation of grouting boreholes

Category A (Direction)		Category B (Flow)		Category C (Other)	
Downward incline	A 1	< 2l/min	B 1	Surface leakage, low pressure	C1
Upward incline	A 2	2-5 l/min	B 2	Other	C2
		> 5 l/min	B 3		

Step 2. Proposed actions

Designation	Action
0)	Nothing, start grouting
1)	Empty the borehole by opening the packer
2)	Fill the hose
3)	Vacuum pumping
4)	Move the packer further in
5)	Mix and inject a shorter, stiffer gel time batch
6)	Mix and inject a shorter, stiffer gel time batch and reduce the pressure

Step 3. Combinations of hole categories and actions

Combination	Action	Combination	Action	Combination	Action
A1+B1	2 and 3	A2+B1	1 and 3	A1/A2+C1+B1	4
A1+B2	0, 2 and 3	A2+B2	1	A1/A2+C1+B 2	4 and 5
A1+B3	0 and 2	A2+B3	0	A1/A2+C1+B 3	4, 5 and 6

4.1.2 Evacuation of air and water from the borehole

Recently, a newly developed product, based on a vacuum pump, has been used in a number of projects. The aim is to remove water and air from the borehole before grouting commences. The benefit is twofold: filling holes and raising the grouting pressure are quicker and at the same time it ensures that boreholes are filled completely with grout. The system comprises two parts: a pump with a 150-litre tank that creates a vacuum, and a valve package linked to the packer. The valve package allows a hose to be inserted down to the bottom of the borehole (borehole with a downward incline). The hose comes into contact with the air and the water can be sucked out through the packer into the tank. At first, the borehole is emptied of water, which takes approximately

1-2 minutes for a normal grouting hole, then the hose is removed and the borehole is put under vacuum. This could be done in a number of boreholes ahead of upcoming grouting holes.

However, the valve package is not removed until just before grouting in the borehole in question is due to commence. A borehole with an upward incline does not need to be emptied of water via the vacuum hose and should instead only be put under vacuum. The vacuum system has been used for borehole flows of less than 2 l/min.

4.2 Grouting taking into account the observations.

By setting up several design windows, see Section 6.3 and Appendix A, where the design value requirement for penetration length is achieved, the most appropriate grouting technique for the borehole or the fan can be applied to a design window. If the first grouting technique selected is not suitable, the borehole distance can be reduced, providing a new window for choosing a grouting technique. Drilling more densely does not always mean that the first fan should be drilled with more boreholes, and instead it should be supplemented with additional boreholes based on the result. In the figure below (Figure 4-3), an example is shown of how the two design windows have been set up where the associated action table (Table 4-1) is based on a number of potential observations.

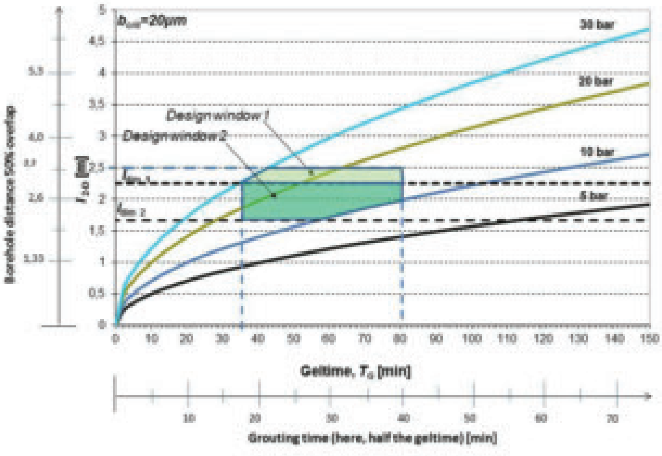

Figure 4-3. Basis for an action table according to Table 4-2 based on observations. The dimensioning requirement is a specific penetration length in a fracture with an aperture of 20 µm.

Table 4-2. Examples of actions based on observations during grouting.

Grouting step	Type of grout	Grouting technique	If the following is noted	Alternative technique
During grouting, Start position, borehole dis-tance 3.3 m	Normal gel time (T_G) = 40 min	3 MPa/20 min	Does not reach the design pressure within 5 min	2.0 MPa/T_G = 60 min/30 min
During grouting	Above	Above	Surface leakage => large volumes => unable to maintain the design pressure or time	Reduce the pressure, quicker gel time; 2.0 MPa/T_G = 20 min/10 min
During grouting	Gel time reduced to 20 min	Alternative technique according to the above	Still large volumes and not full pressure	2.0 MPa/T_G = 20 min/increase pumping time to 15 minutes NOTE: there is a risk that the borehole will be flushed out when the packer is opened.
Following comple-tion of grouting into the hole with large volumes, see line above	According to the above	2.0 MPa/ T_G = 20 min/15 min	The borehole is flushed out when the packer is dismantled.	Inject again at 3 MPa/15 min
Following comple-tion of grouting	Normal T_G = 40 min	3 MPa/20 min	The borehole is flushed out when the packer is dismantled.	Inject again T_G 30 min 3 MPa/20 min.

The table shows that control only covers pressure and time. What is most important is that the pressure is reached and can be maintained during the fixed grouting time. Observations and actions can be summarised as:

- **Design pressure not achieved.** The action is taken to increase the gel time and reduce the pressure.

- **Design time not achieved.** The action taken is to reduce the gel time and increase the pressure.

With the above-proposed actions, the design criterion of a specific penetration length in the critical fracture aperture is always achieved. In certain cases, this results in unacceptably high use of grout and takes too long. Sometimes, pumping of the borehole needs to be completed (with the achieved time and pressure) without the design criterion being satisfied. It is important to communicate at the workplace that the criterion has not been achieved but that a choice has been made to save time and grout.

An interpreted flow scheme based on the above 'Observation table' could be as follows (Figure 4-4). Such a plan should be available for the person doing the grouting on site on the grouting rig.

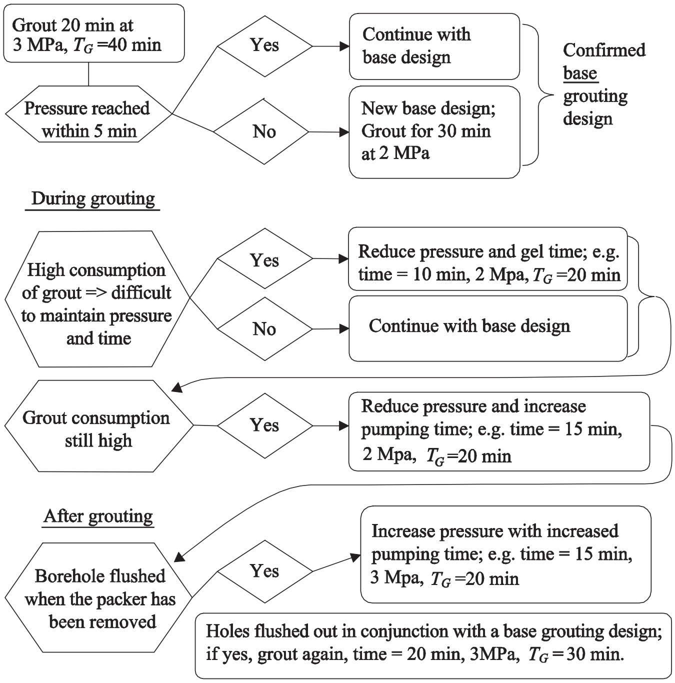

Figure 4-4. Flow chart in principle with a proposal for actions to be taken when the stop criteria of pressure and time cannot be achieved.

5 Basic properties and theories

5.1 General

From a grouting point of view, the fracture structures in the rock and their different properties are essential information if a good sealing result is to be achieved. A simple schematic model of a tunnel and overlying rock is shown in the figure below

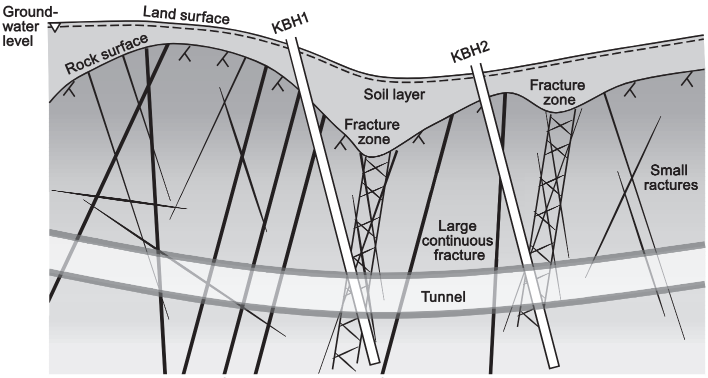

Figure 5-1. Schematic profile of a tunnel, rock and overlying soil layer with the ground-water level marked.

On this scale, only the larger fracture structures or fracture zones are shown, which is also the focus when different grouting initiatives are decided. It is mostly these that are examined with the aid of boreholes in combination with hydraulic tests. From the boreholes, the fracture intensity and the properties of the fractures can be examined. From the hydraulic tests and fracture information, the water permeability of the rock mass can be calculated by measuring the transmissivity, T, and estimating the hydraulic apertures in the fractures. For a detailed description of different hydraulic tests in boreholes and an estimate of the hydraulic conductivity, reference can be made to Gustafson, (2009). A grouting design can apply to different sections of the tunnel – in sections where the expectation is that the leakage will be high because of a fracture zone, or in sections where thicker rock is expected. In summary:

1) Valid for boreholes in each grouting fan. In this case, the choice of grout and grouting technique is governed by the hydraulic tests in the holes (water loss or natural inflow). A basic assumption is needed for how the inflow from the whole of the borehole is in relation to the largest fracture. By maintaining a design where the inflow in each borehole is measured, the largest hydraulic fracture aperture from the borehole can be calculated. The simplest assumption is that the total inflow into the borehole comes from just one fracture.
2) Valid for a forecast part of the tunnel, typical rock/rock category, when one or several fans can be grouted according to a predetermined design.

5.2 When is silica sol an option?

The pre-study and the planning ought to state which grouting fans/boreholes should be grouted with silica sol. Decisions can be reached either generally along sections of the tunnel or in detail for a borehole with certain set criteria, such as a given water loss or inflow.

5.2.1 Overall assessment prior to design

By injecting the rock with a grout that penetrates the rock fractures, lower conductivity in the injected area is achieved compared with the rock's original hydraulic conductivity (K_b). The conductivity in the injected area is designated K_{inj} (m/s). The zone with a lower conductivity is often designated the sealed zone and has a certain spread (or thickness), t, see Figure 5-2.

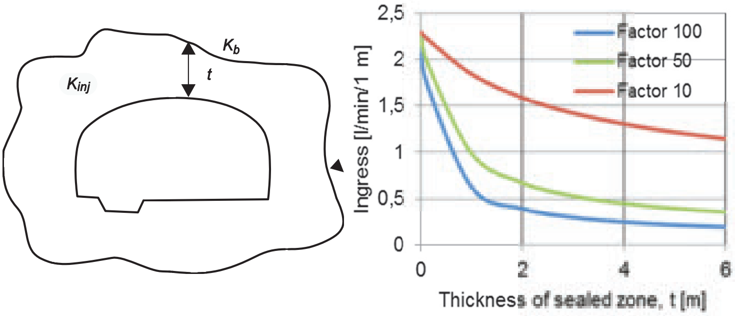

Figure-5.2.
Left: Illustration of the designations K_{inj} (conductivity following grouting) and K_b (the original conductivity of the rock around a tunnel.
Right: Shows the relationship between ingression per tunnel metre and the thickness of the sealed zone, t, based on Equation 3-1 and different relationships between K_b and K_{inj} (factor 10, 50 and 100). In the example, H=50 m, L=1 m, r_t=4 m and ζ=5.

With an estimate of the original conductivity of the rock mass, K_b, and the conductivity of the grouted zone, K_{inj}, the ingression into a tunnel following grouting can be estimated using the link (Gustafson, 2009):

$$q = \frac{2 \cdot \pi \cdot K_b \cdot \Delta h \cdot L}{\ln\left(\frac{2 \cdot H}{r_t}\right) + \left(\frac{K_b}{K_{inj}} - 1\right) \cdot \ln\left(1 + \frac{t}{r_t}\right) + \xi} \qquad (5\text{-}1)$$

where q is the ingression into the tunnel, Δh the groundwater pressure, L the tunnel length, r_t the equivalent tunnel radius, t the aperture of the grouted zone and ξ the skin factor. Ingression into an ungrouted tunnel is set at $K_{inj} = K_b$.

By determining an ingression requirement for q, t and K_{inj} can be estimated using Equation 3-1.

A marked reduction in ingression is already achieved when the spread, t, is 2 to 3 metres in thickness. The spread of the zone is a factor that ought to be taken into account with regard to the penetration length of the grout and planned reinforcement as well as bolting and borehole geometry, i.e. how far the borehole extends outside the tunnel contour and the overlap between the grouting fans.

The level of sealing, i.e. K_{inj}, that can be achieved in terms of hydraulic conductivity in the grouted zone is unclear. The hydraulic conductivity of the grouted zone cannot be measured directly in the rock mass and instead indirect methods need to be used to estimate it. The most suitable and quickest measurement approach is hydraulic tests in boreholes. With analyses and hydraulic tests, forecasts can be made of whether the level of ingression measured at weirs can be achieved. One possibility is to set up provisional weirs as tunnel construction progresses in order to highlight the ingression at an earlier stage rather than in the final phase of construction.

Achieving a sealing factor, K_b/K_{inj}, of more than 50 is frequently desirable to ensure effective grouting. To assess the degree of sealing that can be achieved using a certain grout and grouting spread, specific searches have been made to draw on experience from previous groutings. Among the criteria for successful sealing, it can be stated that in many underground projects the criterion for re-grouting, i.e. a further grouting fan at the same tunnel front, is in the region of $3\text{-}5\cdot10^{-8}$ m/s. In addition, a limit when estimating achieved sealing is linked to water loss measurements in production, where the equipment frequently has a lower measurement limit, equivalent to conductivity of approximately $1\cdot10^{-8}$ m/s (Dalmalm et al., 2000 and Persson et al., 2009). This means that low values, approximately $1\cdot10^{-8}$ m/s, are often reported as ‘sealed holes’.

Based on experience from groutings carried out using cement in hard fractured rock, e.g. (Stille and Andersson, 2008) and (Persson et al, 2009), the assessment is that the hydraulic conductivity that can normally be achieved with cement grouting is in the region of 10^{-8} m/s. Lower conductivity figures, approximately $0.5\cdot10^{-9}$ m/s, have been reported in conjunction with different grouting trials (Emmelin et al, 2004) and (Butron et al, 2008). It ought to be noted that the lower figures show experience from a number of limited grouting fans during well-planned trials.

To achieve a higher level of sealing, trials have been conducted in recent years in Sweden using silica sol (Funehag, 2007), (Ellison, 2007) and (Butron et al, 2008). These trials have been conducted as a number of limited grouting fans in conjunction with major tunnel projects. The grouting method used in the different trials was based on the required penetration of the silica sol.

Trials with silica sol indicate that a degree of sealing by a further factor of approximately 10 in hydraulic conductivity can be achieved compared with cement grouting, i.e. hydraulic conductivity in the injected zone of approximately $1\cdot10^{-10}$ m/s. An even higher degree of sealing using silica sol was achieved in a development project conducted on behalf of SKB. With two to three rounds of grouting using silica sol, a sealing level of approximately $1\cdot10^{-11}$ m/s was achieved (Funehag and Emmelin, 2010).

Planning and performance, i.e. management on site, and other grouting technology, have also been of major significance to the sealing result achieved. Furthermore, the local fractured structure could have an impact to a varying degree on the final grouting outcome.

Prior to design, a general assessment must be made of the degree of grouting that is necessary. A rough assessment of the extent/degree of difficulty is shown in the diagram below (Figure 5-3) (according to Bergman and Nord, 1982). The starting point is the pre-set sealing requirements and an estimate of the ingression into the ungrouted tunnel. It ought to be mentioned that the projects shown in the figure were from the outset considered difficult in terms of grouting. For this reason, silica sol was used and the sealing targets sought were achieved.

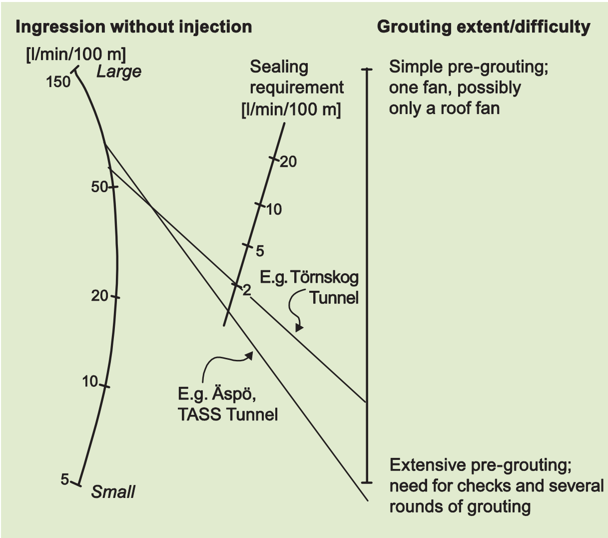

Figure 5-3. Diagram to assess the extent of grouting based on the assessed water ingression into the tunnel and the pre-set sealing requirements (according to Bergman and Nord, 1982). In the figure, two trials are marked: the trial at Äspö in the TASS Tunnel and a 100 m section of the Törnskog Tunnel.

5.2.2 Assessment of penetration capacity

Assessment of the penetration capacity of the grout is unclear and consequently certain indirect methods are used to estimate it. The most common methods are employed mainly in laboratories and some form of special equipment is used, see Eriksson and Stille (2005) and Draganovic (2009). In brief, the penetration capacity can be grouped into cement grouts and non-cement grouts, including silica sol.

Because of their particles, cement grouts have a limited capacity to penetrate a certain fracture aperture. Trials have been conducted in laboratories to determine the critical aperture for cement grouts, see summary by, among others, (Draganovic, 2009). Trials often result in a critical aperture, i.e. where the main part of the grout can penetrate an aperture of 50 to 100 μm, depending, among other things, on the type of cement, the recipe, the mixture and the trial method.

As mentioned previously, silica sol particles are small, i.e. approximately 1000th the size of cement particles, and it has not been possible to conduct any direct laboratory trials in the same way as for cement grouts. Ingression tests in a number of projects have confirmed the penetration capacity of silica sol down to hydraulic fracture apertures of at least 10 μm or so (Funehag, 2007).

This means that assessment of which fracture apertures need to be penetrated to achieve the sealing objectives or equivalent is vital when deciding which type of grout is desirable.

5.3 The impact of the design on the fractures

Geological surveys and core mapping have produced information about the fracture properties, such as length, size and frequency. With core mapping and associated hydraulic tests, the hydraulic properties of the borehole can be obtained. In the case of hydraulic tests conducted on a section basis, the transmissivity of the fractures can also be obtained. During tunnel construction, a large number of other fractures are encountered, varying in length, size, orientation and water transmissivity. The fracture properties that influence grouting are the variation in fracture aperture, the distribution of fracture apertures, fracture filling and how the fractures are connected to each other. The orientation and number (fracture intensity) are also key parameters from a grouting point of view.

The significance of fractures to the design can be linked in the first instance to two aspects: firstly the extent to which the fracture apertures need to be sealed and, secondly, which fan geometry is appropriate compared with the fracture orientation.

5.3.1 Smallest design fracture aperture

The smallest design fracture aperture is vital to the design as this is what determines how far the penetration needs to extend in order to meet the ingression stipulation.

The capacity of the fracture to transport water, i.e. the fracture transmissivity T, is proportional to the cube of the fracture aperture, i.e. hydraulic fracture aperture, b_{hyd}, is obtained with the aid of fracture transmissivity:

$$b_{hyd} = \sqrt[3]{\frac{12\mu \times T}{g \times \rho}} \qquad (5\text{-}2)$$

where μ is the viscosity, g is the earth's acceleration and ρ is the density of the water.

Using the assumption that it is a fracture that is the primary cause of water transmission in a test section, the fracture transmissivity, T, determined from the inflow tests, Q, can be set according to:

$$T = \frac{Q}{2\pi \times \Delta h}\left[1 + \ln\left(\frac{L_t}{2r_w}\right)\right] = \frac{Q\rho_w g}{2\pi \times \Delta p}\left[1 + \ln\left(\frac{L_t}{2r_w}\right)\right] \qquad (5\text{-}3)$$

where Δh is the groundwater pressure or, in the case of water loss measurements, Δp is the exerted overpressure, L_t the section length, r_w the borehole radius and ρ_w the density of the water.

For short tests, of short duration, the transmissivity, *T*, can be set as being equal to the specific capacity (*Q/dh*).

If several test sections with related fracture mapping have been obtained, a distribution of the fracture transmissivity and fracture apertures can be made. Gustafson (2009) and others describe how these distributions can be prepared. The individual fracture transmissivities along the borehole are used as input to prepare a pareto distribution. A pareto distribution presupposes that there is a small number of fractures with a large fracture aperture and a large number of fractures with a small fraction aperture (Gustafson and Fransson 2005). Using the distribution equation below, $P(T<T_n)$, is calculated, i.e. the probability that the transmissivity, *T,* is lower than the section transmissivity, T_n.

$$P(T < T_n) = 1 - \frac{(T_{\max}/T_n)^k}{N+1} \tag{5-4}$$

n is the number of transmissivities in sections, arranged according to size and *k* is a constant for the pareto distribution. *N* is the total number of fractures for the core borehole and T_{max} is the transmissivity of the largest fracture. $P(T<T_n)$, i.e. the probability that the section transmissivity is lower than the total transmissivity. The figures calculated are plotted on the graph using $log(1-P(T<T_n))$ against $log(T_n)$. The line is adapted to these figures, the angle of which is the constant *k*.

The method of using the pareto distribution in a grouting design has been presented (Gustafson et al. 2004). When the distribution of the transmissivities has been produced, this can be proportioned directly in a distribution of hydraulic fracture apertures using 'cubic law'. In the figure below, an example is shown of the transmissivity distribution: Pareto distribution for fracture transmissivities (Figure 5-4).

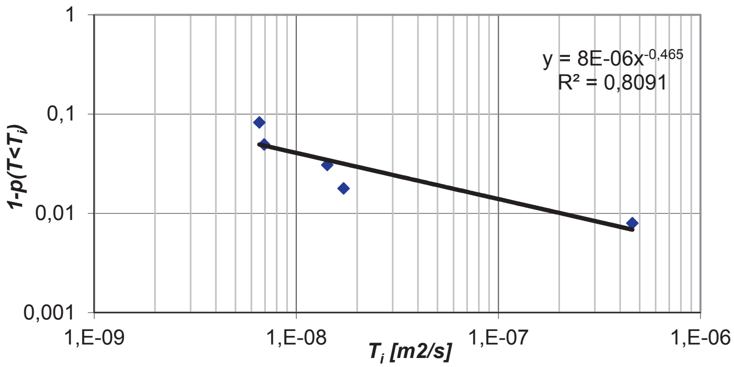

Figure 5-4. A pareto distribution for fracture transmissivities. Shown is an example of a short core borehole from the Telia Tunnel.

The distribution shows the size of the measured section transmissivities and the adapted straight line is thus the pareto distribution using the equation shown in the graph; where the constant, or the form factor $k = -0.465$. The equation is used to generate the probable hydraulic fracture apertures along the core borehole. The problem generally is that it is not possible to measure the flows in individual fractures and because the test sections are not sufficiently small and it is not possible to measure small inflows carefully, this kind of distribution is needed. The figure below shows the fracture aperture distribution that is generated (Figure 5-5).

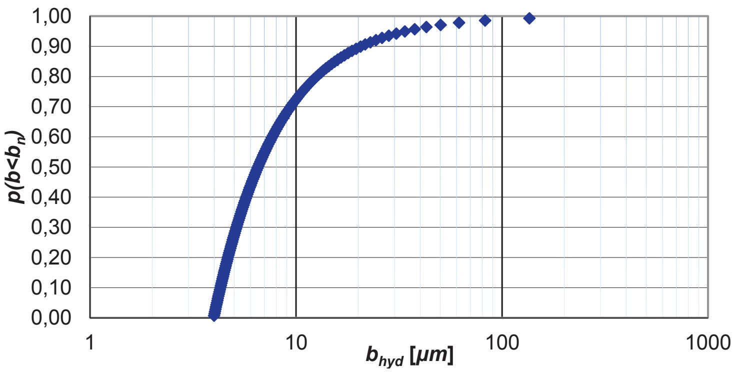

Figure 5-5. Hydraulic fracture aperture distribution calculated from the pareto distribution in Figure 5-4.

The figure shows the probability that the hydraulic fracture apertures are greater than a certain figure, e.g. the probability that the fracture is less than 100 µm is almost 99%.

Using the fracture aperture distribution, a calculation is made of the dimensioned smallest fracture aperture (b_{min}) that needs to be sealed to achieve a specific ingression stipulation. Each fracture aperture in the distribution provides a single leakage into the tunnel. By deducting each individual fracture's contribution to the ingression, the minimum fracture aperture that needs to be sealed is obtained. The contribution made by an individual fracture is calculated via the transmissivity (or conductivity K),

K_{inj} in the ingression formula (Equation 5-1). Depending on the size of the smallest dimensioned fracture aperture, the different grouts can be adapted depending on their penetration capacity. In the table below, the example from above is shown and the ingression into the tunnel is calculated using Equation 5-1. The groundwater pressure, $H = 35$ mvp, the length, $L = 100$ m, equivalent tunnel radius, $r_t = 2.5$ m, thickness of the sealed zone $t = 7.5$ m. $T_{tot} = 2.4\times10^{-6}$ m^2/s.

Table 5-1. Example of how the fracture aperture distribution is used to calculate a design fracture aperture.

Smallest sealed fracture, b_{min} [µm]	Estimated ingression, q_{grout} [l/min·100 m]	T_{grout} [m^2/s]	Comment
None	3.8	2.4×10^{-6}	Without grouting
136	2.9	8.2×10^{-7}	Largest fracture sealed
34	1.0	1.3×10^{-7}	Critical fracture aperture

As the table shows, all fractures with a hydraulic aperture down to 34 µm must be sealed to achieve the ingression requirement of 1 l/min per 100 m of tunnel. Using this approach, a robust and traceable design stipulation is achieved.

5.3.2 Fracture orientation and fan geometry

In the initial phase, the fracture orientations are achieved. This is obtained from geological land surface surveys or from core boreholes. Adapting the grouting fan completely to the direction of the fractures is difficult. It is obvious, however, that the orientation is of significance to the design and that during normal pre-grouting not all fractures are hit, which is also part of the analysis in order to achieve a predictable grouting outcome. Even at this stage, an assessment can be made of the need for post-grouting.

Below, a line of argument is shown for how the fracture orientation affects the design. Fracture data obtained from the geological survey can be plotted in what are termed fracture roses and stereo plots. From these images, the dominant fracture orientations and their angle can be determined. Using this information, the geometry of the grouting fan can be placed and adjusted in such a way that it hits the fractures as optimally as possible, see Figure 5-6. To the left is typical pre-grouting (in this case from the TASS Tunnel at Äspö) and to the right post-grouting. The orientations of the grouting holes are marked schematically as rings in the left-hand figure to highlight the principle. The borehole can be seen as a disc if the borehole is cut at right angles to the orientation. A normal can be added to this disc. If the normal hits the fracture plane at right angles, it also hits the borehole plane at right angles. The initiated reader understands that the normal to the disc is the same as the borehole orientation. The area marked with a 'net' is equivalent to the fractures that are hit by boreholes below an angle that deviates by a maximum of 10° from the right angle. 10° is used as an assumed value for incorrect readings, both with regard to measured fractures and borehole deviation. This analysis can also be used to understand which fractures can 'leak' after blasting the tunnel.

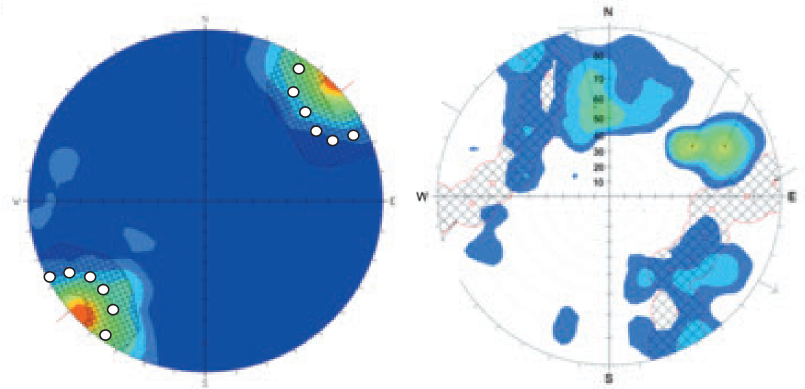

Figure 5-6. How, in principle, borehole orientations can be optimised against specified fracture mapping. The left-hand image is from pre-grouting and the right-hand image is from post-grouting.

6 Grouting design with silica sol

Establishing a complete grouting design is both time-consuming and can be considered difficult. Figure 6-1 below shows one of the most recently used plans in a large grouting project, the TASS Tunnel at Äspö (Funehag and Emmelin, 2010). The process is seen as an iterative process when it comes to fan geometries, where several stages need to be completed to achieve reasonably optimised grouting. The final design in terms of grouting technology, pressure and times is done on site in the tunnel.

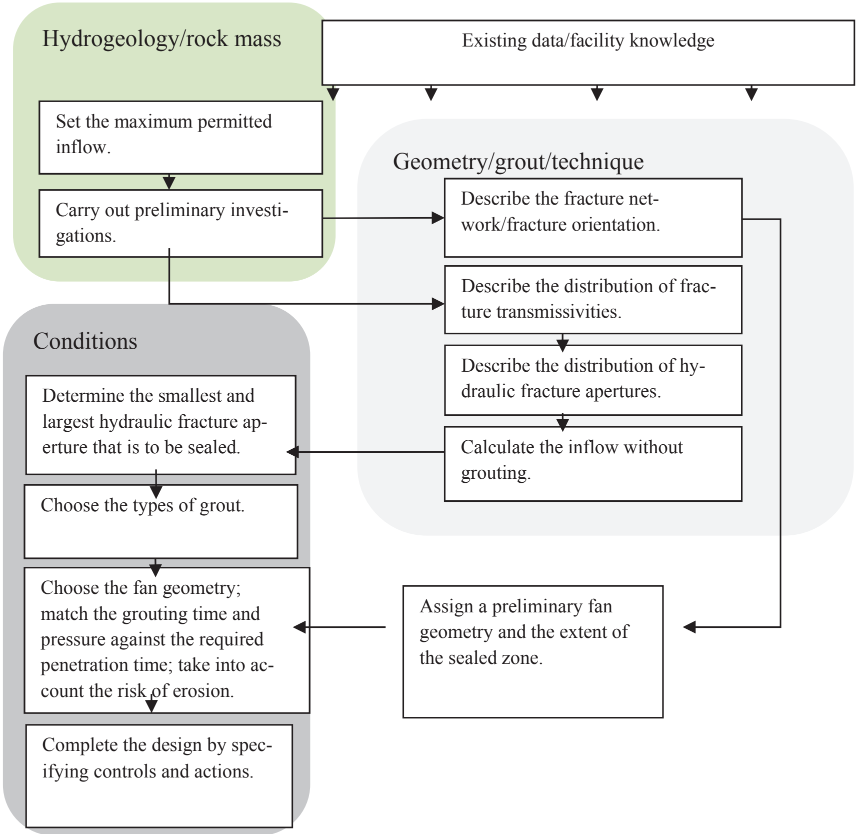

Figure 6-1. A scheme for preparing a grouting design (according to Funehag and Emmelin, 2010)

6.1 General

Based on a prepared geohydrological forecast for the rock, information is obtained about the sealing requirements for the tunnel and which grout ought to be most suitable for the tunnel. In the figure below, a schematic image has been drawn of the course of the grouting in conjunction with pre-grouting. Also shown are the basic principles behind the grouting technique. A grouting design can be summarised as containing the following three fields:

The rock – fracture apertures; smallest required fracture that needs to be sealed to meet the ingression target.

Grouting technique – grouting pressure and grouting time. Suitable equipment.

Grouting material – silica sol, initial viscosity, viscosity growth and gel time.

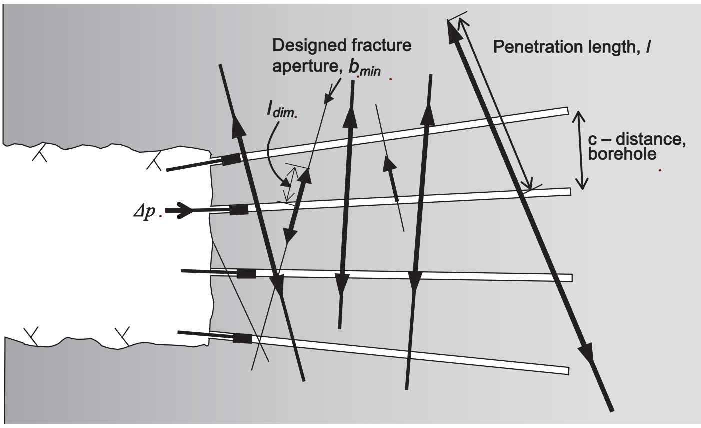

Figure 6-2. Model of how grouting works. The penetration takes place in all fractures that intersect the borehole. Penetration is further in the larger fractures and not as far in the small fractures. The dimensioning of the penetration length is done for the smallest dimensioning fracture.

By calculating the smallest penetration length in the dimensioned smallest fracture aperture that needs to be sealed, a grouting design can be produced for execution. According to the figure above (Figure 6-2), the parameters required for a grouting design with silica sol, apart from the properties of the grout, are grouting overpressure (Δp), design smallest fracture aperture (b_{min}) and the c-distance between the boreholes.

6.2 Silica sol and its penetration

Grouting pressure and grouting time and gel time for the grout must be adapted to ensure that a sufficient penetration length is obtained in the design smallest fracture. Adaptation is based on theoretical links, where the rheological properties are central.

6.2.1 Gel induction time and penetration length

Penetration into a fracture is linked to the viscosity curve, where it can be seen that the penetration reaches almost the maximum length before the gel time has been achieved. The maximum penetration length for two-dimensional flow with silica sol, $I_{max,\ 2\text{-}D}$, is calculated using (Gustafson and Funehag, 2008a and 2008b).

$$I_{\max,\ 2-D} = 0.45 \cdot b \cdot \sqrt{\frac{\Delta p t_G}{6 \mu_0}} \qquad (6\text{-}1)$$

where b is the hydraulic fracture aperture, Δp is the exerted overpressure, t_G is the gel induction time and μ_0 is the initial viscosity in silica sol.

The gel induction time is the time it takes for the initial viscosity to double.

After the gel induction time, the viscosity increase is rapid and the penetration capacity falls dramatically. A rule of thumb is that the gel induction time is one-third of the gel time, (Funehag, 2007). The gel induction time must not be confused with the gel time. See also section 2.3.2.

In deep tunnels, approximately 150-500 m, the risk of erosion is greater and the grouting time ought to be longer than half the gel time, whilst in shallow tunnels, <100 m, and where the gradient is low, the risk of erosion is less and the grouting time can be set shorter, i.e. half the gel time.

The grout can flow in channels along the fracture plane, what is termed channel flow (1-D flow) or along the whole of the fracture plane, what is termed radial flow (2-D flow). Which of the two occurs depends on the fracture features. The radial penetration length is always shorter than the channel flow and when designing, radial flow ought to be assumed.

For many projects, a maximum permitted penetration length ought to be set. It should not affect, for example, nearby tunnels or objects or force the grout up to the surface. It is in the largest fracture aperture where the penetration length will be longest. This ought to be investigated as part of the project. It should be noted that a long penetration length also results in large grout volumes, which is not always necessary to ensure a sufficiently sealed tunnel.

The time the pressure needs to be maintained to prevent erosion of the grout is directly dependent on the gel time. The strength increase of colloidal silica can be observed via the viscosity increase. When the viscosity increases so does the strength.

6.2.2 Calculation of volume for silica sol

A link for assessing the consumption of silica sol has been produced. The link has not yet been verified in the field and must therefore be used with caution, i.e. a first approximation in conjunction, for example, with estimating the batch volume for each grouting hole.

The link is based on the penetration length and results from water loss measurements in the borehole. All grouting holes are normally measured for loss of water before grouting. This means that following grouting of the first grouting hole in the fan, the water transmissivity in adjacent boreholes could have been affected and results from previous water loss measurements become a source of uncertainty when making volume estimates.

The maximum grouting volume for the fracture plane can be assumed to be:

$$V_{\max 2D} = \pi \cdot I_{\max}^2 \cdot b = 0{,}45^2 \pi \cdot b^3 \cdot \left(\frac{I_G}{b}\right)^2 = 0{,}64 \cdot b^3 \cdot \frac{\Delta p \cdot t_G}{\mu_0} \qquad (6\text{-}2)$$

Where I_{max} is calculated according to Equation 6-1.

If several fracture planes have been injected along the grouting hole this gives:

$$V_{\max 2D} = 0{,}64 \cdot \sum b^3 \cdot \frac{\Delta p \cdot t_G}{\mu_0} \qquad (6\text{-}3)$$

where $\sum b^3$ is the sum of all fracture apertures as a cube along the grouting hole.

From a water loss measurement, a flow, Q_w, is obtained in conjunction with an overpressure, Δp_w, and the specific capacity can be determined according to:

$$Q_w / dh = \frac{Q_w}{\Delta p_w / \rho_w g} \qquad (6\text{-}4)$$

With Equations (5-2) and (5-3), and the assumption that more fracture planes are injected along a grouting hole, the following is obtained:

$$\sum b^3 = \frac{12\mu_w}{\rho_w g} \cdot T = \frac{12\mu_w}{\rho_w g} \cdot \frac{Q_w}{2\pi \cdot dh} \cdot \left[1 + \ln\left(\frac{L}{2r_w}\right)\right] = \frac{Q_w \cdot \mu_w}{\Delta p_w} \cdot \frac{12}{2\pi} \cdot \left[1 + \ln\left(\frac{L}{2r_w}\right)\right] \qquad (6\text{-}5)$$

By combining Equations (6-3) and (6-5), a link is obtained for volumes according to:

$$V_{\max 2D} = 0{,}64 \cdot \frac{Q_w \cdot \mu_w}{\Delta p_w} \cdot \frac{12}{2\pi} \cdot \left[1 + \ln\left(\frac{L}{2r_w}\right)\right] \cdot \frac{\Delta p \cdot t_G}{\mu_0} = \frac{3{,}84}{\pi} \cdot \left[1 + \ln\left(\frac{L}{2r_w}\right)\right] \cdot \frac{\Delta p \cdot \mu_w}{\Delta p_w \cdot \mu_0} \cdot Q_w \cdot t_G \qquad (6\text{-}6)$$

Assume in conjunction with normal grouting that $L / r_w \approx 625$ produces:

$$V_{\max 2D} = 8 \cdot \frac{\Delta p \cdot \mu_w}{\Delta p_w \cdot \mu_0} \cdot Q_w \cdot t_G \qquad (6\text{-}7)$$

Equation 6-7 can be used to assess the mixing volumes based on a water loss measurement. It is very simple to include this in a spreadsheet program to produce batch sizes. This can be used for batch grouting to minimise wastage.

6.3 Design

The aim behind the design of silica sol grouting is to assign values for the following elements:

- Borehole geometry
- Penetration length
- Grouting pressure
- Grouting time
- Other practical restrictions

Appendix A, contains a design that follows the design process described in Section 6, Figure 6-1. The different stages, however, are not a stepped process but more of an iterative process to achieve dimensioned grouting and can be summarised in the following figure.

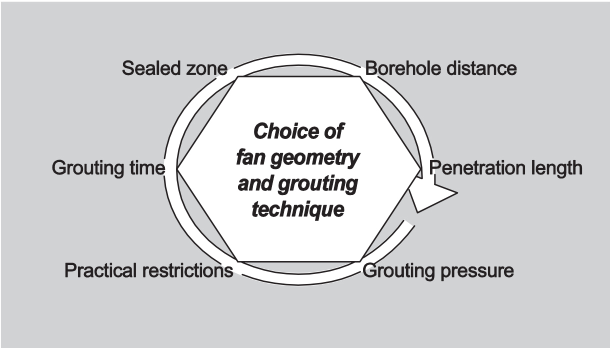

Figure 6-3. The choice of fan geometry and grouting technique is made, among other things, based on practical limitations.

As an initial approximation, an estimate is made of the geometry of the grouting fan, i.e. the length and hole angles. In normal tunnelling operations, the number of rock extractions and the length of the extractions are stipulated. This affects the length of the grouting hole. In critical sections, such as sections with low rock cover or where it is assumed that there are fracture zones with a strong flow and probably poor rock quality, assessments are often made that involve shorter rock extraction, gentler blasting and other technical solutions. In both cases, there is a spread, or exact lengths, in the grouting fans. The overlap between one grouting fan and the next is normally 4-6 m. Figure 6-4 shows how the overlap between the grouting holes and the overlap between the fans is defined.

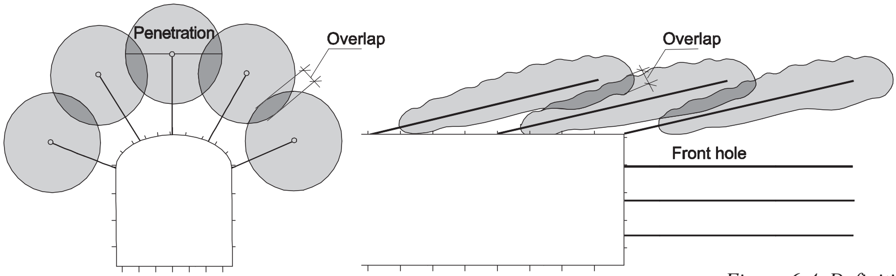

Figure 6-4. Definition of penetration and overlap. To the left, overlap within the fan, and to the right, overlap between two fans. The figure also shows 'stuffing holes' to ensure a 'sealed' front hole when the normal grouting holes in the fan cannot provide sufficient penetration length.

In the case of more critical sections, a long overlap is used. This is done to ensure the sealed zone will also be complete at the overlap between the fans. A special geometric study could be required for more critical sections. Other factors could also affect the spread of the grouted zone, such as bolt length, adjacent spaces, the risk of erosion of the grout or other restrictions.

The overlap of the grout between two grouting holes can be estimated. The overlap should compensate for the fracture orientations not always running at a right angle to the borehole. Overlap of grout between two boreholes means that the penetration from one borehole overlaps the penetration from the other borehole. This is illustrated in Figure 6-5 below. Designing is done to ensure that a certain overlap is achieved in the design fracture aperture. In the example in the figure below, it is 50 µm. The borehole distance is thus of central significance when designing. The penetration length will be half as long in a fracture that is half the size.

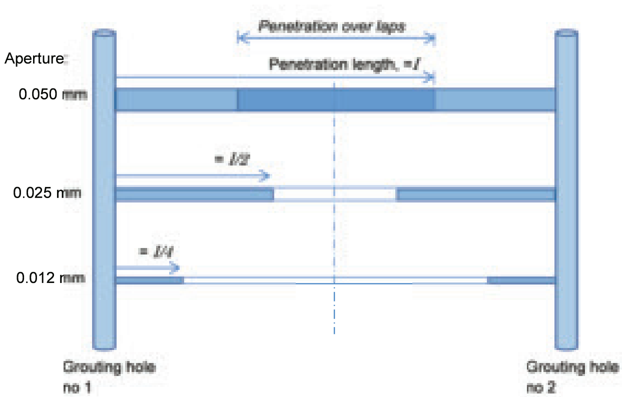

Figure 6-5. A schematic illustration of the grouting process and how penetration takes place in the event of an overlap of 50% in a fracture aperture of 0.050 mm. The penetration lengths are not drawn to scale.

The required or design penetration length, I_{dim} is calculated by setting the desired overlap (as a decimal) and knowing the borehole distance, *d*, using the following equation:

$$I = d/2 * (1 + \frac{OL}{2})$$

How the overlap contributes to the sealed zone is shown in the figure above (Figure 6-5). It is not sufficient to have an overlap between the boreholes and the zone must also be intact between the fans. With a geometric observation, the overlap between the fans can also be calculated and checked. If it is recommended that the overlap between grouting holes should be at least 50%, the overlap between the fans should be at least 20%. The smaller overlap can be explained by the fact that the potential water path is longer along a fan compared with boreholes and thus generates high resistance. This should be studied in more detail along with what is possible in practice. Experience, however, says that an overlap between the fans of 4-5 m with an inclined 5 m has worked. In deep tunnels or in conjunction with post-grouting, there is a risk of large hydraulic gradients, with a subsequent risk of erosion. Even in cases where the penetration length is limited (e.g. small fracture apertures, short grouting times, pressure too low etc.) the normal fan does not produce a sealed tunnel front, which even in these cases could lead to a risk of erosion. It is recommended that a special study be conducted to examine the risk of erosion and to find observations during tunnelling to demonstrate that there is no risk or very little risk. The basic principles behind erosion of grout can be found in Axelsson (2009). The principles were followed and applied to a tunnel at Äspö at a depth of 450 m. Reference can also be made to Funehag and Emmelin (2011).

Using Equation 3-1, the spread of the grouted zone can be estimated although a sealed zone of approximately 4-5 m is frequently a satisfactory zone spread to achieve a sufficiently sealed tunnel. The sealed zone can become the subject of design in critical sections or when optimising the fan geometry where there is good knowledge of the fracture orientation, see Figure 5-6 above.

For silica sol with penetration lengths based on the choice of pressure and grouting time, what is termed a 'design window' can be produced (Figure 6-6). Here the smallest design hydraulic fracture aperture, b_{crit}, is extremely important. Based on the conceptual rock model, see Section 5.1, this fracture aperture can be produced, which means that all fracture apertures down to the smallest fracture aperture must be sealed in order to achieve the stipulated tunnel ingression. It is thus for this fracture aperture that the penetration length, I_{2-D} is dimensioned in order for the chosen I to fall within the interval, $I_{dim}<I<I_{max}$.

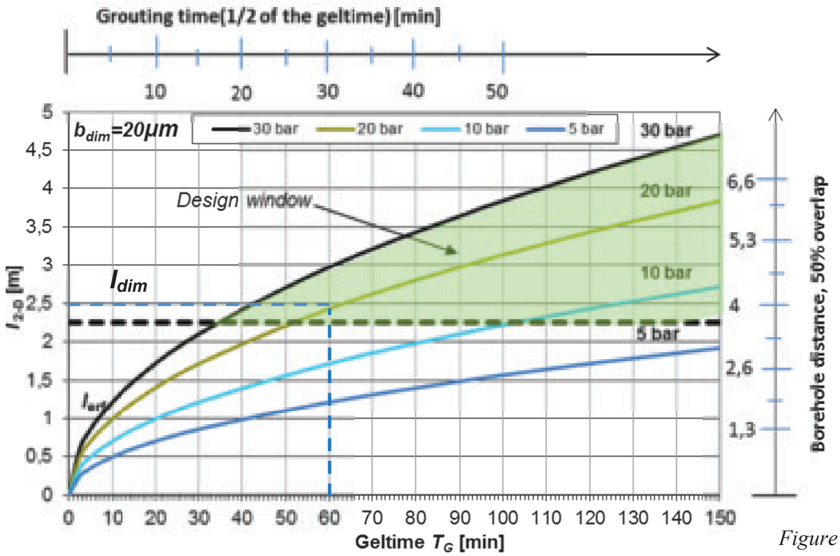

Figure 6-6. The maximum penetration length, I_{2-D}, in a fracture with a hydraulic aperture of 20 μm, has a function of different combinations of grouting overpressure and gel time; gel time ≈ 3 gel induction time). (In the figure, 20 μm is the dimensioning fracture aperture and the theoretically required penetration length is 2.25 m. The condition for the penetration length is satisfied for combinations of gel induction time and pressure within the area marked in green, what is termed the design window. On the outer axes, the comparison between the borehole distance and the penetration length and between the gel time and the grouting time is shown.*

A number of combinations of pressure and grouting time can be produced from the above type of graph. In the figure, there is a broken blue line that shows that a grouting time of 30 min (60 min gel time) at an overpressure of 20 bar produces a penetration length of 2.5 m in a fracture aperture of 20 μm. Using this set of grouting pressures and times, a borehole distance of 3.3 m is sufficient. The grouting time can also be reduced to 20 min although in that case the pressure must be increased. The borehole distance is thus dependent on the penetration length and can be determined based on the grouting pressure and gel time for silica sol. Normally, the borehole distance should not exceed 4-5 m at the same time that a small borehole distance, less than 2 m, could give rise to numerous connected holes, which in turn give rise to a more time-consuming grouting procedure.

If an overlap of grout cannot be achieved in the dimensioned fracture aperture with one single grouting, the solution is two or even three grouting rounds. This could lead to a more optimised grouting strategy where the second round could be needs-based (based on a number of observations). Such a strategy is shown in Figure 6-8. The figure shows that for the first grouting round, the grouting is overlapped in a fracture with an aperture of 0.05 mm. In a fracture of half the aperture (0.025 mm), approximately half the penetration is achieved etc. For these fractures to be sealed, a further borehole is needed between the boreholes in the first round of grouting.

There are restrictions or recommendations regarding the maximum permitted pressure. These are based on the risk of hydraulic jacking or opening of the fractures in the rock. Whether this is a problem or an advantage is still a subject of debate. Whatever the case, all the pressurised components must meet a set pressure with a certain margin of safety.

The gel time at a given viscosity affects how long grouting should take . If grouting is discontinued early, when the viscosity is still low, there is a risk that water will begin to seep into the gel (water penetrates into the gel in a finger-like fashion). This is of particular importance in the event of high groundwater pressure. In Funehag (2007), there is a simple description of how the gel time is related to the grouting time and the desired penetration length in the fracture. If the relationships presented in Section 6.2 are used during grouting, it will be understood that the gel time is an important factor for successful grouting. The table below can be used as a starting point when designing. The figures given are taken from the design window in Figure 6-9 above. After the figures have been obtained for each design step, optimisation can take place.

Design step	**Estimate/Choice**	**Provides information for**	**Checks**
Minimum fracture aperture	20 µm	Penetration length	Permitted ingression
Borehole distance	c. 3 m	Penetration length	Necessary theoretical overlap, hits the ‘right’ fractures
Necessary penetration length in the smallest fracture aperture	0.75 x c-distance = 2.25 m for a 50% overlap	Grouting pressure and grouting time	Maximum permitted grouting pressure
Grouting pressure	>2 x groundwater pressure = 20 bar	Stop criterion	
Injection time	At least half the gel time = 30 min	Gel time, stop criterion	Risk of erosion results in a longer grouting time
Gel time	2 x grouting time = 60 min		Is it reasonable?
Stop criterion 1	Predetermined grouting time at a constant pressure = 30 min at 20 bar		Choose the type of observations for a possible change in the stop criterion
Stop criterion 2	A certain maximum volume	Change in the criterion for *I*.	The design needs to be redone

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General

A tunnel is planned to be built in crystalline rock with an overlying soil layer comprising clay and to a certain extent friction material. The groundwater level follows the land surface almost exactly. Along the envisaged route of the tunnel it is probable that large fracture zones will be encountered with poor rock quality and powerful water transmitting structures.

Available data

- Groundwater levels in hollows
- Drill cores
- Fracture mapping
- Hydraulic tests in the core-drilled holes
- Engineer's forecast for the facility

The drill cores are drilled from the surface at an angle of 60° in order to hit the anticipated fracture zones. The cores reach down and under the envisaged tunnel bottom, see schematic figure below. Further cores have been bored at each of the tunnel openings.

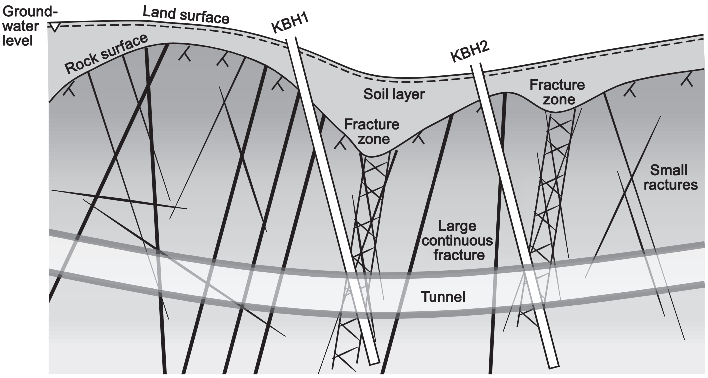
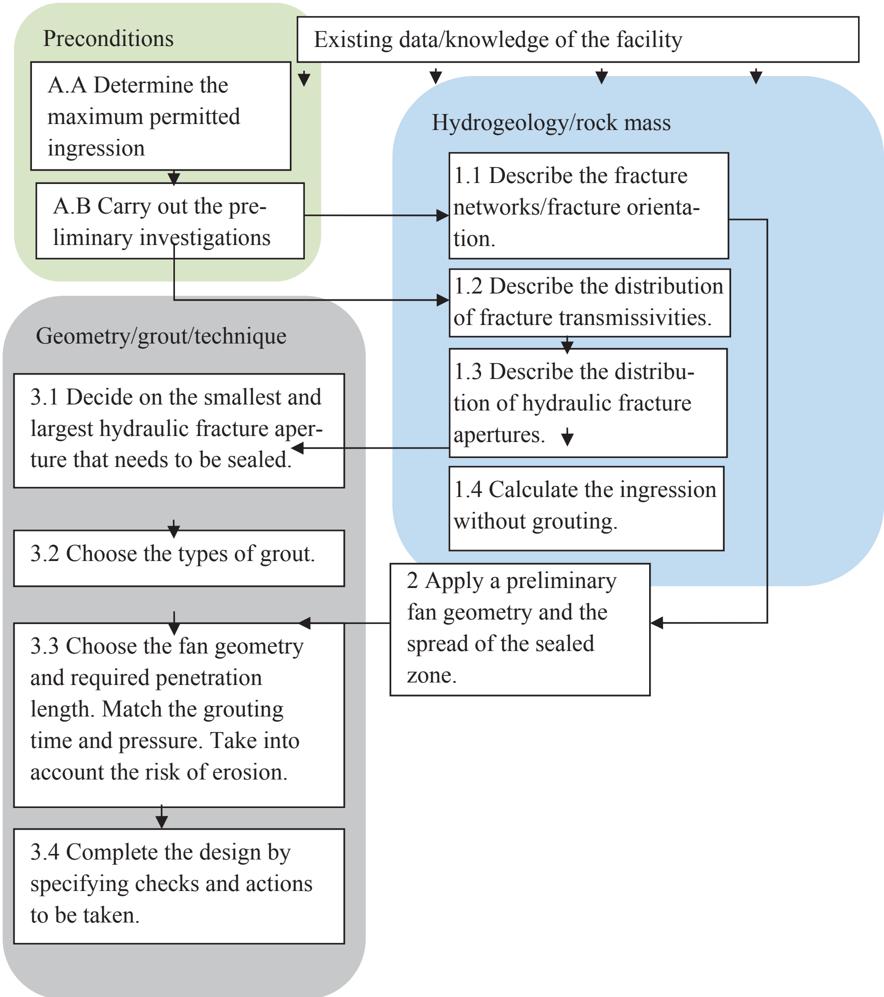


Figure 7-1. A schematic profile of the tunnel, rock and overlying soil layer with the groundwater level marked.

Design

The figure below shows a proposal for the design process. In the following section, each step is gone through, resulting in a design figure or assumption.



Assignment, points A.A and A.B

Based on a forecast by an engineer, a grouting design needs to be created. The grouting must be continuous and reduce the ingression to a maximum of 1 l/min per 100 m of tunnel.

Preliminary investigations have already been made at an earlier stage. The tunnel has a cross-section of 76 m^2. The rock cover is 40 m and the groundwater pressure is 35 m.

Hydrogeology/rock mass

Fracture network and fracture orientation point 1.1

In the preliminary investigation phase, fracture orientations are obtained both from mapping the land surface and from mapping the core. None of the mappings reflect the fracture orientation of the tunnel completely although in the design phase the fracture orientations obtained must be sufficiently representative. It must also be borne in mind that the situation could prove different in actual tunnel operations. In the diagram below (Figure 7-2), the fracture orientations are shown as a fracture rose and stereo network. The fractures are mostly steep and have two dominant fracture sets. One set, set 1, is in a NNW-SSE direction, and another set, set 2, is in almost an E-W direction. The tunnel orientation is 140°. Fracture set 1 runs almost parallel to the orientation of the tunnel and the incline is quite flat, 60°. Fracture set 2 runs almost at right angles to the tunnel and has a steep incline.

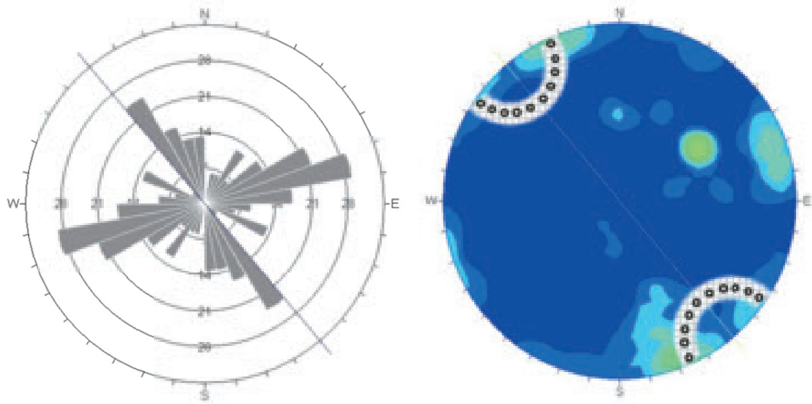


Figure 7-2. An example of a fracture rose and stereo network. In the stereo network to the right, the orientation of the borehole can be seen in a traditional pre-grouting (round rings in a hatched area).

The boreholes drawn in the stereo network in Figure 7-2 have a length of 20 m and are directed 5 m outside the tunnel profile (14°) and are 20 in total. The boreholes penetrate fracture set 2 but miss fracture set 1 completely. Using traditional pre-grouting, this fracture set will remain unsealed. Other solutions in the form of post-grouting could be an alternative.

Such a simple analysis of the fracture orientations and the hit success of the boreholes could provide an expected picture of which fracture planes will be sealed and which will need to be worked on differently.

Transmissivity distribution, 1.2

The number of fractures per metre is obtained (fracture frequency) for core-drilled holes and the core mapping, as well as an interpretation of whether the fractures are open or closed. In the core-drilled hole, water loss measurement has been carried out, which gives the water loss in l/min, at a certain overpressure, per section of borehole in metres. By linking fractures and water loss, an assessment can be made of the permeability and ingression into the tunnel can thus be assessed.

The following has been assumed

- KBH1 is represented by the poorer rock quality along the route of the tunnel.
- The fractures along the core-drilled hole are assumed to be two-dimensional and parallel plane structures (they do not intersect each other near the borehole).
- The surveyed open fractures contribute to the ingression into the tunnel.
- The sum of the individual ingressions is the same as the ingression for the whole borehole.

The transmissivity, *T,* can be calculated using the Moyes formula for a section test:

$$T = \frac{Q}{2\pi \times dh}\left(1 + ln\frac{L}{2 \times r_w}\right)$$

Where *Q* is the achieved flow, *dh* is the overpressure used, *L* is the tested section length, and r_w is the borehole radius.

A typical data summary from the core mapping and the water loss measurement are shown in the following table.

Section number	**Section borehole**		**Measured flow, Q**		**Number of open fractures**	**T using the Moyes formula**
i	From [m]	To [m]	[l/min]	[m^3/s]	n_i	[m^2/s]
1	1.5	3	0.019	$3.2x10^{-7}$	14	$6.9x10^{-9}$
2	3	6	0.047	$7.8x10^{-7}$	33	$1.7x10^{-8}$
3	6	9	0.039	$6.5x10^{-7}$	26	$1.4x10^{-9}$
4	9	12	0.018	$3.0x10^{-7}$	22	$6.6x10^{-9}$
5	12	15	1.26	$2.1x10^{-5}$	29	$4.6x10^{-7}$
6	15	18	5.17	$8.6x10^{-5}$	14	$1.9x10^{-6}$

We can see from the table that there are a relatively large number of open fractures, 6-10 fractures per metre, although the measured flows are small. In this example, the groundwater pressure is 35 mvp.

Based on the transmissivities above, a distribution is prepared known as a pareto distribution (Figure 7-3).

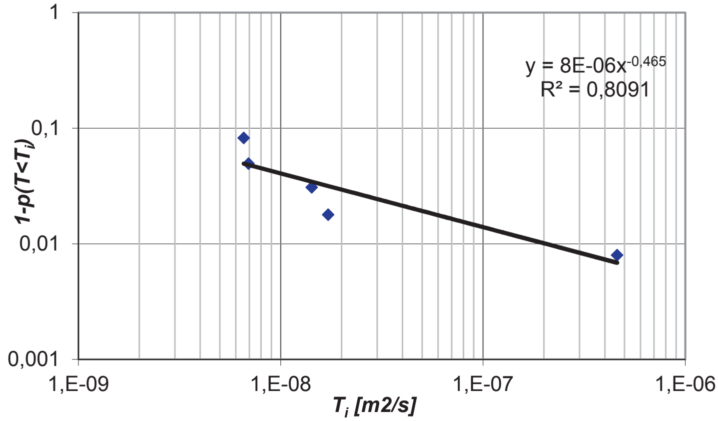


Figure 7-3. A pareto distribution for the measured transmissivities

Above an interval from approximately $5x10^{-9}$ m^2/s to $5x10^{-7}$ m^2/s, the transmissivities follow almost a horizontal line in a log-log graph.

Fracture distribution 1.3

The fracture aperture is a central parameter when designing the grouting. Using figures for the fracture apertures, a penetration length can be calculated and in doing so the execution can be determined. The best estimate of fracture apertures for grouting design is the hydraulic fracture aperture. The link between transmissivity and hydraulic fracture aperture is established using 'cubic law'. With the previously prepared transmissivity distribution, the distribution can generate an individual transmissivity for each open fracture. A hydraulic fracture aperture can then be calculated based on the individual transmissivities (Figure 7-4).

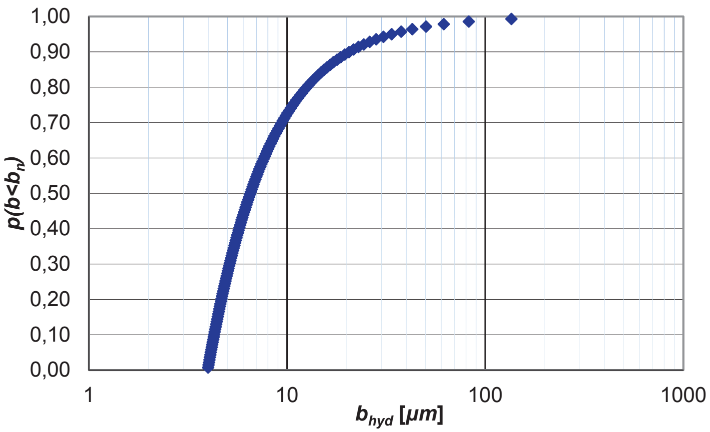


Figure 7-4. Hydraulic fracture aperture distribution is calculated from the pareto distribution in Figure 7-3.

The hydraulic fracture aperture distribution shows that the probability that there is a fracture with a hydraulic fracture aperture greater than 100 µm is very small (0.2%). It does show, however, that there are a large number of fractures with small apertures.

Ingression into an ungrouted tunnel 1.4

Ingression into the tunnel per metre (specific flow) q without grouting is calculated using (Gustafson, 2009):

$$q\left[m^3/s/m\right] = \frac{2 \cdot \pi \cdot T_b / L \cdot H}{\ln\left(\frac{2 \cdot H}{r_t}\right) + \xi}$$

where Δh is the groundwater pressure, L is the section length for which the transmissivity, T_b has been calculated, H is the depth to the tunnel from the groundwater level, r_t is the equivalent tunnel radius, and ξ is the skin factor.

With the following data entered into the equation, the ingression is calculated as

T_b [m²/s]	L [m]	H [m]	r_t [m]	ξ		q ungrouted [m³/s/m]	Q for 100 m of ungrouted tunnel [l/min]
$2.4 \cdot 10^{-6}$	100	35	2.5	5	=>	$6.3 \cdot 10^{-7}$	3.8

Preliminary fan geometry and sealed zone

In order to produce a grouting design, it is easier if there are fixed frameworks for how the grouting should proceed. In normal infrastructure tunnels, pre-grouting is most frequently assumed to cover a whole fan around the whole of the tunnel periphery. The length of the boreholes is adapted to the number of shots used and the necessary overlap between the fans. In this first stage, the geometry is set for a fan, which is then adapted to the production cycle. The following is used as the initial preliminary geometry for a fan:

- Length of boreholes = 20 m
- Number of boreholes = 15-25
- Incline 5 m

The vertical distance from the tunnel profile at the end of the boreholes, denoted "stick" is assumed to be the same as the thickness of the sealed zone around the tunnel. The need for the incline to be adapted in order to hit the flowing fracture plane optimally is shown in earlier sections. The impact of spread (thickness) and the sealing factor that is achieved for ingression into the tunnel are shown in the figure below.

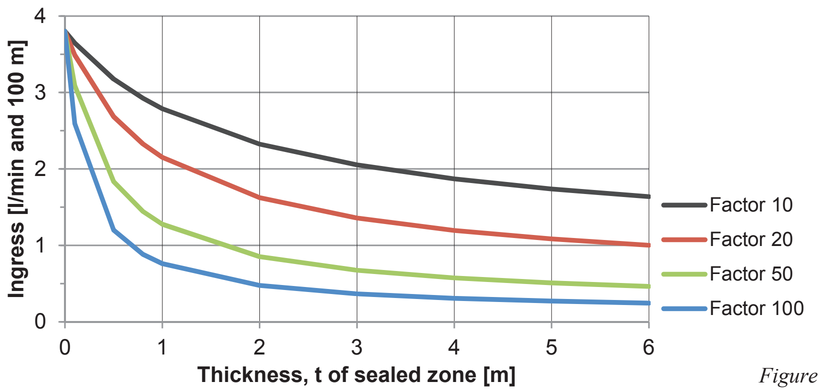


Figure 7-5. Ingression into the tunnel as a function of the thickness of the sealed zone and the sealing factor achieved.

The term sealing factor refers to the relationship between the permeability of the sealed zone and the surrounding rock (T_{tot}/T_{inj}= >1). The ingression, q, is calculated for different thicknesses in the sealed zone, t, according to the following (Gustafson, 2009):

$$q = \frac{2 \cdot \pi \cdot T_b \cdot H / L}{\ln\left(\frac{2 \cdot H}{r_t}\right) + \left(\frac{T_b}{T_{inj}} - 1\right) \cdot \ln\left(1 + \frac{t}{r_t}\right) + \xi}$$

As Figure 7-5 shows, a penetration of 2 m is sufficient along with a sealing factor of 50 to meet the ingression requirement of 1 l/min per 100 m of tunnel. Earlier analyses of the borehole direction in relation to the fracture orientations showed that penetration of at least 5 m would be suitable. Shorter penetration would mean that fewer planes would be hit. Penetration of 5 m and a sealing factor of at least 50 would produce an ingression of approximately 0.5 l/min. The knowledge that we did not hit one of the dominating fracture sets/fracture groups, means that the preliminary choice of geometry is retained. It should be borne in mind that the sealing factor is not a design parameter in this case and only provides an indication of what can be achieved.

Geometry, grout and technique

Smallest and largest hydraulic fracture aperture 3.1

With the aid of the hydraulic fracture distribution in Figure 7-4, a smallest fracture aperture can be determined. The design fracture aperture must concur with the ingression requirement, i.e. all fractures down to the fracture aperture must be sealed.

Assuming that all open fractures are flowing, the contribution of each fracture to the ingression can thus be calculated. For each sealed fracture, the total of the contributions from the unsealed fractures can be calculated according to the ingression formula above. Using such a procedure, the following is obtained (Table 7-1).

Table 7-1. Estimated ingression without grouting, where the largest fracture aperture is sealed, and which fracture aperture (design fracture aperture) needs to be sealed to meet the ingression requirement.

b_{min} [µm]	Estimated ingression, q_{grout} [l/min·100 m]	T_{grout} [m²/s]	Comment
None	3.8	2.4×10^{-6}	Without grouting
136	2.9	8.2×10^{-7}	Largest fracture sealed
34	1.0	1.3×10^{-7}	Critical fracture aperture

The relationship between transmissivity for ungrouted rock and a sealed zone is in this case only a factor of 20.

As shown in the table, all fractures with a hydraulic aperture down to 34 µm must be sealed to meet the ingression requirement of 1 l/min per 100 m of tunnel. This approach provides a robust and traceable design requirement.

Summary of design requirements:

- The design fracture aperture is 34 µm.
- The largest assumed fracture aperture is 136 µm

Grout, 3.2

The flows encountered during core drilling were small. The interpreted hydraulic fracture aperture that needs to be sealed ranges from 34 to 136 µm.

Cement contains particles and its penetration capacity is limited by these particles. A theoretical approach shows that particles can penetrate into columns that are $3xd_{95}$ (mesh aperture where 95% pass during one sieving). For normal cement, d_{95} could be in the size range 16-30 µm. This is equivalent to column apertures of 50-100 µm, which is thus the smallest aperture the cement can penetrate and seal. As the aim is to seal a large number of small fractures, silica sol is selected as the only ordinary grout.

Hydraulic tests should be used to check if the flows can be greater than those expected. If higher flows are found, these boreholes should be grouted with cement. Cement must thus be available at the workplace.

Summary of grouts:

- Silica sol as an ordinary grout
- Cement in the case of larger flows and larger interpreted hydraulic fracture apertures

Fan geometry and the required penetration length 3.3

Determining the smallest required penetration length is an iterative process, where the starting point is either a specified geometry (the distance between the boreholes) or a desired penetration length, and the distance between the boreholes is determined accordingly.

Fan geometry

Below, the starting point is the assumption that the fan geometry has been set (Figure 7-6).

Geometrical data for the grouting fan:

Bore hole length= 20 m
Stick= 5 m
Distance between boreholes at tip= 3.5 m
Number of boreholes= 18
Distance between boreholes at start= 1.7 m

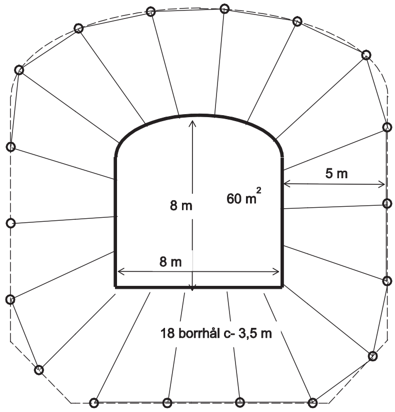


Figure 7-6. Fan layout viewed from above. The penetration is 5 m, which produces 18 boreholes with a distance between each hole of 3.5 m.

Required penetration length

The required penetration length in the dimensioned fracture apertures is determined by the borehole distance at the end. Given the fracture survey and the undulating appearance of the fractures, penetration will not take place at right angles between the boreholes. To compensate for this, what is termed an overlap is made between the boreholes. One recommendation used in many grouting projects with silica sol is a 50% overlap between the boreholes, see Figure 7-7.

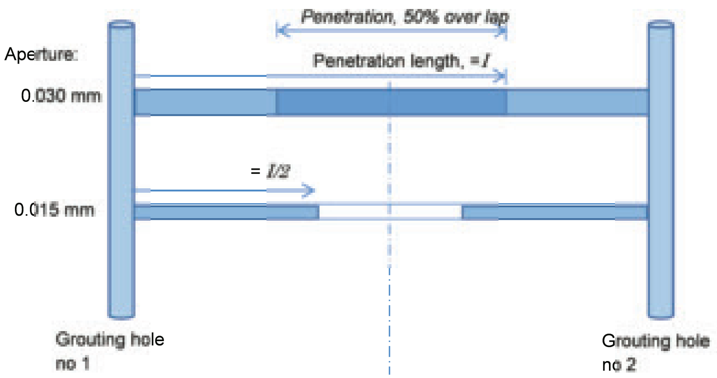


Figure 7-7. Demonstration of the overlap, 50% between two boreholes in relation to the fracture aperture.

The required penetration length, I_{erf} is calculated as

$$I_{erf} = \frac{c}{2} + c\,\frac{OL/100}{2}$$

Where c is the borehole distance at the end in metres and OL is the overlap that has been set in %. With a distance of 3.5 m and an overlap of 50%, I_{erf} = 2.6 m.

The penetration length in a design fracture aperture governs how the fan can be designed. The maximum penetration length for two-dimensional flow with silica sol, $I_{max,\ 2\text{-}D}$, is calculated using (Gustafson and Funehag, 2008a and 2008b)

$$I_{\max,2-D} = 0.45 \cdot b \cdot \sqrt{\frac{\Delta p t_G}{6\mu_0}}$$

where b is the hydraulic fracture aperture, Δp is the exerted overpressure, t_G is the gel induction time and μ_0 is the initial viscosity of silica sol.

In the graph below, the penetration length is shown at different grouting overpressures and different gel induction times and the resulting penetration length. The required penetration length is marked on the graph.

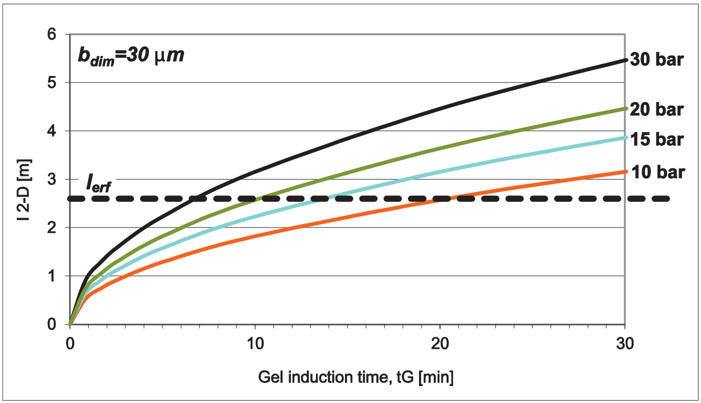


Figure 7-1. The penetration length for a dimensioning hydraulic fracture aperture, 30 µm, as a function of the grouting of pressure and gel induction time. The required penetration length of 2.63 m is marked as a horizontal broken line.

The gel time is three times the gel induction time. A gel induction time of 10 min means a gel time of 30 min. The penetration length at 10 bar overpressure is 1.8 m. At a higher pressure, 20 bar, the penetration length is 2.5 m. As can be seen, there are numerous opportunities to combine pressure and time.

Required penetration length adapted to grouting time and borehole distance

The grouting time that should be used depends on the conditions but it should never be shorter than half the gel time. In the case of deep tunnels >100 m, or where there are steep gradients, there is a considerable risk of erosion. Under these conditions, more careful analyses need to be made regarding hydraulic gradient and the risk of erosion. Generally, the grouting time for deep tunnels should be at least two-thirds of the gel time.

The adaptation of grouting time and pressure should take place based on experience and to make it possible to update the design as grouting proceeds. Below are a number of adaptation possibilities:

- Short gel times <15 min can make it difficult to find time for mixing, pressurising hoses and the actual grouting.
- Long gel times >50 min produce long grouting times and probably a high grout consumption.
- The grouting time is set at half the gel time for shallow tunnels.
- Grouting time is at least two-thirds of the gel time for deep tunnels or where there is a risk of erosion.
- The borehole distance should be adapted depending on which fracture aperture needs to be sealed. A longer distance can be used for larger fracture apertures but should not exceed 5 m.
- The borehole distance should not be less than 2 m during the first round as this could result in a large number of connected holes.
- The grouting overpressure, *Δp*, is a matter for discussion. As an initial guide figure to avoid 'jacking", it should not exceed three times the weight of the rock cover – twice the water pressure according to $\Delta p \leq 3\rho_b g d - 2p_w$

In the graph below, the smallest required penetration length is linked to the borehole distance and grouting time (Figure 7-9).

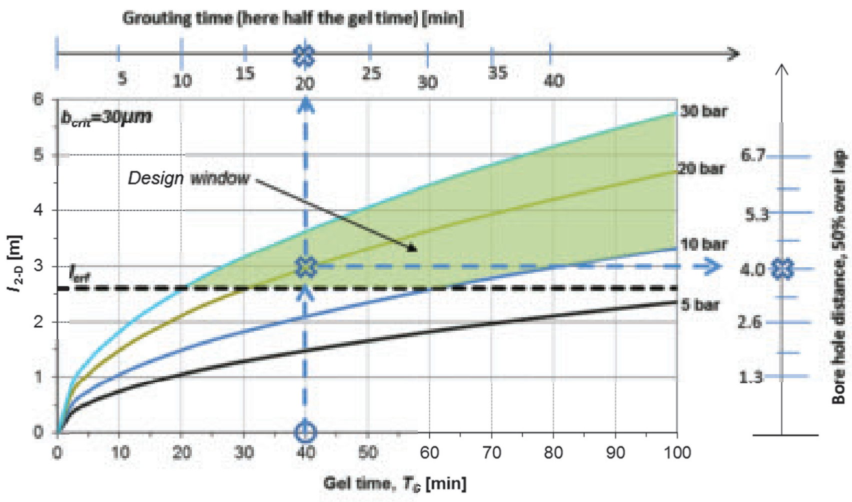


Figure 7-9. Choice of grouting time and pressure in relation to the borehole distance.

The borehole distance in this example was set at 3.5 m, which produced a minimum necessary penetration length, I_{erf}, of 2.6 m, the largest possible grouting overpressure, *Δp,* for our example is 2.4 MPa = 24 bar. If this is used in the graph above, this means, roughly estimated, that the grouting time is 20 min at 20 bar overpressure and a gel time of 40 min. The penetration length, I_{2-D}, would then be 3 m, which is longer than the minimum set penetration length of 2.6 m. This would mean that the borehole distance at the end tip could be increased to 4 m.

Summary of the design so far:

Hole end distance	> 3.5 m < 4 m
Grouting overpressure	20 bar
Grouting time on achieving the design pressure	20 min
Gel time	40 min

Final design 3.4

Checks and subsequent actions to achieve the features that have been established are an important part of the grouting process. The checks include a check of the grout and check that the ingression requirement has been satisfied.

Checking of grout

Checks include pre-testing in the laboratory and in the field as well as ongoing testing in the field.

Pre-testing to produce a recipe is done preferably in the laboratory with the aid of a rotation viscometer, a rheometer. The following parameters are measured:

Feature	Unit
Viscosity, rising viscosity	Pas (Pascal second)
Gel time	Minutes

The viscosity tests should be combined with beaker tests for the gel time. With this introductory study, a recipe can be produced. The chosen shear rate of the rheometer should be related to the shear rate during grouting. Often, the fractures are small, giving low flow speeds. Hence, the shear rate applied to the rheometer should be small, in the range 3-10 1/s.

Measurements should be made at the temperature that is relevant to the upcoming grouting (the temperature in the rock). Gelling is very much temperature-dependent. A simple rule of thumb is that the gel time is halved if the temperature is doubled.

Unmixed silica sol ages with time; silica sol that is approximately two months old gels slightly quicker than totally fresh silica sol.

Before grouting commences in the field, the gel time must be checked at the actual temperature and volume of the mixture. The process is similar to the ongoing testing described below. A beaker test should also be carried out for each new delivery to ensure the grout has the required features as stated by the manufacturer.

Ongoing control of the grout

In the field, beaker tests should be carried out regularly. When a new recipe is to be used, a beaker test ought to be carried out for each mixture until at least three consecutive mixtures reveal a gel time that does not vary more than ± 2.5 min from the expected gel time. If this is successful, the testing can be conducted less frequently and only needs to be done for every third or fourth mixture.

Measures that can be taken to achieve the desired result include an adjustment of the volume of silica sol/saline solution as well as control of the barrel pumps and after-running and the influence of the load cells depending on whether hoses are filled or not.

The following applies to the three mixtures: If the first mixture proves to be below or above the gel time, the hole does not need to be flushed and the grouting can be counted. The next batch, however, needs to be adjusted to achieve the desired gel time. If this mixture falls within the limit for an approved gel time, one more batch is sufficient to achieve three consecutive approved mixes.

Ongoing testing covers control of gel time and temperature as follows.

Feature	**Equipment**
Gel time	Disposable plastic beaker
Temperature	Thermometer

During grouting of a fan, it will be necessary to keep a check on quite a large number of beakers. Each beaker should thus be marked with a borehole number and the time of mixing.

Control and action to be taken to deal with ingression

Carrying out grouting in accordance with the set geometries, grouting technology and grout that result from the design process could, under ideal conditions, achieve the desired sealing outcome for the tunnel. Rock is complex and generally impossible to describe as entirely suitable for grouting. The design that has been prepared to date is based on information from the preliminary investigation and is thus designated as the ‘base design’. The scope for updating the base design should be included in the description.

To make this possible, a *hydraulic test* should be carried out in the grouting boreholes. The tests can show if the expected flows and interpreted hydraulic fracture apertures fall within the limits of the base design. If not, other grouts could be used as well as a more suitable fan geometry and grouting technique.

To check that the desired sealing outcome is achieved between the boreholes (that the overlap and the chosen penetration length are working), control holes can be bored as part of a second round, what is termed ‘split spacing’. For a specific section of the tunnel with similar rock conditions, controls can be carried out to a limited extent. Founded on this, the base design can be updated and then applied to the tunnel section further ahead.

A measurement that has been used quite frequently in a number of projects involving silica sol is comparing the median inflow in boreholes before grouting with the median inflows after the first round of grouting in the control hole. A drop in the median ingression compared with the desired reduction in transmissivity (factor 50, 100 etc.) should be an indication that the design that has been set up is achieving the desired results. However, it is ingression into the tunnel measured at weirs that confirms whether the results have been achieved. It could be possible to set up temporary measurement weirs while tunnelling to indicate whether the grouting is adequate or not.

During the actual grouting, several observations could lead to the base design being updated. Control is always carried out with the aim of achieving sufficient penetration length in the design fracture aperture and the following observations are controlling factors:

- If the design pressure is not achieved – increase the gel time and reduce the pressure.
- If the design time is not achieved – reduce the gel time and increase the pressure.

In certain cases, control could result in an unacceptably high volume of grout and excessive time taken. The preparation of a flow diagram that is accessible for the grouting personnel is vitally important. An example is shown below.

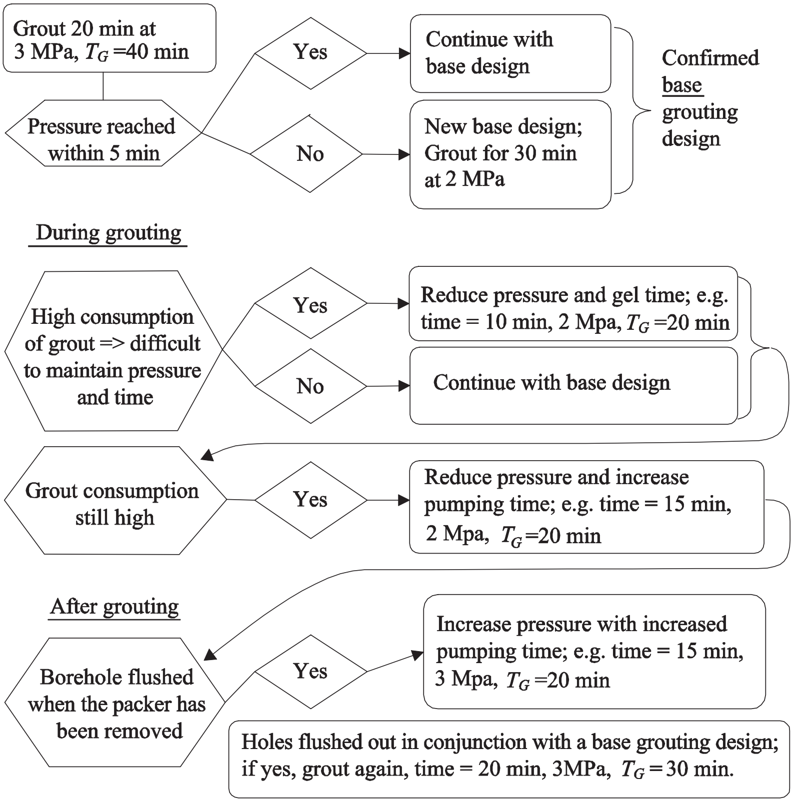


Figure 7-10. A flow plan in principle with proposals for measures when the stop criteria of pressure and time cannot be achieved.

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