R-07-30

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Current competence and development for the final repository

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Preface

This report presents the overall status of rock grouting competence and the development related to the final repository.

The authors are involved in rock grouting research or rock construction and grouting projects on a daily basis. Project experience makes it clear that organisational aspects are of vital importance for the final quality of the work. Therefore organisation and management are also discussed as an input for the planning of the construction project, which is going on within the spent fuel project. It should be emphasised that the suggestions offered as principles for planning, design and execution of grouting reflect the current viewpoints of the authors and may not necessarily coincide with the considerations made and solutions finally reached and presented by SKB.

Valuable review comments were received from among others PhD Mats Holmberg, Tunnel Engineering; PhD Don Moy, Consultant Engineer, Berkshire, England; PhD Arild Palmström, Norconsult; Professor John Hudson, Rock Engineering Consultant and Erik Lindgren, Ramböll. The report was approved by Tommy Hedman, SKB.

Stockholm, June 2007

Ann Emmelin

Contents

1 Introduction

1.1 Background

The Swedish final repository for spent nuclear fuel will be constructed according to the KBS-3 method. This means that the spent fuel will be encapsulated in tight, load bearing canisters and deposited at 400–700 metres depth in crystalline bedrock. The canisters will be surrounded by a buffer to prevent ground water flow and protect the canister, and the rock cavities required to deposit the canisters will be backfilled. To construct the repository, a final repository facility is required, see Figure 1-1. Site investigations are currently under way at two sites: Laxemar in Oskarshamn and Forsmark in Östhammar. These are providing data for rock mass characterization, for planning, and for preliminary layout and design work. Although the repository facility will be located in rock mass of good quality with mostly relatively low fracturing, control of the ground water will be necessary. The measures to control ground water will include the sealing of fractures that are conducting ground water, and may also include local draining or waterproofing as well as infiltration of water. Sealing will be achieved by means of grouting, which means filling the water-conducting fractures with grout so that the permeability of the rock mass close to the tunnel or rock cavern is reduced.

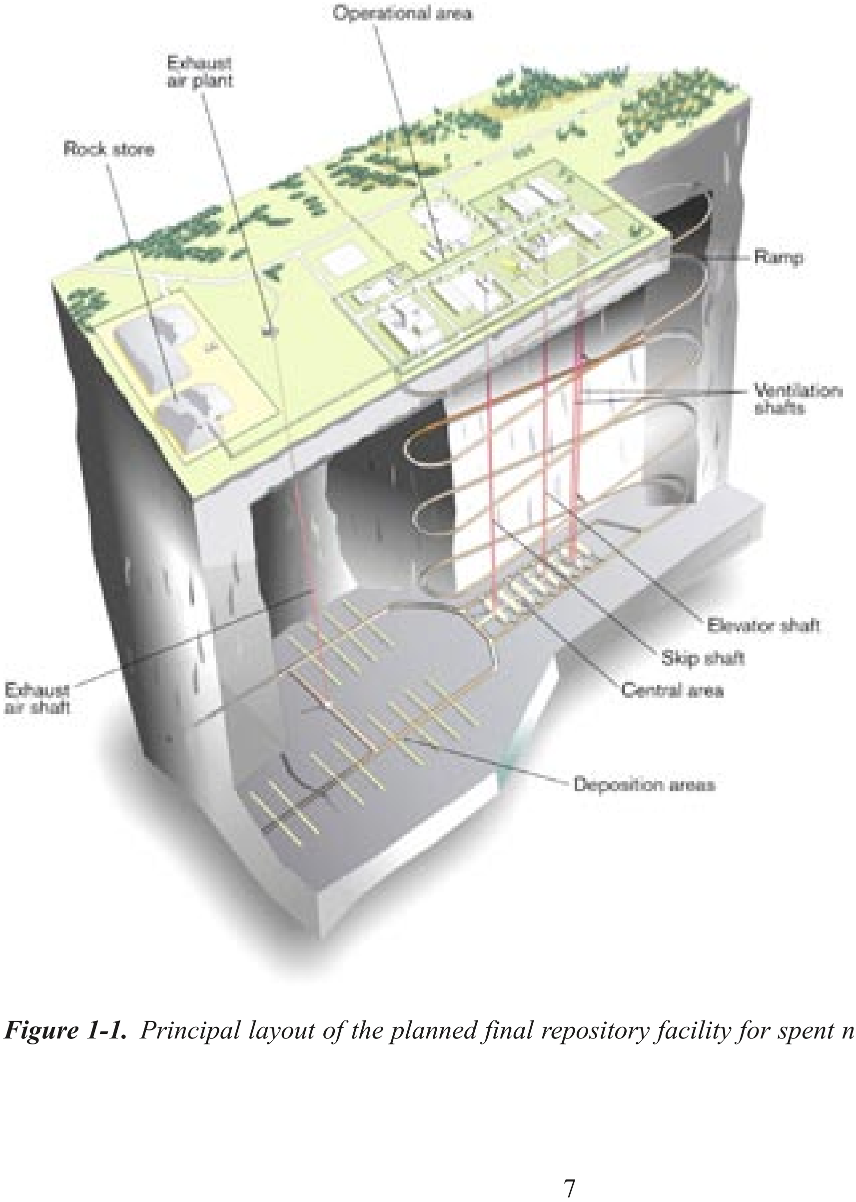

Figure 1-1. Principal layout of the planned final repository facility for spent nuclear fuel.

Swedish bedrock is to a major part composed of hard crystalline rock, favourable for rock construction. This combined with a strong mining tradition and technical development has made Sweden a strong rock construction nation. The rock mass, seen as a building material, is however not readily described by a number of distinct parameters, and the construction technology has therefore to a large extent been based on empiricism.

In 1989 the International Society for Rock Mechanics (ISRM) stated that rock grouting was carried out "although successfully, almost exclusively on an empirical basis". It was concluded that project engineers needed a better basis for planning and implementation of grouting operations and the ISRM Commission on Rock Grouting was founded. The commission task was to compile theoretical knowledge and practical experience related to grouting, and the commission report was presented in 1996 /ISRM 1996/. In a Swedish study it was reported that opinions differ among designers and contractors as to how analyses should be done and especially how grouting should be done in practice /Andersson and Janson 1998/.

The same general hydrogeological requirements will apply for the repository facility as for any other underground construction in rock: allowing only limited lowering of the groundwater table, and limited groundwater flow into the underground excavations. In addition, special requirements related to repository performance and long-term safety must be met.

To meet these requirements and to complement the empirical base with theoretical understanding, SKB has initiated a series of research and development projects concerned with rock characterization for grouting, grouting materials, grouting predictions and grouting design. Projects have been conducted since 1993 and new projects are still under way.

The goal of SKB's grouting research and development has been expressed as follows:

> *To provide competence, grout and equipment to handle all inflow situations, taking into account the special demands made by the final repository.*

Progress in the area of grouting has also been made thanks to studies and research financed by other organizations, and a number of references on the development of grouting theory as well as production grouting are available.

At the same time as grouting technology has advanced, concern for environmental matters including occupational health and safety has also grown, along with a realization that the costs involved in maintaining underground facilities can be quite large. These factors, combined with a higher expropriation rate of land and a growing use of the subsurface space in densely populated areas, have given rise to increasing demands on the sealing process, the disturbances it creates and the sealing result.

Two projects that have added momentum to the aforementioned progress may be mentioned. The first is the construction of the Stockholm subway system, where the excavations for Karlaplan and Mariatorget in the 1960's resulted in a lowering of the groundwater level, with large settlements of clay and structures resting on wooden piles. It was realized that in order to avoid such damage when tunnelling under similar ground conditions, severe restrictions had to be imposed on the extraction of groundwater /Knutsson and Morfeldt 1973/. The second project is the railway tunnel through Hallandsås ridge, where problems have been encountered in sealing heterogenous rock mass under a tight schedule, resulting in environmental damage, lawsuits and severe time delays /SOU 1998:60/. The construction of the Stockholm subway system can be said to mark the start of technical research on grouting in Sweden, whereas Hallandsås highlighted the need for a more holistic approach including organizational aspects of grouting.

1.2 Aims and contents of the report

The report aims at presenting the overall state of grouting competence and development relating to the final repository and at motivating and giving detail to the grouting sections presented in the 2007 version of the overall SKB RD&D report “Programme for research, development and demonstration of methods for the management and disposal of nuclear waste” that is presented to the government every three years. The report offers suggestions for principles for planning, design and execution of grouting and describes the further work thought to be necessary in order to meet the requirements of the final repository, that are currently given as working premises. The report also provides a comprehensive presentation of the viewpoints, concepts and knowledge that have emerged from the grouting development work at SKB and in other organizations in order to disseminate this information within SKB’s own organization for the continued work on concepts, design, planning and application for the possession, construction and operation of the final repository facility. This report does not aim to, and cannot, describe the grouting processes in detail. For details of current concepts, experience and development work, a list of references is provided.

In Chapter 2, the task of sealing the underground repository is examined and an overall approach presented. Although the requirements related to this task are preliminary, it is made evident that they concern both the actual grouting results and the process leading to the achievement of these results.

Chapter 3 is a conceptual description of grouting and the factors that govern the spreading of grout in the rock mass. It is intended as an introduction to Chapters 4–6, which describe the state of grouting competence and the tools available for the sealing of the final repository facility. Both common practice and cutting-edge research are dealt with in these chapters, mainly relying on references where available. Chapters 4 and 5 focus on the system consisting of the fundamental components the rock mass, the grout materials and the grouting technology, and how these system components interact whilst, in Chapter 6, the rock/grout technical system is viewed in a brief organizational context.

Based on the requirements on results and the overall grouting process on the one hand and the current competence in grouting theory and practice on the other, a strategy can be arrived at to meet the requirements. The proposed strategy is presented in Chapter 7. The gap between the requirements on results and process and the available competence is discussed in Chapter 8, leading up to a presentation of proposed plans for activities and development work needed to close this gap.

The level of detail given in the text varies. Fundamental concepts and principles are presented as a basis for more detailed descriptions of new concepts currently under development. These basic concepts mostly concern areas that are under development, and the level of detail provided is intended to clarify both the conclusions that are presented and the plans for further work.

SKB’s general requirements and organizational aspects are discussed elsewhere and are primary topics in other SKB reports or contexts. However, project experience to date makes it clear that these matters are of vital importance to the final quality of the work, and discussions on how to meet the project requirements cannot be completed without taking the organizational aspects of grouting into account. Thus, this report does not deal with technical matters only.

2 Goals and requirements on processes and grouting results

2.1 The final repository facility – a nuclear facility and an underground construction project

From the day SKB receives a permit under the Nuclear Activities Act to build the repository facility, SKI's regulations "SKIFS" will apply to the project. The SKI regulations of most importance for the final repository and final repository facility are SKIFS 2002:1 concerning safety in connection with the disposal of nuclear material and nuclear waste, and SKIFS 2004:1 concerning safety in nuclear facilities. Even though the grouting has no barrier or safety function it is obvious that the nuclear character of the project raises demands on transparent, comprehensive and systematic processes and careful management of the processes.

The final repository facility differs from other nuclear facilities as the purpose is to construct a final repository that shall be safe for thousands of years after the facility has been phased out and sealed and not only during the operation and decommissioning phases. Some characteristics can be pointed out, as follows:

- Construction will continue for a very long period of time and will be carried out in parallel with the handling and emplacement of the canisters containing spent nuclear fuel.
- A nuclear power plant should maintain the production and nuclear safety during operation and is continuously supervised, maintained and improved. In the case of a final repository, the safety functions are passive and shall be provided throughout the long-term safety assessment period.
- Regular supervision and inspection of tunnel stability and watertightness cannot be undertaken once a deposition tunnel is backfilled and sealed.
- The final repository must not require any maintenance once it is sealed. This means that the long term safety of the repository cannot be dependent on the durability of the grout unless this durability has been proven.
- The materials used for grouting must not interfere with the integrity of the repository during its entire life span.
- During construction and operation investigations, modelling and detailed design must run in parallel to each other. During construction of the repository the knowledge about the site conditions increases progressively. For the construction of a nuclear power plant the premises are known from the beginning.

In short, it can be concluded that meeting the actual sealing requirement will not be sufficient. SKB must carefully consider the processes to be used during grouting technology development, as well as processes related to design and execution of grouting. Furthermore, at the time of application, SKB must demonstrate the feasibility of the grouting technology and processes to be implemented. The meaning of this is further examined in Section 2.3.

Because it is an underground rock construction project, the project must meet special requirements. The nature of a rock construction project is governed by the fact that the building material is the rock mass, and the properties of the rock mass cannot be completely known, see Section 2.4. This also applies to the planned repository facility, even though extensive investigations have been carried out.

The dual nature of the project as a nuclear project and an underground construction project defines the premises for the project. The processes and the organization must be comprehensive and robust in the sense that they must not only allow for identified, expected, normal and unfavourable situations, but also be prepared for the unexpected. Design and execution have to be carried out in a controlled way. The approach must be systematic and the final design must be based on actual conditions and requirements.

2.2 Requirements on grouting and grouting results

The requirements and restrictions on the actual grouting process for the final repository will stem from three primary concerns: long-term safety, the environment (including occupational health and safety), and efficiency in achieving production goals. The long-term safety-related requirements and restrictions are unique for the final repository project, while the others are typical of all tunnelling projects.

Requirements on the final repository facility will be systematically managed in SKB's requirements management system. The system provides a database where stakeholder requirements are broken down into system, subsystem and design requirements, so that all requirements can be traced down to a stakeholder, i.e. a party who has (legitimate) interests and right to make demands.

Some of the requirements on sealing results will be dependent on the geohydrological situation and are thus site-specific. Others are dependent on the design and performance of other subsystems. Because site investigation and development of subsystems such as backfill currently are under way (Complete site investigation stage, Design step D2), requirements are not definitely set. It can also be noted that final requirements may vary for different functional areas, i.e. for repository accesses, central area and deposition areas respectively. This regards not only actual sealing results but may also regard methods and materials used.

The current understanding of the long term safety is that it imposes demands with regard to inflow to the facility, the materials allowed for use and the disturbance of the rock mass, since the rock mass is one of the barriers in the KBS-3 system. Limited inflow is necessary to guarantee that the buffer and backfill can be emplaced without being eroded. The limitation will probably be stipulated as both maximum permissible spot inflows and accumulated inflows to a facility part, see Table 2-1. Limited inflow is also related to the risk of upconing and intrusion of salt water into the repository, as high salinity may have an adverse effect on the buffer and backfill. To protect the integrity of the rock environment, foreign materials cannot be freely used, and there is a preference, from the long-time safety perspective, to minimize the amounts of foreign materials at repository closure. Also some materials could be more adverse for repository performance than others. Limitations on pH of materials will, according to the current understanding, apply and the amount of any material used and its spread into the rock fractures should be controlled. Furthermore, any disturbance of the surrounding rock mass should be limited, which means that the drilling of holes for investigation, grouting or control outside the tunnelling contours should be limited.

Environmental requirements are concerned with the external environment (mainly at or near the surface) and the internal environment (within the rock excavation). Ground water inflow to the repository must be limited for the sake of both environments, as it could result in a lowering of the groundwater table, which could cause settlement of the ground surface and structures, the drying-up of wells, and disturbances in the ecosystem. Within the rock excavations, large inflows or excessive dampness could adversely affect worker health, working efficiency and quality, materials and equipment. Although not considered as a part of the load bearing structure, the grouting of a fracture zone intersecting a tunnel may also be an important part of the measures undertaken to ensure stability, as it will stop rock material from being washed away. Inflowing water has to be drained, pumped and treated, which in itself causes an impact on the environment. A general requirement is that the grouting materials used are the best available, taking into account environmental aspects – including occupational health and safety. The controlled spread of grout is also of environmental concern, and requires a controlled process for decisions and execution.

Grouting is a time and resource consuming activity, and is one in a series of activities in the tunnelling cycle that take place at the face. Depending on whether there are one or more faces available, this is more or less critical for progress. Efficiency in achieving production goals is not quantifiable readily, and it should be noted here that investigations and checks at the tunnelling face are as important as the other activities in the production chain. The requirement of production efficiency must be considered early in the overall planning. The technical and organizational framework, including timetables, must be set so that it is possible, especially during the start of construction works, to discuss, execute and evaluate different designs and ways to proceed.

Based on the preliminary stakeholder requirements and the discussion above, working premises for the grouting research and development work are set, as follows:

- Only grout that gives a leachate with a pH that is lower than 11 may be used.
- Superplasticisers and other additives may be used.
- There are no pre-set limits to the amount of materials that may be used, but in choosing between different approaches, the one giving the lowest material use is preferred.
- Long-term durability (durability longer than 5–10 years) is not an issue.
- Grouting boreholes outside the tunnel periphery may be used.
- Grouting or other bore-holes must not intersect deposition holes.
- Inflow requirements according to Table 2-1.

It should be noted that the evaluation of the working premises above include evaluation of different superplastizisers and that the estimated amounts of grout presented in the designs will be used as an input to the long-term safety assessment and their impact on the safety analysed.

The requirements for the design work are presented in the reports "Underground Design Premises" (UDP). UDP is progressively updated as the design process proceeds. Design premises for step D2 include the premise that the grouting concept should be based on low-pH ($pH \leq 11$) cementitious grout for larger fractures (hydraulic aperture > 0.1 mm) and silica sol for smaller fractures.

It is realised that the finally allowed inflow levels will be as tough or tougher than in more conventional underground construction projects such as road or rail tunnels at moderate depths. Limits of around 1–3 l/min, 100 m can be considered a common level for a road tunnel in a geotechnically sensitive urban area, and it should be born in mind that the inflow is directly proportional to the surrounding ground water pressure. The preliminary allowed inflows for Design Step D2 to different facility parts are shown in Table 2-1. The preliminary levels may be modified as a result of the development and analyses work under way.

Table 2-1. Inflow requirements; values approved by SKB for design step D2 until further notice.

Deposition hole	Spot inflow: 0.1 l/min
Deposition tunnel	10 l/min, 300 m of tunnel Spot inflow: 1 l/min
Shafts and access ramp	10 l/min, 100 m of tunnel
Other underground facility parts	10 l/min, 100 m of tunnel

2.3 Demonstrating feasibility of grouting technology and processes

SKB has to demonstrate the feasibility of available grouting technology and the capability of applying it. This includes both credibility that the required sealing result can be achieved and that we have the means and competence to actually achieve it. In order to identify what should be demonstrated, the concept of “competence” and related terms are explored.

The code “Quality Management systems – Fundamentals and vocabulary” /SS-EN ISO 9000:2005/ defines competence as the “demonstrated ability to apply knowledge and skills”. The ISO-code does however not define the elements “ability”, “knowledge” and “skills”.

A similar approach to the concept of “competence” is made in /EPC 1996/ where competence is described as a “mixture of specialist skills, knowledge and know-how”. EPC states that to enable responsible innovation a fourth element “understanding” is also needed. However, to underpin competence within current practice only a little understanding is actually necessary. EPC also provides explanations of the elements included in the definition. Based on these explanations, the interpretations of the elements required for grouting would be:

- Knowledge: Knowledge refers to information on the structures and properties of elements like fractures, grout, pump capacities, system properties from field investigations and the performance of similar systems from databases and reports etc.
- Understanding: Understanding means a conceptual understanding of the processes involved and the resulting behaviour of the system, i.e. the interactions occurring within the system comprised of rock fractures – grout – grouting technology.
- Know-how: Know-how provides a problem-solving capability acquired through experience. This involves having adequate processes for managing the grouting, including processes for evaluation and acting on the results. It also includes the know-how to set up and run the organization (project model, contract, compensation and other incentives) in such a way that it encourages and allows for technical competence to be put to use.
- Skill: According to /EPC 1996/ “A skill is best defined as a complex sequence of actions which has become so routinized through practice and experience that it is performed almost automatically”. The specialist skills needed include both “manual skills” like operating the machinery and equipment needed to carry out the task, and “intellectual skills” like designing, communicating and making decisions.

In order to cover “feasibility and capability” the list of competence-related elements described above, has to be complemented by the element “means”:

- Means: Means should be interpreted here as being materials and equipment. There are special requirements relating to chemistry and pH, to high groundwater pressures and to the need to seal very fine fractures. Materials and equipment which fulfil these requirements and are suitable for operation must be available.

It should be noted that none of the elements understanding, knowledge, know-how, skill or means; can exist without the others. Observations and results from the field and laboratory are needed to provide mutual feedback and further develop the elements. In other words, competence has to be ensured through cooperation between technical universities and industry.

To demonstrate feasibility, the following actions have to be undertaken and the results presented:

Understanding and knowledge

In the past few years, there has been a substantial expansion of the theoretical basis for making predictions, for choosing grouting materials and for execution. Gradual application and evaluation in different infrastructure and research projects is of vital importance for the validation and continued development of the theoretical basis and for extending the database.

Know-how

The demonstration of know-how has, to a large extent, to be based on the execution of different infrastructure projects, mainly undertaken and presented by other organisations. Focus should be on showing that there can be a controlled process of adaptation to the rock conditions encountered, that the mechanisms and parameters that guide the grouting results can be controlled and that operations lead to the desired results. Methods and project-specific criteria for follow-up and control have to be defined based on the actual requirements of the repository in order to be able to ensure that the grouting goals are accomplished.

Skill

As a basis for the skill required for the construction of the final repository, management and workers must have theoretical understanding as well as relevant field experience. A process for demonstrating and documenting the relevant knowledge necessary to do the job should be considered.

Means – Materials and equipment

The requirements should be analyzed and described, and the availability of suitable materials and equipment must be guaranteed. This includes equipment for the precise registration of the grouting variables as a means of controlling and permitting adaptation to local conditions.

2.4 Confidence and uncertainty in underground construction

Underground construction in rock is about dealing with a material that cannot be completely known. This applies to any rock construction project, including the final repository, even though extensive site investigations and analyses are carried out. The premises are thus quite different from, for example, concrete construction projects, where the material is specified beforehand and rejected if it fails to meet the specifications.

The nature of uncertainties can be divided into two main categories; aleotory and epistemic uncertainties. Uncertainty due to true randomness of the process is known as aleotory. Tossing a coin is a typical example of such a process. The outcome is completely random and the process can be repeated. The other category is called epistemic, for which the uncertainties exist because we do not know enough about them. If we will get full information the result will be deterministic. Uncertainties in ground conditions therefore stem from the second category and are related to our lack of knowledge (information) about materials and geometries /Christian 2004/. The uncertainties are related to the number of measuring points, the relevance of investigation methods, the relevance of measuring points, the precision of the data collected and the actual variability of the rock.

It may also be pointed out that the interpretation of the probability concept itself will also be different. In geotechnical engineering, it is difficult to have a frequentistic approach as every situation is unique. The frequentistic definition makes no sense. Uncertainty is more related to our degree of belief of how likely a certain event is. For this type of problem a special view has been developed called "school of degree-of-belief". The probability will then be a measure of confidence in an uncertain outcome. This view has also got the name Bayesian statistics after Bayes' theorem of updating. We want to model our uncertainties to get a basis for good engineering decisions, and not to describe a reality which, fundamentally, cannot be described.

In discussing data uncertainty, it is important to distinguish between error, precision, bias and accuracy, see Figure 2-1. Data are analyzed and models fitted presenting both deterministic and stochastic data as a basis for design. Assumptions made in interpretation and synthesis adds to the uncertainties. Models are updated in steps and investigations are focused where uncertainties are found to be the greatest. This procedure implies a possibility to verify the model at the limits necessary to enable an engineering design and to ensure that the grouting objective is achieved.

Consequently it has to be demonstrated that a process exists that can cope with the uncertainties present at each stage.

The epistemic related uncertainties in the rock mass have given rise to an interactive design process, where a design approach is progressively updated and detailed as knowledge concerning rock mass conditions increases. The purpose is to reduce uncertainty and devise mitigating actions until it can be shown that the risk is acceptable. The alternative would be a fixed design based on worst-case conditions, which in most cases is not an alternative from a production efficiency point of view. For the planned repository, such a fixed and conservative design is also not an alternative as this would unnecessarily risk damaging the KBS-3 rock barrier with excessive grout holes and grout volumes.

The early stages of design assume typical ground conditions, after which it is demonstrated whether a technology exists that is robust enough to cope with the probable variations in conditions. Gradually, as experience is gained, uncertainties are reduced. It is not until the construction stage is completed that the design is final. In the case of grouting, observations of system behaviour, for example by means of inflow measurements, will confirm that the adopted sealing measures are sufficient.

The new Eurocode offers a formal means for an interactive design process, the "Observational Method", which handles situations where design has to be based on uncertain data and models. The principle entails progressive checking of the grouting results against predictions. It is anticipated that the design and execution of the grouting for the final repository facility will be managed by controlled adaptation to encountered conditions according to the principles of the Observational Method.

In a risk management context, the geological uncertainty is related to geological hazards. There are also technical, organizational and contractual hazards that should not be overlooked. A systematic system for risk management can be considered to be another prerequisite.

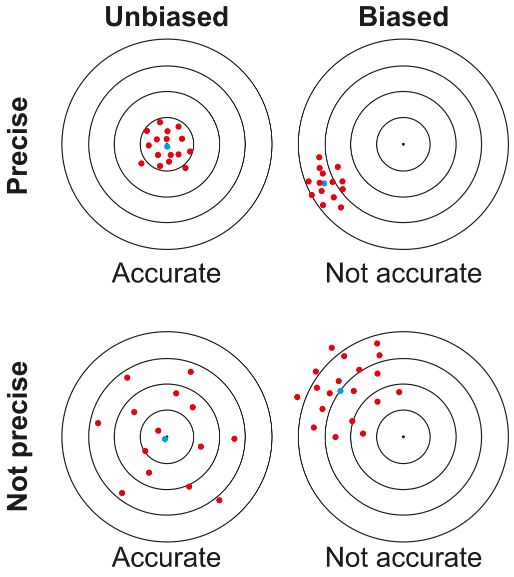

Figure 2-1. *An illustration of uncertainty in data; accuracy, precision and bias. From /Stille et al. 2003/.*

3 A conceptual description of grouting

3.1 Introduction

In this chapter, the purpose is to describe grouting conceptually. Further details and models are presented in Chapters 4 and 5.

Grouting is a process whereby a grouting material is injected into boreholes drilled into the rock mass around an excavation, with the purpose of sealing any fractures that intersect the borehole, i.e. to make the rock mass less permeable. The goal is to limit the inflow of water to a level that can be accepted. It is the task of the designer to determine the best technique or method for grouting.

3.2 Inflow into underground openings

Inflow into underground openings is determined by the permeability of the rock mass, the groundwater pressure, the size of the underground opening and the properties of water.

The intact rock is essentially impervious to flow, whereas the fractures conduct water and other fluids. The fractures form a more or less interconnected network. The degree of fracturing, the connectivity of the fractures and the type of fractures are the most important attributes to consider from a grouting point of view since they will determine not only the groutability but also the permeability of the rock mass and the inflow of water.

Fracture-controlled flow is discussed in many textbooks, see for example /Jamtveit and Yardley 1997/ where it is stated that the permeability field is determined by crack-like pores in the rock and is pressure sensitive. On a scale ranging over two to three tunnel radii, the properties of the individual fractures are the most important factors to consider.

The depth of the underground opening governs both the pressure and the pressure gradient. When the opening is excavated, a large pressure gradient is immediately created. As the pressure is redistributed, the gradient decreases and the flow reaches a steady state. In a low permeability rock mass, high pressures may also occur close to the opening.

The size of the underground opening also influences the flow within a reasonable range and a larger opening theoretically results in a somewhat higher inflow. However, this issue is complicated due to scale effects and possible skin effects see /Eriksson and Stille 2005/. In /Gustafson et al. 2004/, it was concluded that the size of the opening is of less importance.

After grouting, the fractures surrounding the underground opening should have been sealed so that the inflow of water is limited. The success of the grouting depends on the effective sealing of the fractures around the opening. This is often simulated or compared to a sealed zone surrounding the opening, where the permeability is determined by the unsealed fractures and the extent by the grout spread distance. The permeability and extent of this zone, the depth and the size of the underground opening then govern the inflow. See Figure 3-1 for an illustration.

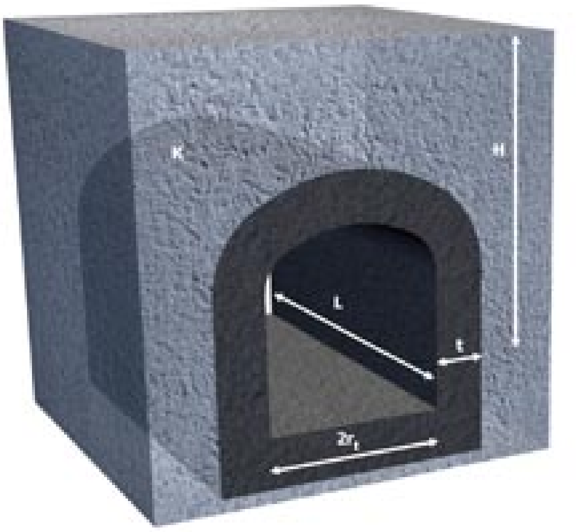

Figure 3-1. *Illustration of the sealed zone and the notations in Equation 5-1. K is the hydraulic conductivity of the rock mass, Kg denotes the hydraulic conductivity of the grouted rock mass and t the thickness of the zone. After /Eriksson and Stille 2005/.*

3.3 Elements influencing the sealing result

Sealing result refers to the reduction of the permeability of the rock mass, resulting in a reduced inflow.

The result of the grouting is determined by how well the fractures are filled with grout, in other words on how the grout spreads in the rock mass and how well the grout fills the fractures. An understanding of the fractures is fundamental for effective grouting, and different geological scenarios lead to decisions to use different grouting methods and grouts /Eriksson 2002/. These aspects are therefore essential for the grouting design, and they will be discussed in greater detail in Chapter 4.

The distribution of fractures within the rock mass is the result of numerous processes acting over time. For grouting purposes, the description can be focused on the properties of the rock mass and the fractures that affect grouting, i.e. characterizing the rock mass from a grouting point of view /Fransson 2001/. The characteristics of the rock mass should be described so that they can be used to choose a suitable grouting method, i.e. for grouting design. The grouting material and the grouting technique are chosen and optimized to achieve a good production and a good sealing result in the fracture system.

3.4 Grouting

Grouting is commonly done by drilling boreholes that project out of the planned contour of the tunnel, hence called a “fan” of boreholes, see Figure 3-2. The figure illustrates pre-grouting, which means that grouting is done ahead of the face. Grouting can also be done in boreholes in the excavated opening and is then called post-grouting. In general, pre-grouting is easier than post grouting, because of the effect of the excavation on the flow of groundwater and grout, backflow of grout and necessary limitation of grouting pressure to avoid rock fall.

Figure 3-2. *Illustration of a part of a grouting fan in a tunnel. The boreholes that intersect conductive fractures contribute to the sealing effect. After /Eriksson and Stille 2005/.*

Grouting is mainly carried out in the following order (from /Dalmalm 2004/):

- Drilling of grouting/probe holes.
- Cleaning of boreholes.
- Water loss or inflow measurements.
- Grouting.
- Hardening or "setting" of the grout.
- Drilling of control holes.
- Water loss or inflow measurements.
- Hole filling.

It is important that the boreholes intersect the fractures to be sealed. The fan layout should therefore be adjusted in relation to the orientation of the fractures. The boreholes are filled with pressurised grout. If the grout can penetrate the fracture and if the fracture is conductive, the grout starts flowing out into the fracture and fills it. The grout is expected to also reach and seal connected fractures. On this subject very little research exists. One study however, /Kikuschi et al. 1995/, presented observations from a grouting test where it was shown that grout transferred between intersection fractures.

The flow and the final penetration length depend on the fracture aperture, the properties of the grout, the pumping time and the grouting pressure /Gustafson and Stille 1996/. The manner in which the pumping operation is controlled can also have a substantial effect on grout penetration. With the same grout and the same pressure, a higher flow and a longer penetration length is achieved in fractures with a larger aperture. The fracture has a varying aperture and the grout can penetrate further in some directions than in others and hence produces a channelled spreading pattern.

The grout flow decreases with time, because of an increasing shear resistance along the grouted path. If the grout has a yield value (defined in Section 4.2.2) above zero, a zero flow can be obtained, but if the grout behaves like a Newtonian fluid with no yield value a steady flow is eventually obtained. At some point, the grouting is concluded. This should be done when the grout spread and the sealing effect are judged to be good enough to satisfy the project requirements.

The challenge in grouting is to achieve a sealing of the fractures to meet these requirements. Different strategies can be adopted based on the nature of the fracture system. The biggest difference in the fracturing is the distribution of apertures. A rough categorization could be:

- Mainly small aperture fractures.
- Some large aperture fractures.
- Both small and large aperture fractures.

These three different situations require different strategies from a grouting point of view. The more numerous the fractures and the more variable the apertures, the more difficult it is to achieve a high sealing effect.

Due to the spatial distribution of the fractures, probing or investigation is necessary in order to determine what kind of fracture situation exists ahead of the face. It can also be relatively difficult to determine what the fracture situation is and to choose a suitable grouting method. This makes it expedient to work with grouting classes, where a special indicator value suggests a special grouting method. The simplest system is naturally that if a water flow of some magnitude is measured in the probe hole, grouting is carried out, otherwise not.

An important aspect of the characterization and analysis of grouting is that there are uncertainties in both the input values and the models. There is considerable variation in the properties of the rock mass, which complicates both description and analysis. This can also be seen in practical grouting work, where there may be a variation in inflow of several orders of magnitude between different boreholes in a fan, see e.g. /Emmelin et al. 2004, Malm 2005/. This variation makes it more difficult to choose the most suitable technique for grouting. A probabilistic approach /Gustafson et al. 2004/ has certain interesting and promising features, and has been used successfully /Funehag 2007/.

4 Elements of the system

4.1 Rock mass

4.1.1 Rock mass description

As described in Chapter 3, an understanding of the characteristics of the rock mass is essential in grouting design. The ground water is conducted in the fractures of the rock mass, so the most interesting properties of the rock mass are the fracture properties.

The rock mass contains spatially distributed fractures of varying size and aperture. Descriptions of individual fractures based on the distribution of apertures have been the topic of many papers, e.g. /Hakami 1995, Zimmermann and Bodvarsson 1996/. The eight parameters used by Hakami to characterize a fracture include: aperture, roughness, contact area, matedness, spatial correlation, tortuosity, channelling and stiffness. Even though fracture flow is often estimated using parallel-plate theory, it is important to bear in mind that fractures have varying apertures and often contain infilling material. Figure 4-1 shows an illustration of a natural fracture.

The aforementioned parameters are believed to influence the grouting. However, a difficulty arises since direct investigations of the fractures cannot be carried out during construction in rock. Grouting design must therefore be based on a certain degree of uncertainty.

Grouting design is based on the most important properties of the rock mass:

- Transmissivity or specific capacity (distributions) and hydraulic aperture which are different measures on the flow properties of the rock mass features.
- Fracture frequency, orientation and connectedness.
- Depth including hydraulic head, gradient and rock stresses.

Based on these properties, a theoretically justified grouting design can be chosen, see /Eriksson 2002, Gustafson and Stille 2005/.

One of the parameters determined by hydraulic testing is referred to as transmissivity, which is the ability of a conductive features to transmit water. Between parallel plates, transmissivity is related to the so-called hydraulic aperture, b, based on the "cubic law" (see Equation 4-1):

$$T = \frac{\rho \cdot g \cdot b^3}{12 \cdot \mu} \qquad \text{Equation 4-1}$$

where ρ is the density of water, g is the acceleration due to gravity and μ is the viscosity of water.

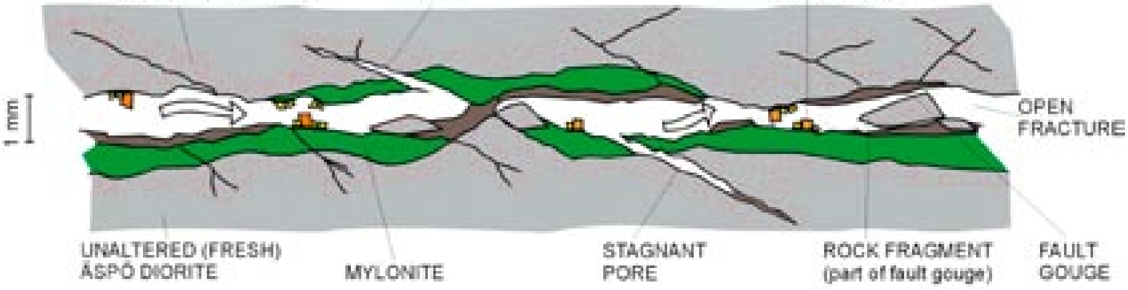

Figure 4-1. *Illustration of a fracture with a varying aperture and varying infilling materials /Winberg et al. 2000/.*

4.1.2 Assessment of rock mass properties

The assessment of rock mass properties is based on the characterization process. The objective is to provide the design with the necessary input to choose the most suitable grouting method.

Methods used for characterization for grouting purposes are described in /Fransson 1999/, who divides them into two groups: experience and measurements. Experience is a common foundation for describing rock mass properties and may relate to previous projects of relevance. Measurements may include geological mapping, and hydraulic or geophysical testing.

The most important method for determining the grouting properties of rock fractures is hydraulic tests. This category includes probing, water pressure testing, Lugeon testing and the like, and is routinely used in grouting projects. Due to their importance, a more detailed description of the different hydraulic tests is given below. The common practice today is that only hydraulic conductivity is evaluated from full-length borehole tests, using the water injection test (water pressure test, WPT). The result of the WPT is normally described by the Lugeon value, which can be related to the hydraulic conductivity. However, the Lugeon value can be misleading in the absence of data on the aperture and number of fractures in the test zone. From a grouting point of view, more information concerning the rock mass can be obtained from water injection tests if more thorough analyses are made.

Hydraulic tests are often combined with geological mapping to complete the conceptual model of the fracture system. An example of how to use hydraulic tests in the characterization process is presented in Figure 4-2. In this example from the TASQ tunnel project at Äspö /Emmelin et al. 2004/ investigation holes, probe holes and grouting holes all were used to investigate the fracture system.

The hydraulic head is often assumed to be equal to the depth or is measured in a closed borehole.

To describe the properties of the rock fractures, statistical methods are often employed, see e.g. /Dershowitz and Doe 1997, Gustafson et al. 2004/. The fractures are spatially distributed; hence a deterministic description is very difficult. A statistical description provides a basis for choosing the most appropriate design and describing classes. A general description of probability-based design methods is given in /Stille et al. 2005/.

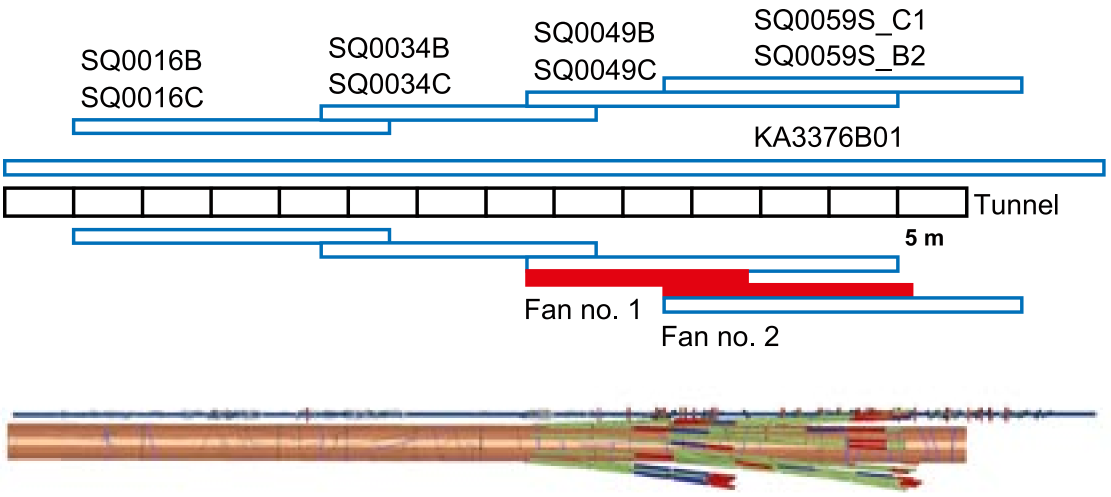

Figure 4-2. Illustration of the methods and the results of characterization used in the TASQ tunnel /Emmelin et al. 2004/. In the top figure, the investigation (KA3376B01), probe (SQ00xxx) and grouting holes (marked red) used for characterization are shown. In the lower figure, the interpreted result is shown. The inflows in grouting holes were measured in sections and leaking sections < 2 l/min are marked with blue while leaking sections > 2 l/min are marked with red.

Hydraulic (in situ) measurements /de Marsily 1986/ reflect the geometry of the conductive features of the rock mass. The idea underlying a hydraulic test is to measure the effect of a controlled disturbance of groundwater flow and then determine the hydraulic properties of the rock mass.

The parameters measured in the test are either the pressure variations at constant flow or the flow variations at constant pressure. Another way of determining the hydraulic properties for a relatively limited volume of rock mass is to inject a small volume of water in a borehole and measure the outflow of that pulse. The volume of rock mass that can be investigated depends on the duration of the test and the properties of the rock mass. When the test and the measurement of changes is conducted for one borehole, it is called a single-hole test; in the case of multiple boreholes, it is an interference test. Some of the hydraulic test methods discussed in /Almén et al. 1986/ are: (1) the constant-rate-of-flow injection test; (2) the pressure fall-off test (after the first test); (3) the transient constant-pressure injection test; (4) the pressure fall-off test (following the previous test); (5) the water injection test with constant pressure under assumed steady-state conditions. In addition to these, there are three pulse response tests: the slug test, the pressure pulse test and the drill stem test.

Tests (3) and (5) above use a constant pressure for the injection of water. The same principles apply to a pressure build-up test, but instead of injecting water, the borehole is initially left open and water flows out. By closing the borehole valve, a pressure build-up test is performed. Test (5) above is commonly used for grouting purposes and referred to as a water pressure test (WPT) or water loss measurement.

The flow rate can also be measured in individual borehole test sections of length L using the Posiva Flow Log /Rouhiainen 2000/ with assemblies of soft rubber discs that limit the section of inflow. The test section is moved in steps with a step length of dL. For "sequential flow logging" the test length is equal to the step length, whereas for "overlapping flow logging" the test length and each step length are different. The aim of the overlapping mode is to determine the exact depth of fractures or fracture zones. In addition to flow measurements, the Posiva Flow Log allows single point resistance measurements. This permits exact depth determination of flowing fractures and geological structures. A disadvantage of the Posiva Flow Log is its upper measurement limit, making natural inflow measurements during drilling a good complement.

The Posiva Flow Log, the water pressure test and natural inflow measurements all assume steady state conditions, mainly reflecting the rock mass surrounding the borehole. A transient, time-dependent test, such as the pressure build-up test, is able to reflect properties of the rock mass further away from the borehole.

4.1.3 Rock mass conditions at possible repository sites

The candidate areas for site investigations at Forsmark and Laxemar were selected because of their location in relatively homogeneous crystalline bedrock, without mineralization and without regional major deformation zones.

The following general description of the Forsmark geology is summarized from /SKB 2005/. At Forsmark, the candidate area is restricted to a tectonic lens, striking in a northwest-southeast direction and surrounded by regional deformation zones. The lens itself is dominated by a granitic to granodioritic rock (> 90%), which is foliated (and lineated) but not banded and has a rather homogeneous texture and mineral composition in the major part of the lens. In the upper part of the rock mass, hydraulically active fractures are common. Most of these fractures have gently dips, and a significant fracture zone separates upper fractured domains from a more sparsely fractured domain below. The fracture zone outcrops in the northwestern part of the lens and dips through the lens gently to the southeast. It affects the size of the lower, less fractured domain in these parts of the lens. Occurrences of localized gently dipping open fractures can be expected in the lower domain as well. There are a few, steeply dipping, minor fracture zones passing through the tectonic lens.

Statistical analyses of the rock mass fractures indicate a large spatial variability between the domains as well as within rock domain RFM029. At depths below –360 m, there are essentially no measurable water flows outside the deformations zones, but infrequent occurrence of low transmissive joints cannot be fully excluded. Generally, the fracture frequency is low, 0.2 fractures per metre in fracture domain FFM02. In the lower fracture domain FFM01 the frequency is lower and estimated at less than 0.01 fractures per metre. At shallower depth (< 200 m) some deterministically located fractures will be crossed by the access ramp and shaft according to the preliminary design /Brantberger et al. 2006/. There will also be some fracture intersections in the tunnels at deposition depth. The properties of the deformations zones vary widely. The zones at shallower depth have transmissivity values up to 10^{-3} m^2/s, whereas the deeper zones range up to 10^{-6} m^2/s.The length of the tunnel intersecting a zone may be in the range of 1–15 m.

The description below is summarized from /SKB 2006/. The pre-dominating rock type in the Laxemar area is to a large extent homogeneous with respect to lithology, texture and mineralogy. However, its composition varies between granite, granodiorite, quartz-monzonite and quartz-monzodiorite. A certain minor variation is recognized between neighbouring outcrops, but a larger rock boundary runs through the area in a northwest-southeast direction. Southwest of this boundary, the rock is dominated by quartz-monzodiorite to monzodiorite. Mineralogically, it has a higher content of dark, mafic minerals and lower content of felsic components. Along the boundary between the two major rock domains the rock is rather heterogeneous. The southwestern rock domain dips to the northeast and thus becomes larger with depth. Through Laxemar, a number of deformation zones of varying size penetrate the rock. Most of them are steep and have a restricted width.

The Laxemar area in general has a more permeable rock mass than the Forsmark area. The results of the complete site investigations are not available, but the preliminary investigation indicates a factor 10 of higher permeability in the bedrock at Laxemar compared to the Forsmark site. In terms of frequency and transmissivity, fracturing is reasonably uniform with depth, but there is a high variability in fracture orientation /SKB 2006/. Deterministically located fracture zones surround the area and the intersection of deformation zones will also occur at deposition depth.

In summary, the candidate areas are likely to contain a wide range of grouting situations in different areas of a repository, ranging from the intersection of a highly conductive zone with reasonably high groundwater pressure in the access ramp to reducing local leakages at the deepest levels. Thus, the toolbox for grouting must include several alternative methods to cope with these different situations.

4.2 Grouting materials

4.2.1 Grout description

The most common grouting material is based on cement. The grout is a mixture of cement and water and may contain additives, such as superplasticizers.

There are two main types of cement, Portland and slag cement, which are different in their chemical composition. The chemical composition also varies with the origin of the base material. A third type of cement is aluminate cement, for which the binding time can be controlled by using gypsum as an additive. The most commonly used cement is based on Portland cement, and commercial products are available from several manufactures.

The cement is often milled to a fine particle size 0–30 µm and is then referred to as micro cement /Eriksson and Stille 2005/. Micro cement is regularly used in grouting projects in Sweden and elsewhere.

Posiva in Finland is currently developing a low-pH cementitious injection grout. Several different recipes have been evaluated in the laboratory and some have been tested in the field as well. The most promising system according to the results presented in /Bodén and Sievänen 2005/ consists of ordinary Portland cement and silica fume.

As an alternative to cement-based materials, various solutions have been evaluated as grouting materials.

Silica sol or colloidal silica is an aqueous dispersion of discrete colloidal amorphous silica particles /Funehag 2005, Axelsson 2005, 2006/. There are several commercial products of silica sol. In /Funehag 2007/ three different products were used with small differences between them. Adding a saline solution initiates the gelling process. The properties of silica sol can be changed with different proportions of the added saline solution. A major change in gelling time is achieved by different mixing proportions of silica sol and saline solution, as shown in Figure 4-6.

The strength of silica sol continues to increase for a long time /Axelsson 2005/ and is linked to the relative humidity. At low humidity, a quicker strength is obtained but also a tendency to shrink.

Other grouts are for instance Polyurethane and Periclase. Polyurethane is used as a grouting material for high flowing formations and as a plug-grout in grouting holes and for post-grouting /Anderssson 1998/. Periclase has previously shown promising results but in /Bodén and Sievänen 2005/ it is not recommended for further studies.

4.2.2 Grout properties

Grouts can be described based on their:

- Rheological properties, i.e. the flow properties.
- Penetrability properties.
- Curing (gelling) properties.
- Bleed.

These are all important properties for a grouting material and its satisfactory function.

Another property to consider is durability. Sufficient durability is considered to be obtained in infrastructure projects by using cementitious grouts, but the use of solutions is often questioned. The durability of different grouts is further discussed in /Vägverket 2000/.

Flow properties are often described using accepted rheological models, such as Newtonian or Bingham models. These models represent the behaviour of the grout.

It is generally accepted that cement-based grouts can be described using the Bingham model. The Bingham model contains 2 parameters: a yield value (τ_0) and a viscosity value (μ_B), shown in Figure 4-3.

Solutions are commonly described using the Newtonian model that only contains the parameter viscosity (μ), shown in Figure 4-3. According to /Funehag 2005/, silica sol can be described using the Newtonian model.

The properties of cement-based grouts vary with the w/c ratio (water to cement ratio by weight). According to /Håkansson 1993/ the w/c ratio is the most important single factor for the rheology. The rheology is also governed by the grain size distribution of the cement, and a finely milled cement requires more water than a coarser one in order to achieve the same flow properties /Håkansson 1993/.

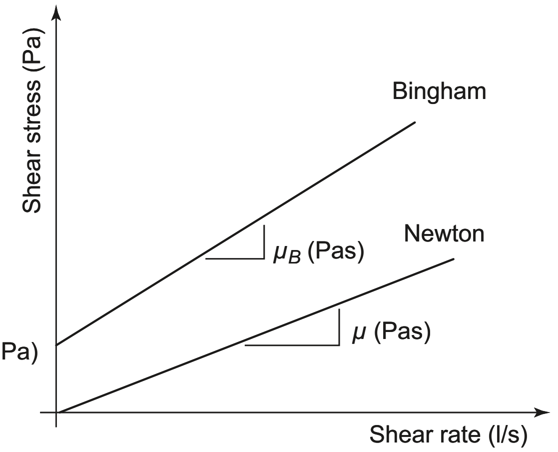

__Figure 4-3.__ Illustration of Newtonian and Bingham rheological models.

Different additives can be used to change the properties of the grout. The most common are superplasticizers, which are used to increase the flowability of the grout and to improve mixing (dispersion). In /Friedrich and Vorschulze 2002/ and in /Eklund 2005/, the results of measurements of rheology and penetrability with different amounts and different kinds of additives are presented. These investigations show the complexity in the function of additives. In /Eklund 2005/, for example, both steric and electrostatic superplasticizers were compared and the results were found to show that the function of the electrostatic superplasticizer was more short-lived than that of the steric, as illustrated in Figure 4-4.

Other additives are accelerators, silica and bentonite. Accelerators are used to shorten the curing time of the grout and is used sometimes in high flowing formations. Silica or silica fume is added to increase stability or to lower the pH value of the grout, see further Section 4.2.3. Bentonite is sometimes added to the grout as a stabililizer but is nowadays commonly considered not to function well with microcement.

The parameters b_{crit} and b_{min} are related to the penetrability of a grouting material and indicate which fractures are groutable with a given grout /Eriksson 2002/. At apertures larger than b_{crit} the grout is not affected; at apertures smaller than b_{crit} the grout is filtered; and at apertures smaller than b_{min} there is no penetration, see Figure 4-5.

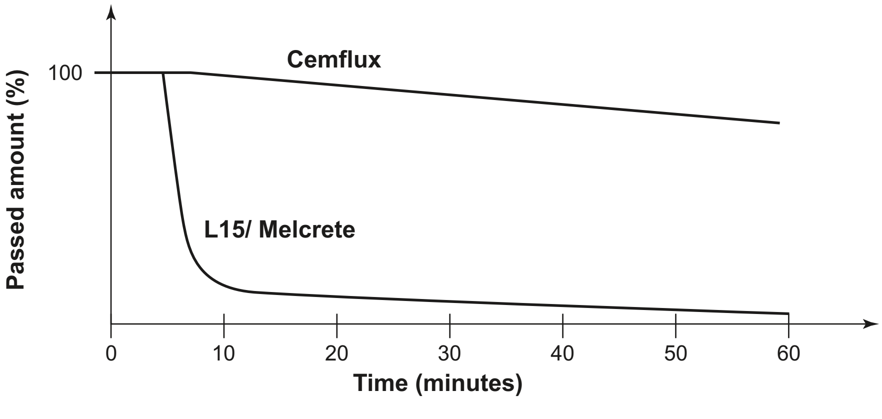

__Figure 4-4.__ The passed amount of grout through a filter, for two grouts containing a steric (Cemflux) and an electrostatic (L15) superplasticizer, respectively. The influence from the superplasticizer varies, depending on time after mixing and type of superplasticizer. From /Eklund 2005/.

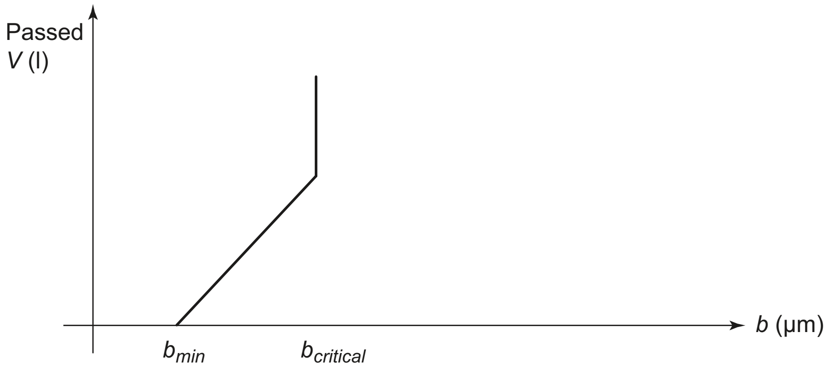

Figure 4-5. *Description of* b_{min} *and* $b_{critical}$ */Eriksson and Stille 2003/.*

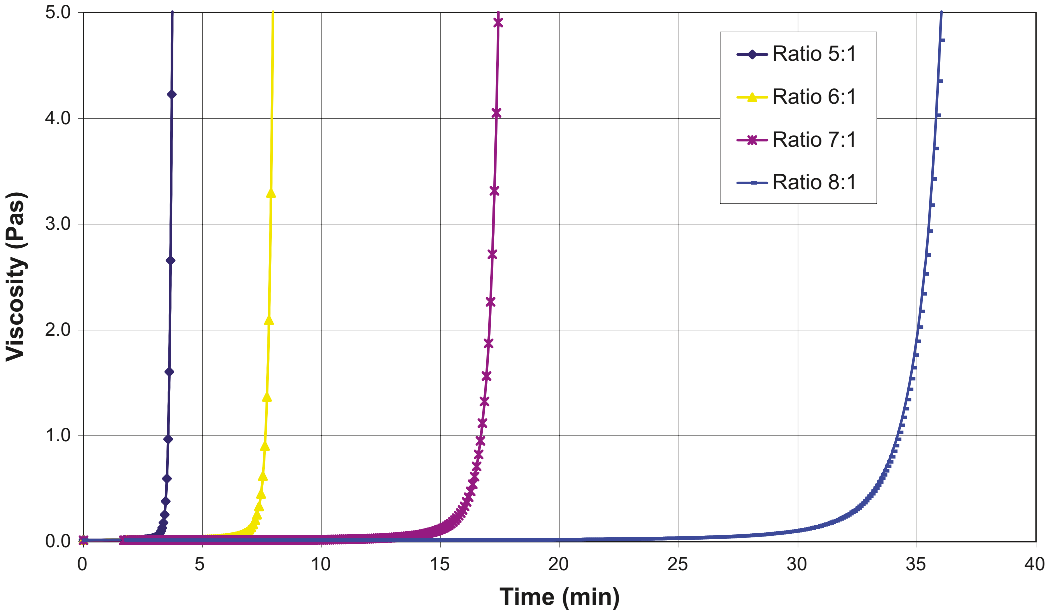

Figure 4-6. *Viscosity of silica sol mixed with a saline solution at four different ratios at 8°C. From /Funehag and Axelsson 2003/.*

Curing is the successive hardening of the grout. Traditional cement-based grouts have slow curing. There are also cement-based materials with faster curing, and curing can be controlled by various additives /Fjällberg and Lagerblad 2003/. The gelling of Silica sol is determined by the amount of salt added to the mix, see Figure 4-6.

Curing in different materials is also influenced by temperature. Curing of traditional cements is only influenced by temperature to a limited extent, but the curing time of faster setting cement and silica sol is strongly dependent on the temperature /Dalmalm et al. 2000, Funehag 2005/.

Bleed refers to the separation of water and binding material in the grout and is a property of the grout that may influence its ability to fill and seal fractures. Recent research has indicated that a complex pattern of factors influences the amount of bleed see /Draganovic 2007/. It has been found that bleed in small fractures is likely to have little influence on the final sealing result.

Bleed is not an issue for silica sol, because the particles are of colloidal size. However, shrinkage can occur if the sol is placed in a dry environment.

4.2.3 Assessment of grout properties

The various grout properties mentioned in the previous section can be measured by various methods, direct or indirect. Several aspects need to be considered when measuring and describing the properties of grouts. One aspect is the high variability of the measured result, as presented in /Eriksson et al. 2004/. These variations are believed mainly to emanate from variations in the material but uncertainties in the measurement methods are also present.

The rheology of grouts is measured with a rotational viscometer. This gives values of viscosity and yield value. There are different kinds of rotational viscometers to choose from /Eklund 2005/. Other methods, for instance the Marsh-cone for evaluating fluidity, are indirect methods in which time is measured and viscosity is evaluated based on this. Håkansson described and developed a method for assessing the rheological properties of grouts /Håkansson 1993/. For rheology, a viscometer is suitable for laboratory studies, and in the field the Marsh-cone can be used. /Axelsson and Gustafson 2005/ presented the yield stick as a robust method to determine the yield value of grouts in the field. An important aspect of viscosimeter measurements discussed by Håkansson is that the properties should be measured over a relevant range of shear rates.

The penetrability of grouts can be examined by sand-column tests, or by the use of a filter pump, the NES test or a filter press. These are all various methods for evaluating and comparing the penetrability of different grouts and are described in /Eklund 2005/ and in /Draganovic 2007/. /Eriksson and Stille 2003/ presented a method for evaluating the critical (b_{crit}) and minimal (b_{min}) aperture of grouts using filter press measurement values. These values make it possible to model the filtration process in a fracture and evaluate the penetrability of the grout. The difficulty of measuring the penetrability and the influence of different factors are examined in /Eriksson and Stille 2003/ and in /Draganovic 2007/. Since the critical and minimum apertures are described as grout properties, they must be able to be measured objectively and be related to the issue of penetrating fractures. This has not yet been finalized, and a common practice for measurement has not yet been determined.

Curing is measured according to standard methods with a Vicat /SS-EN 196-3/ or simply by using the fall-cone test /SS 02 71 25/. These methods make it possible to measure the strength of the grout versus time. In the field, curing is commonly evaluated by means of the mug-test in which mugs are filled with grout and turned upside down to determine when the grout is hard enough to stay in the mug.

Bleed is commonly measured using the standard test for concrete /SS 13 75 31/ This standard is obsolete, however, and has been replaced by a European standard /SS-EN 445/. Based on research results, other methods should be used to determine bleed in grouts, for instance using a small cylindrical cup /Draganovic 2007/.

According to /Vägverket 2000/, the durability of cementitious grouts can be evaluated by means of a strength test /SS-EN 445/ and by evaluating the permeability of the hardened grout. No recommendations are given in /Vägverket 2000/ concerning solutions but /Yonekura 1997/ concludes that colloidal silica is durable based on a leaching and shrinkage test. A mechanical strength test is also possible, although a standard is unavailable. /Axelsson 2006/ uses traditional geotechnical testing methods to investigate the mechanical properties of silica sol.

4.2.4 Selection of grout material

The selection of a grout material is an essential part of grouting design. It is not realistic to expect that all the desirable qualities of a grout can be achieved, hence a prioritization is usually necessary.

As discussed in a previous section, the grout must penetrate the fractures to seal them. It is therefore necessary that the grout has the ability to penetrate fractures small enough to meet the requirement on maximum inflow. These fractures must also be filled to a certain penetration length, which is dependent on a combination of the grouting technique and the rheology of the grout.

Concerning cement-based materials, /Eriksson 2002/ presented an analysis of what grout properties are of importance in different fracture intervals, see Table 4-1. Silica sol can be employed where cementitious grouts cannot penetrate.

The grout must also remain in the fracture after grouting has been completed. This leads to requirements on yield value, curing rate and final strength.

4.2.5 Grouting material for the final repository

Some special requirements apply to the final repository as far as grouting material is concerned. These requirements are discussed in /Bodén and Sievenän 2005/. The most demanding requirement is to limit the pH pulse in the groundwater to below 11, which will, according to current understanding, not disturb the function of the bentonite buffer. At present, no distinction has been made for different facility parts and a low pH grout may be required for the entire facility.

The objective is to achieve low pH sealing materials that can cope with grouting situations encountered in the final repository. The aim of SKB, Posiva and NUMO in their joint project is to achieve this with a cementitious grout for larger fractures (hydraulic aperture ≥ 100 µm), and to use a non-cementitious grout for smaller fractures. Silica sol is evaluated as a non-cementitious grout.

A low pH grout must possess required and desired properties with respect to rheology, penetrability and bleed as well as workability and strength, see /Bodén and Sievänen 2005/.

Silica sol is evaluated as a grouting material in two separate research projects at Chalmers University /Funehag 2007, Axelsson 2006/. Silica sol should not have any particular negative impact on the environment if used correctly, meaning that the mix should gel in the rock. If gelling is incomplete, the sol can percolate along with the water.

Table 4-1. Evaluation of important grout properties in different fracture intervals /Eriksson 2002/. ++ represents high importance, + important, – not important.

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

4.3 Technology

4.3.1 Grouting equipment

The basic form of grouting equipment has remained the same for many years. It consists of a mixer, a pump, hoses and packers. For production reasons, an agitator is usually also used.

The main changes in grouting technology over the last 10 years have to do with better measurement and control of the grouting process. New computer technology has enabled the flow and pressure of the grout mix to be monitored continuously.

An important factor is mixing the cementitious grout. The fine and ultra fine cements produced today require a better mixing process to obtain good quality. /Hjertström and Pettersson 2003/ discuss the effect of the speed and duration of mixing on the dispersion of cement-based grouting material, and suggest that, in general, the mixing of modern cements is insufficient.

Generally available grouting equipment was developed for cement-based grouts and for medium and highly permeable formations. However, due to today's requirements on low inflow, relatively impervious rock mass also needs to be sealed and the need to grout low-frequency and small-aperture fractures is a common situation. Equipment specially developed for these circumstances would be valuable.

Equipment for grouting materials other than cement-based ones are specially manufactured and not normally sold. However, the basic requirements on the equipment should not differ between cement-based and solution grouts and the same equipment can be used for both cement-based and solution grouts. The main differences are found in the mixing equipment and the pumps. In the mixing of cement-based grouts, especially with micro cement, thorough mixing is required to obtain the desired qualities. Mixing with an agitator is sufficient for silica sol. The pump needs to achieve a low-flow rate to get the maximum effect from solution grouts.

Grouting at repository depth will require high grouting pressures. This imposes special requirements on components such as pumps, packers and hoses. Mechanical packers can usually be locked in the holes to resist high pressure. Packers for one-time use are common today. They must however be verified to ensure they can withstand high pressures, and the material needs to be evaluated for use in the repository. At the groutings in the TASQ tunnel at Äspö at 450 m depth level, normal mechanical packers were used. The function of these was fully satisfactory with the grouting pressures used.

One problem encountered in grouting projects is the occurrence of unfilled boreholes. In /Dalmalm and Roslin 2007/ an investigation of this possibility was presented and several examples of the problem were identified. The development of grouting equipment with a new packer system and a more automated cleaning of boreholes, fitting of packers and so forth would probably be favourable not only on for the sealing results but also for production efficiency.

4.3.2 Pressure

The total pressure is commonly referred to as the grouting pressure. This pressure is the groundwater pressure plus a certain excess pressure. Following the basic rule for cementgrouting of having an excess pressure equal to the groundwater pressure /Gustafson and Stille 1996/ gives a total grouting pressure of at least 10 MPa, or 100 Bar, in a 500 m deep facility. This is a high pressure and is around the limit of what pumps are capable of delivering today.

There are different opinions concerning choice of pressures as reported in /Eriksson and Stille 2005/. The "traditional" opinion is to use a low pressure to avoid deformation in the rock. Recent reports, for example /Statens Vegvesen 2004/, favour using a high grouting pressure and allowing deformation in the rock. This method, along with a low volume criterion, was applied in the grouting works done at Arlandabanan /Hässler et al. 1998/.

A finding in /Andersson 1998/ is that a high pressure should be used when grouting solutions with a low viscosity, which thus includes thin cementitious grouts and silica sol. The pressure should be sufficiently high to cut off streaming water, to prevent flushing out and "fingering" in the grout. Fingering refers to a front stability problem where the ground water penetrates the grouting material.

A higher pressure is preferable in fractures with small apertures. The effect of different grouting pressures in different aperture intervals was investigated in /Eriksson 2002/, see Table 4-2.

SKB is funding research aimed at advancing our fundamental understanding of this topic /Gothäll 2006/. The aim is to develop guidelines for the selection of grouting pressure.

4.3.3 Fan geometry

The geometry of a fan is based on achieving a sealed zone outside the contour. For this reason, it is common to let the grouting holes project outside the contour. An alternative is to pre-grout with boreholes within the contour but the possible drawbacks of this is yet to be investigated.

Theoretically it can be demonstrated that the sealed zone around an opening does not need to be very thick if it is sealed enough, which follows from Darcy's law. It is therefore important to design the fan geometry to promote low conductivity, and not to cover as much rock mass as possible. It should however be ensured that, following grouting, any future drilling, for example rock bolt installations, should not penetrate the grouted zone. A thicker grouted zone might also extend the "life" of the grouting.

The final conductivity of the grouted zone is likely to be lower if more boreholes are used, since this requires a shorter penetration length /Eriksson 2002/. The probability of intersecting water conductive fractures also increases. However, the required grout volume largely depends on the number of boreholes, since the amount of grout that is used to fill a borehole is often comparable to the grout take of the rock mass. An evaluation of the required number of boreholes in relation to the required conductivity and to the grout take may be appropriate.

Inflows from fractures in the face of the tunnel sometimes occur. Therefore boreholes in the face of the tunnel sometimes are necessary.

4.3.4 Stop criteria

During execution of the grouting it must be decided when to stop the grouting and the criteria for this are called stop criteria.

There are several types of stop criteria that can be used:

- A maximum grouting time, where grouting is stopped when it has proceeded for a given length of time.
- A maximum grouting volume, where grouting is stopped when a certain volume has been injected.
- A minimum grouting flow, where grouting is stopped when the grouting flow is lower than a certain value.

The stop criterion can largely influence the sealing result according to the results presented in /Eriksson 2002/. In small aperture fractures, the minimum flow criterion becomes important. In fractures with a larger aperture, a high maximum volume may be needed, see Table 4-2.

A relationship between penetration length and grouting time was presented in /Gustafson and Claesson 2004/. This relationship was further developed in /Gustafson and Stille 2005/ and can be used as a theoretical basis for selecting a time stop criterion. In the studies presented by /Kobayashi and Stille 2007/ and in /Stille 2007/ this time stop criterion has been evaluated based on measured data.

Table 4-2. Evaluation of important technical issues in different fracture intervals /Eriksson 2002/. ++ represents high importance, + important, – not important.

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

4.3.5 Selection of grouting technique

The selection of a grouting technique refers to determining the grouting pressure, the fan geometry and the stop criterion. The purpose of the design is to put all these together and make it probable that the requirements will be met using a special technique and a special grout.

Input for the selection of a grouting technique was studied in /Eriksson 2002/ and rough guidelines are presented in Table 4-2. This indicates that, as was the case with the selection of grout, the selection of grouting technique is based on the expected apertures of the fractures.

Based on calculations using, for instance, the principles presented in /Eriksson 2002/ or in /Gustafson et al. 2004/, a grouting design for a particular rock mass can be determined.

5 Analyses of system behaviour and design of grouting measures

5.1 Approaches

Analyses regarding grouting will be performed in different steps during the design and construction of the underground facility. For the forthcoming design step D2, premises are given in the "Underground Design Premises/D2", referred to as "UDP/D2" /SKB 2007/, and the reference design presented in the requirements database. The Site Engineering Report (SER) that is under preparation will present an engineering description of the rock mass for the underground part of the repository. According to UDP/D2, the inflow of water to the various excavations of the facility must be determined for the different functional areas and ground types outlined in the SER. The inflow must be determined by considering ground behaviour both with and without grouting measures. The interaction of ground behaviour and grouting measures is called system behaviour in UDP/D2. The system behaviour must then be compared to the sealing requirements for the underground openings which are given in the reference design. The analyses of water inflow to the various excavations are also used as a basis for the design of grouting measures including the choice of grouting material and grouting technique (see Chapter 4).

The design of grouting measures is basically the process that leads to a specification of grouting measures in order to meet the sealing requirements. The design process also includes establishing a plan for describing measures for control of the grouting work and verification that specified requirements have been fulfilled. The design process thus includes the choice of:

- Design parameters.
- Methods for analyses.
- Grouting measures (grouting material and grouting technique).
- Measures for control and verification.

Historically, the choice of grouting material and grouting technique has been based on empirical methods, which include the use of experience from other projects. Over the past 40 years, see /Stille 1997, Eriksson and Stille 2005/, further knowledge has been acquired that facilitates a well structured, theoretically based and traceable design. Different methods for analyses have also been developed. Examples of research work that have formed a basis for the analyses described in this chapter are presented in /Hässler 1991, Janson 1998, Fransson 2001, Eriksson 2002, Funehag 2007/. In designing grouting measures, specific analyses are performed of, for example, grout spread and stop criteria. Analyses of system behaviour (inflow to tunnels) should be performed iteratively in conjunction with analyses related to design.

Two different approaches can be used for the analyses. One is to view the rock mass as a continuum material (continuum analysis) and the other is to consider the individual fractures (discrete analysis). The different approaches are illustrated in Figure 5-1.

Continuum analyses are based on the assumption that the rock mass can be described as a continuum on a certain scale. Based on continuum analyses, different estimates can be made as a basis for the design of grouting measures, such as:

- Calculation of inflow to ungrouted and grouted tunnels.
- Estimation of grout spread and grout volume with different grouting techniques and grouting materials.

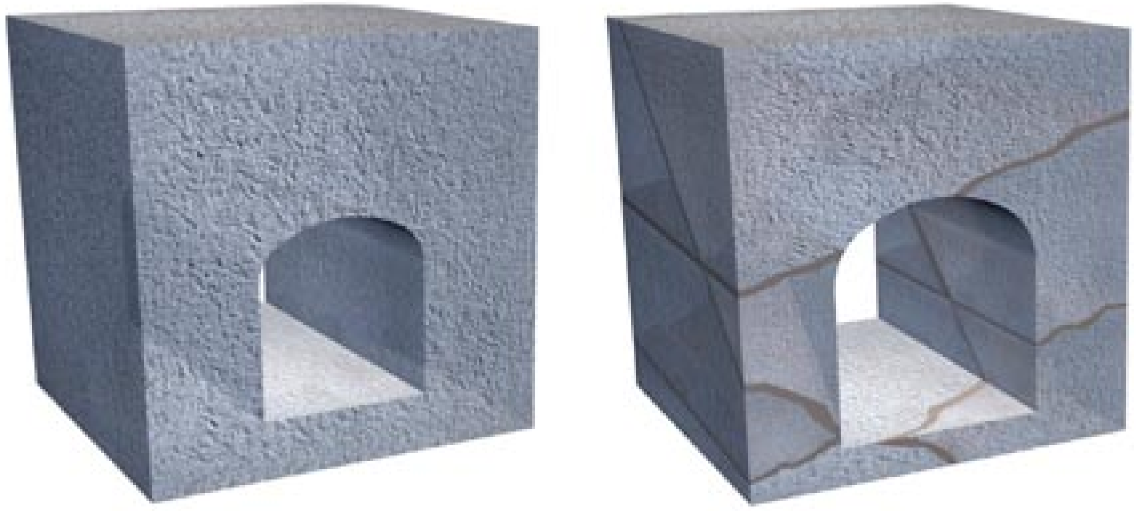

Figure 5-1. *Illustration of different approaches, continuum (left) and discrete (right). After /Eriksson and Stille 2005/.*

Discrete analyses refer to calculations of grouting in individual fractures. The analyses developed are based on the simplification that the fractures are singular. Based on discrete analyses, different estimates can be made as a basis for the design of grouting measures, such as:

- Calculation of inflow to ungrouted and grouted tunnels.
- Estimation of grout spread and grout volume with different grouting techniques and grouting materials.
- Estimation of grouting time and sealing effect with different grouting techniques and grouting materials.

Analyses with a focus on post-grouting are described in /Fransson and Gustafson 2006/. These analyses are based on the theoretical principles presented in the publications cited above, but with specific consideration of issues related to post-grouting. One of these issues is the increased pressure gradient compared to pre-grouting. Another reference regarding post-grouting is /Ingenjörsbyrån Saanio och Laine 1979/.

Analyses can be made assuming one, two or three dimensional flow. Single fractures intersecting a borehole would allow a 1D or 2D description, whereas a higher fracture frequency and varying orientations will result in a network of highly connected fractures probably making a 3D description closer to reality. The dimensionality of the flow will influence both water flow and grout spread.

Analytical as well as numerical methods have been developed for the analyses. The choice of approaches and analysis methods is dependent on several factors such as the purpose of different steps in the design and construction phases, ground type, amount and quality of input data, sealing requirements and available time for the analyses. In an early stage of the design process, when the aim is to show feasibility or compare different methods for sealing the rock mass, it may be sufficient to perform continuum analyses. For detailed design, a better description of the fracture distribution is needed in order to determine which fractures need to be sealed. For more detailed analyses, a discrete approach should thus be preferred. In Section 4.1.3, it was also concluded that the candidate areas will probably contain a wide range of grouting situations, ranging from the intersection of high conductivity zones with reasonably high water pressure to reducing spot leakages at the deepest levels. Several methods for analyses must therefore be used to cope with different situations. The results of all analyses must in any case be evaluated together with engineering judgement.

Due to the difficulties in describing the material properties and grouting parameters, their interaction and the uncertainties involved in practical execution, there is a pronounced variation in results. For instance, it is well known that the grout take often varies considerably in different grouting holes in one grouting fan and between grouting fans in the same geological environment. This complicates giving a deterministic answer to several of the questions concerning grouting, which means that probabilistic methods are preferred, even though they are not easily performed /Gustafson et al. 2004/. Probabilistic analyses of different issues can be done using Monte-Carlo simulations or similar approaches with variation of the different input parameters. Probabilistic analyses are also preferred for assessing the possible range of behaviour according to the principles of the observational method.

For further development, two types of grout are considered: cement-based grouts and silica sol. Analyses with a focus on grouting of hard rock with cement-based grouts are described for example in /Eriksson and Stille 2005/. Principles for grouting with silica sol are described in /Funehag 2007/. Design and execution of grouting with silica sol in two tunnel projects are described in /Funehag and Gustafson 2004, 2005/.

In the following sections, analyses are presented which may be used both for rough estimates in the early phases of design as well as for analyses in the detailed and final design (also see Chapter 7). It should be noted that no requirements are specified regarding the choice of analysis methods in the forthcoming design step D2.

5.2 Models and analysis methods

5.2.1 Inflow to tunnels

Estimates of the inflow to tunnels are used as a basis for the design of grouting measures. Based on these estimates, requirements on the sealing effect can be specified. The sealing effect can be expressed as the relative reduction of inflow due to grouting. Based on the estimated inflow to a tunnel, it is also possible to quantify the highest acceptable hydraulic conductivity of the grouted zone (for a given grout spread). An estimate of the apertures that need to be sealed can then be made using Equation 4-1.

Both continuum analyses and discrete analyses can be used to estimate inflow to tunnels.

Calculations of the inflow to a grouted tunnel, Q_{tunnel} (m^3/s), based on a continuum model can for example be made using Equation 5-1 /Hawkins 1956, Gustafson et al. 2004, Eriksson and Stille 2005/.

$$Q_{tunnel} = \frac{2\pi \cdot K \cdot H \cdot L}{\ln\left(\frac{2 \cdot H}{r_t}\right) + \left(\frac{K}{K_g} - 1\right) \cdot \ln\left(\frac{1+t}{r_t}\right) + \xi} \qquad \text{Equation 5-1}$$

The notations used in Equation 5-1 are explained in Section 3.2. The skin factor, ξ, is a dimensionless parameter that takes into account the conditions at the periphery of the tunnel. This factor is not fully understood and it may vary depending on the prevailing conditions. For engineering purposes, a value of 2–5 for tunnels is recommended in /Eriksson and Stille 2005/.

Based on the same principles as in Equation 5-1, it is possible to calculate the inflow to a borehole. From the measurements of inflow to boreholes, it is then possible to estimate the inflow to the tunnel and the result of the grouting (sealing effect). However, when estimating the inflow to tunnels based on inflow to boreholes, the stochastic nature of the rock mass properties, the scale effect and possible interference between bore holes must be taken into consideration (see for example /Funehag 2007, Funehag and Gustafson 2005/).

The principle used in discrete models is that the flow in a fracture occurs between two parallel plates and that laminar flow is predominant. With these assumptions, the transmissivity of the fracture is proportional to the cube of the aperture (see Equation 4-1). Analyses of the inflow to tunnels based on the distribution of apertures are described in /Brantberger et al. 1998, Fransson 2002, Gustafson et al. 2004/ (also see Section 5.2.1). Based on the transmissivity distribution, the residual transmissivity and inflow to a tunnel can be predicted, assuming that progressively smaller apertures are sealed.

A discrete approach should also be preferred when analyzing the inflow to disturbed or fractured zones of limited width. For rough estimates, a continuum approach may be sufficient, see for example /Chang et al. 2005/.

Analyses of inflows to tunnels do not provide precise estimates. However, for engineering purposes, they are normally accurate enough to predict the inflow and serve as a basis for feasibility studies and the design of grouting measures. These analyses are often based on continuum analyses. Discrete analyses are not usually used, but they have been used in for example the Citybanan project, the Botniabanan (Bothnian Railway) rail tunnel project and Törnskogstunneln (see /Funehag and Gustafson 2005/). The infrequent use of discrete methods is mainly due to a lack of knowledge about them among designers.

5.2.2 Penetration length and grout volume

Estimates of penetration length and amount of grouting materials can be made at different stages of the design process using different methods.

The principal approach regarding maximum penetration length is that it is limited, due to the shear strength of the grout, often called the yield value (see Figure 4-4). For a given yield value, τ_0, efficient grouting aperture, b_g, and grout over pressure, Δp, the maximum penetration length, I_{max}, can be calculated with Equation 5-2 (see for example /Hässler 1991, Janson 1998/ and /Gustafson et al. 2007/). The maximum grout penetration length according to Equation 5-2 is illustrated in Figure 5-2.

$$I_{max} = \frac{\Delta p \cdot b_g}{2 \cdot \tau_0} \qquad \text{Equation 5-2}$$

The grout volume can be estimated for a given grouting technique and given grout properties. This grout volume, for grouting of a single bore hole, $V_{borehole}$, can be estimated with Equation 5-3 /Janson 1998/.

$$V_{borehole,max} = \left(\frac{\Delta p}{2 \cdot \tau_0} \right)^2 \frac{12 \cdot K \cdot L \cdot \mu \cdot \pi}{\rho \cdot g} \qquad \text{Equation 5-3}$$

where Δp is the grout over pressure, τ_0 is the yield value of the grout, L is the length of the borehole, K is the hydraulic conductivity of the rock mass, ρ is the density of water, g is the acceleration due to gravity and μ is the viscosity of water.

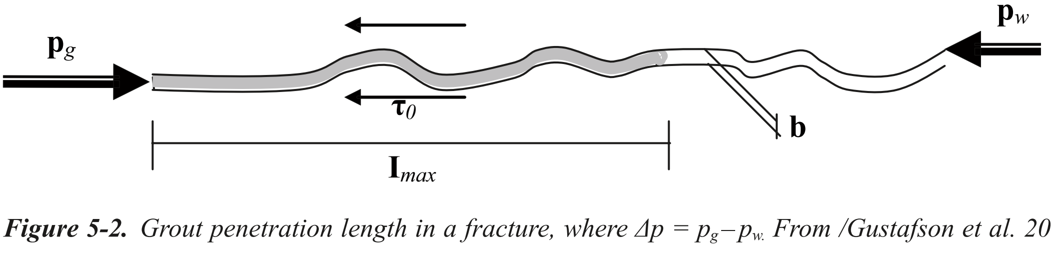

Figure 5-2. *Grout penetration length in a fracture, where $\Delta p = p_g - p_w$. From /Gustafson et al. 2007/.*

The penetration length of the grout given by Equation 5-2 and grout volume given by Equation 5-3 do not take into account the time-dependent properties of the grout, limitations in the penetrability of the grout, or the stop criteria. Thus, Equation 5-2 and Equation 5-3 normally overestimate the penetration length and the volume in a borehole. Further descriptions of similar models for calculation of the penetration length and volume are given in /Janson 1998, Gustafson and Stille 2005/.

Estimates of the grout volume can also be made on the assumption that the porosity in the rock mass is filled with grout to a specific distance from the borehole or tunnel. According to /Eriksson and Stille 2005/ the porosity is the mean value of the void of fractures and cavities in the rock mass for a given volume. The porosity of interest is normally the voids in which water may flow. This porosity is sometimes referred to as the secondary porosity. Various relationships between the hydraulic conductivity and the porosity have been presented, resulting in different porosity values for the same conductivity. One relationship between the porosity and the hydraulic conductivity of the rock mass is given in for example /Dershowitz et al. 2003/.

One of the main uncertainties involved in describing the rock mass based on a continuum approach is describing the hydraulic conductivity that will be subject to grout flow. A prediction of the grout spread can also be made using an analytical method that describes the penetration length in fractures as a function of time. The basis for calculation of the penetration length is the dimensionality of the flow, which is finally determined based on the measured flow and pressure at the grouting equipment. A description of this method is provided in /Gustafson and Claesson 2004/ and it is further developed and described with an emphasis on stop criteria for rock grouting in /Gustafson and Stille 2005/.

The theory of the method was discussed in /Gustafson and Stille 2005/ based on data from a grouted borehole. Good correlations between calculated and measured flow and volume were obtained. In /Kobayashi and Stille 2007/ the principal theories were developed into practical tools, theories were tested based on data from grouting works and further analyses were made of the difference between calculated and measured grouting results. The conclusion from the test of the method was that a good correlation was obtained between calculated and measured data, and that the method can be used as a tool for estimating the grout spread. According to /Kobayashi and Stille 2007/, the most important factor for a good correlation was that the dimensionality of the flow is correctly determined.

The grout spread can also be estimated by means of numerical analyses. The advantage of numerical analyses is that the effect of variations in aperture as well as the time-dependent penetrability and curing properties of the grout can be accounted for. These analyses require both expert knowledge and special computer programs. Numerical analyses using different approaches are described in /Hässler 1991, Eriksson 2002, Funehag 2007/.

One specific issue not considered in the analyses is the rock mass response during high pressure grouting. A conceptual model is presented in /Gothäll 2006/, but further research work is needed.

Methods for analyses of grout spread and grout volume are subjects of research and are not commonly used in practice. Results from recent studies (see for example /Kobayashi and Stille 2007/) indicate that the method described in /Gustafson and Stille 2005/ can be used as a design tool in forthcoming design steps but further studies are preferred. The advantage of the method is that no input data on the distribution of apertures are needed.

It should be noted that grouts based on silica sol have a yield value of zero. The factor that influences the grout spread is instead the gel time, which is controlled by the type and amount of silica sol and gelling agent. Rheological behaviour and models for calculation of penetration length are discussed in /Funehag 2007/.

5.2.3 Stop criteria

In order to get the necessary grout spread around the tunnel and between the grout holes, analyses can be made of relevant stop criteria. These analyses are based on the method that describes the penetration length as a function of time (see Section 5.2.2). The result of the analysis is the time, grout flow and grout volume for a required grout penetration length. The required minimum grout penetration length should be chosen so that the fractures between the grouting boreholes are filled with grout (see Figure 5-3). Based on the required grout spread in the smallest fracture that needs to be sealed, a criterion for stopping the grouting can then be specified. The method described in /Gustafson et al. 2004/ can be used to estimate the smallest fracture that needs to be sealed. It is also possible to adjust the grout pressure and the properties of the grout based on the result of the analysis.

Recent studies /Kobayashi and Stille 2007/ indicate that the method can be used as a tool for establishing stop criteria even though further improvements are possible. The procedure is not commonly used in practice today.

5.2.4 Break-up scenarios

Grouting problems associated with the low strength of fresh grout should be analyzed in order to choose the appropriate grouting measures. Different scenarios related to these problems are called break-up scenarios in /Gustafson et al. 2007/. Analyses of break-up scenarios are of importance especially when the groundwater pressure is high. The following break up scenarios are described and analysed in /Gustafson et al. 2007/.

- Back flow in fractures.
- Fingering.
- Erosion.
- Back flow through grouting bore holes.

Back flow in fractures may occur if they are in contact with the tunnel. Fingering occurs when the grouted fracture is penetrated by water, due to the water pressure in connected fractures that are ungrouted. This leads to fresh channels forming within the grouted fracture. If the fracture is not completely filled with grout the risk for erosion by flowing water is increased. Finally backflow through grouting boreholes may occur if packers in the holes are removed too early.

If too high a grouting pressure is applied, the fracture being grouted may be widened by hydraulic jacking, and an uncontrolled spread of grout in the fracture will occur. If this process involves plastic deformation of the fracture, then there may be an increase in the rock mass permeability as a result of the grouting, rather than a decrease.

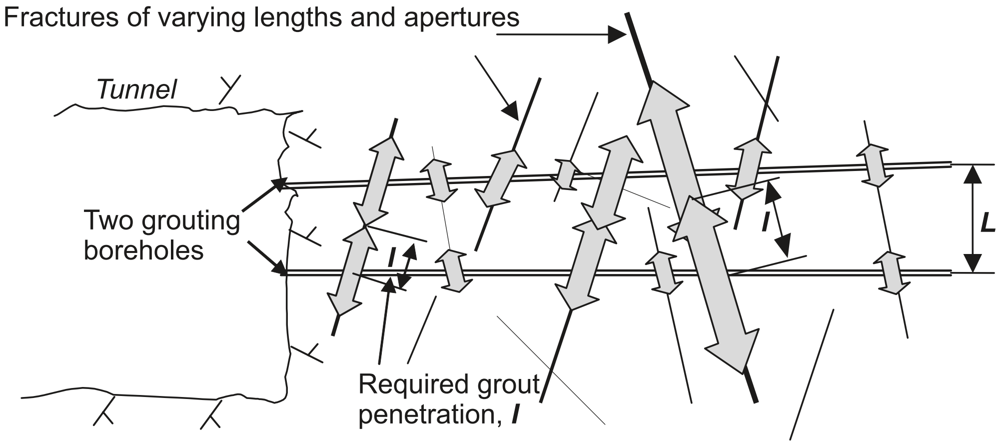

Figure 5-3. Illustration of the required minimum grout penetration length. L is the distance between the grouting boreholes. From /Funehag 2007/.

Suggestions of methods for analyses of the different break-up scenarios aiming at choosing grouting pressure, rheology of the grout and grouting time, are presented in /Gustafson et al. 2007/.

An example of the results of analyses of break-up scenarios is shown in Figure 5-4.

5.2.5 Engineering judgement

Due to the complex nature of the flow of water and grout in a fractured rock mass, analyses of system behaviour and grouting design are associated with uncertainties. As a consequence, the use of engineering judgement for the evaluation of results and the choice of grouting measures is important. The results of all analyses should always be regarded as a first estimate, and better estimates must be based on observations from the construction phase.

Engineering judgement should consider the limitations in the methods used, the amount and quality of the input data and the complexity of the grouting work, as well as experience from other projects. Experience from design and execution of grouting works is presented in for example /Dalmalm et al. 2000, Emmelin et al. 2004, Funehag and Gustafson 2004, 2005/. Experience from grouting works is also presented in the form of proceedings at, for example, Bergmekanikdagen (Rock Mechanics Day), which is arranged by SveBeFo (Swedish Rock Engineering Research). Examples of proceedings are /Eriksson and Palmqvist 1997, Klüver and Iversen 2003, Lindblom et al. 2005/. Swedish experience from grouting works where the groundwater pressure is high is rare, however. Experience has been gained from grouting works during construction of the Äspö HRL, and grouting works in a tunnel at the 450 m level is presented in /Emmelin et al. 2004/. Grouting works in water-conducting fracture zones at the Äspö HRL are described in /SKB 1992, Stille et al. 1993/. More references are given in /Chang et al. 2005/. Grouting works have also been done in deep mines, but the required sealing effect is normally low in mines and no published references have been found. Experience from Norway is described in /Statens vegvesen 2001/.

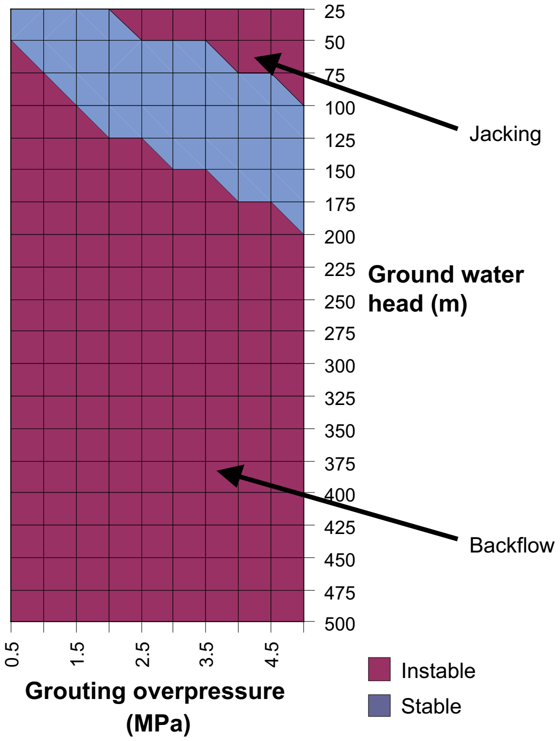

Figure 5-4. *Example of results of analyses of backflow in joints giving feasible grouting pressures (stable conditions). Yield value of grout, τ_0 = 5 Pa, viscosity of grout, μ_g = 0.03 Pas and grouting time, t = 30 min. From /Gustafson et al. 2007/.*

6 Organization, management and tools

6.1 Management of underground projects

The construction industry has acknowledged that managing the complex process of underground construction in rock and at the same time meeting stringent requirements in an effective manner requires the right incentives, and that changes are needed. This is demonstrated by a number of initiatives such as “Nätverket Unga Bergbyggare” (“Young Rock Builder Network”) with their report on success factors in rock construction /Bergström et al. 2003/, the Swedish Rock Engineering Research project “Tenders for grouting” /Brantberger 2006/, and the joint National Road Administration and Rail Administration’s initiative “FIA, Förnyelse I Anläggningsbranschen” (“Renewal in the Civil Engineering Industry”) /FIA/. A project example that can be mentioned is Tunberget, part of the Norrortsleden Road Project, that was awarded FIA’s Quality Prize 2006 for its structured cooperation between client and contractor leading to cost reductions and still meeting unchanged quality requirements.

The above initiatives identify several requirements on the framework provided by the contract. These include realistic cost estimates, realistic time schedules for the preparation of tenders and construction, contracts that are economically equitable, distribute risks fairly, and are robust enough to take unforeseen events into account. Such a robust framework is particularly important for grouting, as uncertainties regarding ground conditions and hence costs and time are great.

An illustration of these factors is provided by looking at how the contractor in a general contract has traditionally been reimbursed, according to the volume of measures undertaken, in other words according to the number of boreholes drilled and the volume of grout pumped. When combined with large financial penalties for over-running a tight time schedule, this puts financial pressure on the contractor if the grouting works do not produce the predicted results. The incentive to claim that ground conditions are not as specified in the contract is great, shifting the focus from trying to accomplish the sealing task to settling a dispute. In some projects, reimbursement based on the time needed to get the job done has been successful, as in the construction of Clab 2, the central interim storage facility for spent nuclear fuel.

For larger projects, an advisory board is often appointed. Tasks and authority may vary, but the fundamental idea is that the board should be detached from the operational organisation. Having no financial ties allows the board to perform independent reviews aimed at ensuring that the project has the right focus and that communications work. Not being involved on a daily basis such a board also can be more clear-sighted, and see whether the right things are being done, at times when the project organization may be busy checking that the things that are being done are being done properly. Such an outside quality assurance and risk-mitigating function was used as part of the Clab 2 project. The advisory board performed special reviews of construction drawings at important and sensitive junctures, so called “GK3-granskning” /Boverket 2003/, but they also performed general reviews at predefined “tollgates” /Ericsson Group 1994/ to check that work processes and measures were optimal.

Tools for managing a project are presented in the following sections. They include the observational method, as it is considered not only a technical method, but also a method that greatly influences how a project is set up and how the grouting work is controlled.

6.2 Tools

6.2.1 Quality systems

In recent decades, major stakeholders in the underground construction industry – clients, consultants and contractors – have introduced different quality management systems. These systems are often tailored for specific organisations and satisfy the requirements for quality systems as presented in European Standard EN ISO 9001:2000. The systems are often integrated with an environmental management system based on EN ISO 14001:2004, or the environmental system may be run in parallel.

Key elements in the systems are

- description of responsibilities and authorities,
- formulation and implementation of organisation goals,
- handling of nonconformities,
- preventive and corrective actions,
- training and education and,
- quality audits.

Quality systems should address issues that are of critical quality importance and are therefore closely related to the management of risks. A broader definition of the concept of quality including a risk management approach has been introduced by /Stille et al. 2003/. This report argues that the conventional ISO-based systems do not put sufficient focus on the identification of important factors and problems, but merely aim at ensuring how things are done. In this report, project models, risk analysis, system analysis, technical audits and team qualification are all seen as quality tools.

6.2.2 The observational method applied to grouting

There is always a degree of uncertainty associated with geotechnical engineering and an observational procedure was adapted early on within soil mechanics /Peck 1969, Bredenberg et al. 1981/. The concept "Active Design" has been used for rock construction in Sweden /Stille 1986/. The latter concept involves the three steps: prediction, observation and action.

The Eurocode, and in particular the standard for geotechnical design, SS-EN 1997-1, which is planned to be implemented in Sweden 2009, offers a formal method for handling design situations where the design has to be based on uncertain data and models. The idea is to consider the predicted system behaviour in relation to an initially proposed design, with verification of the design carried out during construction, on the basis of data from observations during the work.

Guidelines to the code and examples formulated in relation to rock stability are found in /Holmberg and Stille 2007/. It is there concluded that the method can be applied to constructional rock design in a broader sense, as long as the components prediction, observation and action are included. A documented approach in the use of the observational method for grouting is found in the documentation for the Dounreay shaft barrier grouting carried out on behalf of the Scottish Environment Protection Agency /Donaldson Ass. Ltd 2006/.

As SKB plans to design and construct the final repository in agreement with the code, the code and a possible interpretation for grouting application are presented below.

The code sets out the following conditions for using the observational method in design:

> *"(1) When prediction of geotechnical behaviour is difficult, it can be appropriate to apply the approach known as "the observational method", in which the design is reviewed during construction.*

(2) P[1] The following requirements shall be met before construction is started:

- *acceptable limits of behaviour shall be established,*
- *the range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits,*
- *a plan for monitoring the behaviour shall be devised, which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully,*
- *the response time of the monitoring and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system,*
- *a plan of contingency actions shall be devised which may be adopted if the monitoring reveals behaviour outside acceptable limits.*

(3) P During construction, the monitoring shall be carried out as planned.

(4) P The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put in operation if the limits of behaviour are exceeded.

(5) P Monitoring equipment shall either be replaced or extended if it fails to supply reliable data of appropriate type or in sufficient quantity."

Geotechnical behaviour, or just *behaviour* can be either ground behaviour, i.e. inflow without grouting measures, or system behaviour, i.e. inflow after grouting measures.

Acceptable limits of behaviour should be based on the requirements, in this case on inflow of groundwater into the facility. The first step in the design process is, therefore, to assess the minimum tightness of an injected zone with a specified extent around the planned excavation. As there is no method to directly register the extent of a grouted zone, the requirements also have to be formulated in terms of observable criteria that are theoretically related to the original requirement. The criteria, valid during actual grout injection, can be the grouted volume or the grout flow as a function of grouting pressure and time. The actual grouting result will be checked against these criteria. The criteria to be checked when the grouting of all the holes in a grouting fan or round is completed can include, for example, the maximum inflow in control boreholes. After excavation, the results can be checked against the original requirements by measuring the actual water inflow for a section of the tunnel.

As the relationships between inflow, tightness of the sealed zone and grout injection execution are not – and cannot be – fully known, we will thus have four levels of assessing geotechnical behaviour: before grouting, during grouting, after grouting but before excavation, and after excavation, see Table 6-1.

The assessment of the *range of possible behaviour* should be based on an analysis of the uncertainties present. Firstly, the ground behaviour without sealing measures should be assessed, with the characterization covering both probable behaviour and deviations from the probable. Then, appropriate sealing measures should be proposed, including a prediction of their result. To make this possible, and to yield a manageable interval, it is advisable to make a classification, see further below, and to analyze each class.

Acceptable probability that the actual behaviour will be within the acceptable limits means, in general wording, that it must be shown that the planned measures will be appropriate, and will

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[1] (P) = ("Principles"). "The principles comprise: general statements and definitions for which there is no alternative, as well as; requirements and analytical models for which no alternative is permitted unless specifically stated."

Table 6-1. The actual behaviour is checked against the predicted behaviour before, during and after grouting.

When	Prediction to be verified	Requirement	Observation, criteria	Action
Before grouting	Ground behaviour: ungrouted rock mass conditions	Current values within Indicator value limits for the predicted class	Hydraulic and fracture data collected in probe holes	Assessment or change of grouting class
During grouting	System behaviour: the performance of the grout in the rock fractures	Specification on pressure, flow, volume	Pressure, flow, volume; backflow	Adjust grouting measures within class
After grouting, before excavation	System behaviour: the tightness of the tunnel to be excavated	Tightness in grouted zone	Water loss in control holes	Re-grouting
After excavation	System behaviour: the inflow to the excavated tunnel	Inflow to tunnel section	Inflow in weir	Post-grouting, lining

lead to the desired outcome in most cases. When applied specifically to the singular grouting fan, the acceptable probability is the risk the client is willing to take that the final check shows that the result cannot be accepted and that supplementary grouting has to be undertaken.

A plan for monitoring the behaviour shall be devised. Whether included in the monitoring plan as defined above or not, a first observation – probing – is to be made before the actual grout injection commences, with the aim of confirming the assessed ground behaviour. During grouting the observations will be for example grout take and pressure to be controlled against the criteria for acceptable limits of behaviour. After each round, control holes will be drilled to check inflow or other observations. After excavation, wet spots or drips will be observed and seepage water collected in weirs.

A plan of contingency actions shall be devised which may be adopted if the monitoring reveals behaviour outside acceptable limits. Observations may well reveal that another grouting round is needed, in case the criterion for acceptable system behaviour limits – i.e. limited inflow – is not met. Plans for such re-grouting are normally included in grouting design and are conditional on the result of checks. They should therefore be referred to merely as standard measures or actions, whereas contingency action should be reserved to denote measures such as post-grouting which, within current practice, always is avoided. Expanding and interpreting the text to fit grouting, it would state that the *plan for actions* defined by the grouting design should be linked to the observations and provide instructions for actions based on the results of probing before grouting, measurement during grouting, control holes, mapping and inflow, in order to achieve the desired result.

The results of the monitoring shall be assessed at appropriate stages – besides the continuous observations and adaptations described above, an important concept is that of the “tollgates” that should be defined by the designer. Appropriate stages for these could be for example after a few initial grouting rounds, followed by assessments at regular intervals, or when commencing grouting in an area where uncertainties or difficulties are judged to be high. This can be regarded as an internal review of the grouting concept, aimed at ensuring that the ground conditions and theories used in the design are validated by the results, and also at improving performance and efficiency.

6.2.3 Classification

Generally speaking, classification is a tool for placing objects, situations or actions in groups. The purpose may vary, but a common point is that classification is used to get an overview.

Within rock construction, classification is used as a tool either to describe rock mass quality or to describe a pre-defined set of actions to be undertaken. Applied to grouting, classification can be used as a tool to describe either different situations to be encountered and handled – for example a certain part of a facility to be sealed to a certain tightness and placed in a rock mass volume with a certain fracturing and ground water pressure – or the grouting and verification measures to be undertaken for that facility part, such as fan geometry, grout type and grout pressures to be used, and the checks to be carried out to verify the result. In the latter type, sometimes referred to as a design class, the first class type would be an indicator, i.e. one of the conditions upon which the design class is defined.

It should be noted that we are not referring here to the so called engineering classification systems, which are fixed classifications that do not permit adaptation to the repository project.

In tunnelling, the aim of classification of the rock mass is to reduce the number of choices to be made at the tunnel face, thus simplifying and speeding up the process. Classification will also facilitate communication and the pricing of tunnelling works. Project-specific classification for grouting has proven a suitable tool and is frequently used.

Requirements in establishing classes are found in /Stille and Palmström 2003/. The main requirements are that classes must be exhaustive and mutually exclusive. Further, indicators and the rules for the combination of indicators to establish classes must be defined.

The basic indicators for a design class for grouting are the rock mass properties and the permitted inflow after grouting, including any other restrictions for the repository part in question. Other indicators should be based on variables of importance for the design of the grouting, but must also be observable. The choice of indicators must also consider what can actually be observed in different stages. During execution, probe holes and water loss measurements can reveal some observable properties. Observations at the face will reveal fracture frequency and fracture orientation. The inspection of cores from a bore hole and the logging of flows along the borehole can provide detailed information that may be used as a base for classification.

As classes must be set up based on what can be observed, the classification, if done early on, may have to be modified during the project. Another reason for changing classes is that the purpose of classification will vary between different project stages. Still another reason is the gradually improved information available and the requisite adaptation to encountered conditions.

After grouting, a check will reveal whether the measures have produced the predicted result. If the desired result is not achieved, there are two possible courses of action. Either the measures prescribed in a class can be changed or the rule for classification can be changed.

Classification, including changing the classification rules or the measures to be implemented, is considered to conform well to the rules of the observational method. The establishment of properties (ground behaviour) and the predefined actions to account for them are vital parts of both methods. The acceptable limits of behaviour to be established are represented by the inflow requirement, which is an indicator of the grouting class. Based on pre-investigations, the prediction is that a rock mass volume at the tunnelling face belongs to a certain class. Probe holes and other observations made at the face before grouting to see whether the rock mass volume lies within the limits for the predicted class are part of the monitoring plan. If these show that the prediction is wrong, the required subsequent action is to change the class. Observations of flow during grouting or in probe holes after grouting may indicate the unsuitability of the measures undertaken for that rock mass volume, and the subsequent action is that the rules for classification or the planned measures are changed.

6.2.4 Risk analysis and risk management

A systematic approach to managing risks in ground construction is fairly new, although on the other hand it may be argued that rock construction and contracting is all about mitigating risks.

Risk analysis should also be seen as a tool to help structure problems, making communication easier, and identify requirements and the threats against them /Stille et al. 2003/.

In a general context, a word like "risk" is used quite freely but, for the purpose of risk management, a precise vocabulary is vital. Risk analysis uses the concepts risk object, hazard (which is a property of the risk object), initiating event, and subsequent damage /Sturk 1998/. If there is an initiating event, the hazard will be triggered and may result in subsequent damage. Apart from geological uncertainties, the technical, organisational and contractual hazards should not be overlooked. Often they are triggered in combinations.

Hazards related to grouting can, for example, be

- The fractures are different than anticipated.
- Management or reviewers do not have competence to understand grouting theories or the necessity of an iterative approach.
- Theories are not valid at great depths.
- Workers do not follow instructions.
- The fulfilment of the requirements set up by the client is difficult to verify during construction.
- The contractor does not have the incentive to perform well.

Different risk analysis methods and management systems are available and are applied in different projects depending on the complexity and stage of the project, but also the preferences of the responsible organization. In their simplest form, risks are listed as they appear together with the risk owner, i.e. decision maker, and the actions planned and undertaken are recorded. More advanced analysis systems may quantify probabilities and consequences or sort risks in order of relative importance.

An important tool for understanding and mitigating risks are "warning bells" /Sturk 1998/. It should be noted that there is always an indication or a warning bell and that listening to the signals should be encouraged and care should be taken that signals are not ignored. That means that, however sophisticated a system is, it will not guarantee that risks are not triggered; it is merely a tool in the hands of the organization.

A concept of interest is robustness. A robust construction method can handle different geological conditions that may arise with adjustments within the method, but without a change of the main construction principles /Isaksson 2002/. Robustness of the grouting design may concern the choice between systematic pre-grouting and selective pre-grouting. Systematic pre-grouting means drilling full fans covering the entire tunnel, whereas selective grouting means that fans are only drilled where this is indicated necessary by models or probing results. With selective grouting the risk for post-grouting is increased; i.e. selective grouting is less robust.

7 Proposed strategies to meet final repository goals and requirements

7.1 Overall strategy and working mode

Grouting can never be deterministically described. To analyze a situation, different approaches, including engineering judgement, may be needed to identify the problem and its solution. The approach and working mode for the repository facility will therefore always be iterative. The iterative working mode will be applied at the actual tunnel face, where the response of the ground to actions undertaken will provide information as to how the next round should be grouted, should additional measures be necessary. The iterative working mode will also be applied throughout a project where different stages raise different questions and require different qualities and amounts of data for analyses.

In view of the above situation, and the high demands on sealing results, verification and traceability of the process, it is obvious that the new knowledge and understanding along with a systematic approach are necessary for successful sealing of the final repository. SKB will therefore apply the classification tool and the principles of the observational method when designing, updating and executing sealing measures.

Passing on results to the next stage is essential. Reasons for solutions proposed and solutions rejected should always be documented, so that the understanding is transferred. The systematic documentation of hazards is especially important.

A requirement on the quality system to be applied is that it must ensure that the specified standard and outcome of the work is achieved. On an overall project level, the basis for achieving quality is assurance of appropriate staffing of the project. With respect to grouting, ensuring the specified quality would require verification that the required grouting result is reached. The system should also apprehend that meeting requirements on environment and safety, processes and approaches are as important as achieving the desired results. Quality control must be applied to all stages of the grouting process and verify that plans are relevant and activities are carried out according to plan. As there will still remain an uncertainty concerning the grouting result, quality control during the execution of grouting is thought to fit in as an integrated part in the observational method.

Due to the fact that it concerns the construction of a nuclear facility, the construction contract or operational procedures for the final repository will have to be an arrangement that allows SKB to maintain control of the technical solutions. Through its designers, SKB will be responsible for repository design, including the necessary grouting measures.

7.2 Design steps and execution

7.2.1 Planning during Site Investigation, step D

The overall task for this stage is to show that the project is robust and supports both the long term safety and the environmental cases. In the case of grouting, this means demonstrating that sealing to the required levels is feasible even when any restrictions on the applicable technology are taken into account. This result will be part of SKB's application for a permit to build the final repository facility under the Nuclear Activities Act and the Environmental Code. It will thereby also form a basis for the permit and conditions issued by the Government, SKI and the Environmental Court. The design work in step D will also serve as a basis for the further design.

Demonstrating feasibility means that it must be shown through experience or estimates

- that there is a technology that is realistic and can meet the requirements,
- that the technology is robust enough to allow for possible variations in rock mass conditions,
- that there is a process for handling the uncertainties related to the technology at that stage, so that it can be ensured that the requirements will be met after execution,
- that the amounts of grouting required, the time taken and the associated costs will not be prohibitive.

The design work in step D considers alternative sites. Uncertainties and overall robustness will be input to site selection. The analyses are to be performed for the functional areas repository access, central area and deposition area.

The premises, process and documentation for grouting design step D are presented in UDP/D2 /SKB 2007/. The Site Engineering Report (SER) that is under preparation will present an engineering description of the rock mass for the underground part of the repository.

The SER will provide:

- design parameters for mechanical properties,
- design parameters in the form of technical criteria that will be applied in design,
- general engineering guidelines based on the analysis of problems of specific concern for the repository.

Analyses will consider probable and unfavourable conditions for each functional area. The analyses must demonstrate appropriate grouting measures. Control programmes, actions and special measures to cope with difficult situations will be described. The overall judgement of feasibility and uncertainty will be assessed and critical design parameters listed.

The analyses will primarily use analytical methods or be based on experience, including studies presented in the planned CECR-reports (SKB Construction Experience Reports, for Laxemar and Forsmark, respectively). The calculations will focus on target hydraulic conductivity and the extent of the grouted zone. Grouts that may be considered are silica sol and low-pH cement-based grout, both of which are under development or evaluation.

The presentation of results will include drawings with the proposed grouting measures.

7.2.2 Detailed design

Detailed design aims at creating a firm foundation and a framework within which the works can be carried out. The design work and approach will be on a more detailed and complete level than in design step D. Whereas the design work in step D examines typical and extreme situations to prove feasibility, the detailed design has to cover all situations to prepare for actual execution. For the detailed design, there will also be some additional data from investigations aimed directly at construction.

Detailed design will consider the results and experience obtained in earlier steps. For the access shaft and ramps, this means looking back at design step D. When the detailed designs are to be prepared for the deposition tunnels, experience from the actual execution of the designs for the accesses and central area will be available.

Detailed design includes the planning and preparation of tendering documents, which is normally carried out based on, and in parallel with, the actual technical work. Both the division of responsibilities and the organization of quality assurance work are of great importance and must be reflected in planning and documents. Because the project falls under the Nuclear Activities Act, SKB must take full responsibility for technical solutions.

The result of the work at this stage will form the basis for further planning, for the calculation of time, resources and money, and for procurement and execution. The major decisions to be taken at this stage are SKB's decision to invest, the decision to send out tendering documents and the decision to sign a contract. These actions and decisions define the requirements on the work process and its result.

The technical detail of the design shall be at such a level that it can be used as a basis for tenders. To permit calculations, both regarding SKB's own budget and a contractor's bid, the premises for design must be made clear. This also has a bearing on traceability for long-term safety.

The design should be flexible. The ambition to produce a design that can be priced must not lead to a fixed design with no flexibility, as the design always should be based on the actual conditions encountered, which means that modifications will have to be made in the execution stage. In order to get an overview of the detailed design, the different design situations will be organized by means of classification, which also promotes efficient production and cost estimation. The detailed design will not be considered complete without an instruction describing the remaining uncertainties and how they can be handled during execution. Control programmes and procedures must consider production friendliness, without neglecting demands that the verified results must meet the sealing requirements.

The design work will follow the same principles as the design in step D, i.e.

- Inventory of ground data, geometries and functional data.
- Analysis of ground behaviour, i.e. predicted behaviour without grouting measures, indicators and rules for the definition of classes.
- Testing of different grouting approaches; evaluation of fulfilment of sealing requirements and choice of class, based primarily on robustness.

The design documents resulting from the detailed design work are assumed to comprise

- Design report.
- Technical descriptions/specifications.
- Drawings
  - predictive,
  - constructional.
- Method statements.
- Control programmes.

The design and the design documents must consider the planned use of the observational method and also relate to the planned type of contract and organization.

The planning of time and resources must consider the time needed for external review, as well as for internal review at "tollgates" so that the appropriate attention can be given to achieve improvements of processes and results. The scheduled advance rate must allow for an initial adjustment period with slow progress whilst the organization gets acquainted with and improves the methods and procedures.

The organizational and contractual frameworks are important premises for the execution of the work. Financial agreements and division of responsibilities for uncertainties provide incentives to act in different ways, but also for different technical solutions. This means that technical and financial issues and documents cannot be dealt with separately. They must be approached in an integrated fashion, which requires a work process where administrative matters are handled by the persons responsible for design in cooperation with persons with experience from the contractual side of ground engineering contracts and from working under the Nuclear Activities Act.

7.2.3 Final design and construction, during construction and operational stages

Once the construction work has reached repository level and the deposition areas are being excavated, it is assumed that deposition of spent fuel and tunnel construction will be carried out in parallel, in separated areas. It is assumed that before excavation of a new deposition area is begun, investigations will be carried out from the central tunnel to verify the suitability of the preliminary chosen part of the rock mass. It is also assumed that the viability of sealing the rock mass at the required levels will be one of the issues to be assessed.

Grouting drawings, method descriptions and a control programme are obtained from the detailed design and provide the technical framework for the execution of the works. Overall project planning provides the organizational framework. The construction task is to manage the process so that grouting is carried out within the framework and so that the goals are achieved without any negative impact. Based on the detailed design presented in drawings, and guided by the method descriptions, the grouting design in the current position has to be decided upon. The results are then checked and the design confirmed by carrying out the checks specified in the control programme. Working according to the specified frameworks should satisfy the requirements for traceable and documented work, permitting local adaptation as well as general improvements.

Just as a new part of the rock mass has to be verified as suitable for a deposition area, it is assumed that every potential deposition tunnel position will be verified for its constructability and intended use. This verification is assumed to be based on one or more cored boreholes along all or part of the tunnel.

Grouting works are part of the rock works contract and part of the excavation cycle. Grouting also has its own cycle of operations. It can be assumed that the operations in the grouting cycle may typically have the following sequence: probing with hydrogeological tests and mapping, assessment of rock grouting class, drilling of grout holes, grouting of holes, drilling of probe holes, check of inflow in holes against acceptable limits. Depending on the inflow in probe holes, this is followed by drilling and grouting of a new round in the same fan position or returning to the excavation cycle with drilling for blasting. All actions are recorded in protocols.

It is during construction that the goals have to be accomplished. Apart from the technical and environmental goals there are project goals related to time and money. This puts the focus on an efficient process. Since the goals may often conflict, and since uncertainties are an inherent part of all rock construction projects, decision-making, including setting priorities, is a vital part of the process. It is therefore essential to have a working process that ensures that all relevant information will reach the decision-makers at different levels, permitting well-informed decisions.

The process is managed with the help of drawings, method descriptions and control programmes including grouting classes and checks. But it is during construction that it must be ensured that design and execution are based on actual conditions. The basis for the control programme is the identified uncertainties and risks that have to be controlled in order to ensure the quality of the works. Checks are aimed at verifying the intended grout properties and the sealing results in terms of watertightness and residual inflow. They are also aimed at monitoring the actual grouting process by measuring flow, pressure and grout take curves. The analysis is aimed at ensuring that the premises on which the design is based represent the actual situation.

Based on checks and other observations, adjustments to design and execution may be called for. Adjustment may mean a local change in one position. Adjustment may also mean that grouting classes are redefined. Redefinition can mean a change in the indicators defining when the class should be applied, or a change in the design and execution described for the class.

These adaptations can be seen as the final design of the grouting work. This design work and the resulting final design should be documented and replace previous documentation.

An important part is passing the “tollgates” previously defined by the designer. A tollgate may be located after the completion of a number of grouting fans, for example. The idea is to have a predetermined and systematic review of the design, execution and results, as well as of the overall efficiency of the process, and to get formal clearance from the designer on how to proceed. It is believed that a substantial effort will have to be put into the fine tuning of classes at the beginning of the work, and that this effort is well worthwhile even if the sealing requirements are met by the initial design.

Tollgates should also be located and passed before the start of the construction in areas where uncertainties or difficulties are judged to be great, in order to ensure extra attention and review of the planned design and execution.

Giving the intended attention to tollgates will guarantee as far as possible that the process will be efficient and the result can be accepted even when it has been impossible due to uncertainties to achieve detailed planning and design in advance. The control programmes and tollgates are part of the quality assurance of the project in the wider sense as presented in Section 6.2.1 and have to be compatible with the organization and contract.

The requirements for final design and construction are thus that the organization, process and contract with the contractor, or other operational arrangements, must be set up so that they provide procedures for handling, documenting and resolving a situation where adjustments are continuously made in a fair and transparent way. Another prerequisite for successful execution is that the permits from the Environmental Court and the Government do not restrict the planned mode of action. The applications for these permits must stress that flexibility within defined frames is necessary in order to achieve the project goals.

7.3 Requirements on organization for execution

The overall SKB organizational approach is planned and devised on a common level within the SKB Spent Fuel Project. However, as organization and staffing has been identified as one of the vital issues for successful rock sealing, it is stressed in this report.

It is essential to build up a competent organization with a clear division of powers and responsibilities and appropriate and well defined channels for communication. The project organization and the procedures have to be set up in such a way that any need for changes can be met in an efficient and controlled way. This also poses demands on the client’s organization, which must be prepared to make decisions with short notice. The final repository project has a strong focus on long term safety and the overall priorities between project goals should be clear at the beginning of the project. When technical difficulties arise, attention should be focused on resolving these difficulties. This requires mutual trust between the parties involved, which in its turn requires a contract or other operational arrangements that supports cooperation and defines a distribution of risks that is considered fair.

Competence is stressed and includes both the competence of the individual and of the organization.

On an individual level, competence refers to theoretical knowledge and understanding in combination with years of experience. It also includes an understanding that for the final repository goals related to process, verification and documentation are as important as the advancement of the tunnelling face. Part of the necessary competence is an understanding at higher levels of the project organization that grouting is necessarily an iterative process and that achieving good sealing results takes time, due to purely physical reasons.

The organization also needs to be competent. In other words, the organisational framework must allow knowledge and experience to be put into use. This means

- that responsibilities are only delegated where individual competence exists,
- that communications must be assured so that information for decisions reaches the relevant organizational functions
- that it must be clear who sets priorities and makes other decisions and on what grounds,
- that procedures to handle changes must be clearly defined,
- that the contract and operational procedures must stimulate communication and cooperation.

An example of confirming that the information is properly transferred is when the contractor or operations personnel takes the technical specification and transforms it into method statements thereby demonstrating that the task is understood. An example is the Äspö Hard Rock Laboratory "Activity plans" that are routinely used for work at Äspö.

As process and documentation are of special importance

- resources for managing the documentation need to be allocated, so that technical experts will not be involved in routine reporting.

8 Programme

8.1 Evaluation

The factors governing the grouting works will be the project requirements, the grouting-related properties of the rock mass, and the available grouting materials and techniques. High groundwater pressure will be encountered at the lower levels of the access tunnels and shafts and in the central area and deposition areas, which will require dealing with special problems. In some areas, the challenge will be to pass through highly permeable fracture zones whilst, in others, the challenge will be to eliminate spot leakages.

Current competence is discussed in this section in order to identify and justify further research, development and demonstration activities. As shown in Chapter 2, competence should be regarded as being composed of the elements understanding, knowledge, know-how and skill. These must be combined with a willingness to perform.

Our understanding and knowledge of the individual elements of grouting has advanced considerably during the past few decades, thanks to the research and development work that has been done on the characterization of rock masses and on the grout including the assessment and importance of different grout properties. Work is continuing in these fields and our understanding is gradually improving. The basis for designing and controlling both the grout spread and the sealing achieved is also improving continuously. However, as yet, this toolbox is not fully utilized in designing and executing grouting in most projects, even though examples do exist and are getting more numerous.

Thus, know-how and skill regarding design and verification need further improvement and demonstration, and this can only be achieved by implementation and testing. Know-how and skill can be considered both as a joint resource within the construction industry, and as properties of specified organizations or individuals. Thus, not only the improvement of SKB's skills and know-how, but also the general enhancement of skill and know-how in the industry is of vital interest. As SKB does not carry out underground construction projects on a regular basis, SKB must actively take part in joint projects or otherwise promote informed approaches and procedures in other grouting projects. It is also clear that SKB must develop SKB's own know-how and skills within the actual final repository construction project, not least considering the special features of the project.

The need for further development work is clearly noticeable in the design process and the observational method for grouting projects. A design process, or rather a design of grouting measures taking into account the advances made, has been applied and tested to some degree, but more experience is needed. In order for the observational method to be applied, different detailed issues need to be resolved in relation to grouting. One such issue is verification of the results.

It is important to demonstrate and verify new models, materials and equipment as applicable in practice. Grouting the Apse TASQ-tunnel at Äspö /Emmelin et al. 2004/, demonstrated competence in describing grouts, designing grouting technique and predicting grouting results when using cement-based grouts. Cement-based grouts have limitations in penetration ability, and other grouting material and techniques may be needed to seal fractures in the deposition tunnels. Due to its ability to penetrate small fractures, silica sol is considered to be a promising candidate for this work, but needs to be tested and verified at high water pressures. Low-pH cementitious grouts must also be verified as useful in practice at high water pressures.

The possible need to pass through highly permeable fracture zones at high groundwater pressure requires an understanding of technical methods, but it is likely that time and resource planning is equally important to guarantee successful passage through these zones during construction.

The need for post-grouting cannot be ruled out, and our current understanding of the post-grouting situation needs to be verified and the potential of the method assessed and demonstrated.

Due to new grouts and high groundwater pressures, the suitability of currently available grouting equipment needs to be evaluated. To meet the project's high demands on both the grouting results and the need for verification of the process, logging and monitoring devices on the equipment need to be evaluated and quality-assured. It has been concluded (e.g. /Liljestrand 2006/) that 25% of the cost of grouting is related to materials, while 75% is related to time, including the cost of equipment and labour. Thus, there is a potential for a process where the different activities such as packer setting, preparation for grout hole filling, testing of grout etcetera are automated.

Another issue is the estimation of the volume of grouting materials required for sealing, i.e. the estimation of grout take. This is of special interest for the final repository. Recently, a new method (see Section 5.2.3) was presented as a tool for controlling grout spread and developing stop criteria, and the focus should be on designing, managing and executing grouting in order to control grout spread. For this reason, available analysis methods could be used as design tools for comparison of different possible grouting measures and estimating the relative decrease in inflow after grouting. However, further demonstration activities are needed to verify the usefulness of the analysis methods and obtain a good body of information for recommendations in practical use.

Grouting in the underground facility will require a high grouting pressure in the deeper parts, due to the high groundwater pressure. Conceptual models are presented in /Brantberger et al. 2000, Gothäll 2006/ but further studies are recommended including an international review. Of interest is the rock mass response in general and in the zone close to the tunnel in particular, and how this should be considered in different analyses.

Ensuring competence on an individual level means both that qualified individuals must be available and that their competence needs to be documented. On the design and executive level, as a result of the grouting research that has been done, there are now a number of individuals who devote most of or a large part of their daily work to grouting, thereby creating their own personal reference cases. It should therefore be possible to appoint staff who are qualified enough to deal with any unexpected situations. On the labour level, things have proved more difficult. It will be necessary to both provide basic training in grouting and in SKB's special case. Initially it will also be necessary to actually stand by and supervise the work, by checking, explaining and instructing.

8.2 Planned and ongoing SKB grouting projects

Planned and ongoing SKB grouting projects extend from studies of individual properties to implementation projects. Projects being conducted by SKB, projects where SKB is one of several clients and projects being actively promoted by SKB are presented below.

The overall goal is to be able to present a comprehensive concept for grouting at the time for the applications, and the projects that are presented here stretch as far as year 2009. The further development and adaptation of processes and practical methods have to be achieved during the actual construction of the repository facility. These efforts, as well as any projects taking care of any new issues resulting from the ongoing research, are not included in this report.

Sealing of tunnel at great depth

Scope and purpose: The main goals of this project are to confirm that silica sol is a useful grout at the water pressures prevailing at repository level, and to confirm that it is possible at this water pressure to seal to the preliminary tightness requirement for a deposition tunnel. To achieve this, an approximately 100 m long tunnel will be constructed at the Äspö Hard Rock Laboratory. Execution will be step-wise and is planned to include grouting with grout holes inside the contour, tests with post-grouting and tests of the sealing of drips. The extent of grouting will depend on properties of the rock mass encountered, and on the results achieved in previous steps. If the rock mass conditions are suitable, tests of the suitability of low-pH cementitious grouts are planned. The project will implement and evaluate grouting characterization methods and grout spread models as developed by KTH and Chalmers.

Status and realization: According to the plan, field work will start in 2007 and the results will be available early 2009. The work is fully funded by SKB. The research programme and execution of the project will be carried out by Chalmers researchers.

Post-grouting

Scope and purpose: Work that aims to recommend potentially successful strategies for post-grouting. It includes the characterization of a pre-grouted rock mass so as to assess the situation to be dealt with by post-grouting, theory development and testing of the theory in the field.

Status and realization: Theories are being presented /Fransson 2006/ and planning for a field test starting in 2007. Suitable site not yet found. Possibly a project that is jointly funded thorugh SveBeFo.

Grout spread in hard jointed rock using high grouting pressures

Scope and purpose: The Swedish approach is usually based on the use of moderate grouting pressures. Experience from the use of high-pressure grouting outside Sweden should therefore be compiled and analyzed. An ongoing doctoral study is aimed at gaining a better understanding of the effects of high pressures on the rock mass response (fracture deformation) as a basis for recommendations for the design of grouting technique.

Status and realization: Compilation of experience is planned for 2008. A basic conceptual model is presented in a licentiate thesis /Gothäll 2006/. Work to support the model continues, with final reporting in a thesis in 2009. The study is fully funded by SKB and will be carried out at KTH.

Penetration ability and bleed of grouts

Scope and purpose: This project is a doctoral study that will continue the research on penetrability and bleed of grouts /Draganovic 2007/. Its objective is to develop an improved understanding of grout penetration and bleed and how these factors influence the sealing result.

Status and realization: The project is jointly funded through SveBeFo. SKB is taking active part in the reference group. The study is the second part of a doctoral study being carried out at KTH and will start in 2007. Final results are expected to be presented in 2009.

Characterization

Scope and purpose: This project is a research study to develop a 3-D model for identifying relevant parameters for the purpose of improving characterization and grouting methodology.

Status and realization: The project is a continuation of an earlier doctoral study /Fransson 2001/. In the current project, modelling based on the basic conceptual idea is being applied and tested on field data from the Apse TASQ tunnel grouting /Emmelin et al. 2004/ in order to prepare for an application of the characterization method and modelling in the sealing project at Äspö. The outcome of the sealing project is partly dependent on the characterization project, in the sense that theories and performance will be partly evaluated by application to Äspö in 2008. A licentiate thesis is planned to be published in 2008. The study is fully funded by SKB and will be carried out at Chalmers.

Evaluation/development of cement-based low-pH grout

Scope and purpose: Different grout types will be needed to meet the different rock mass situations. The aim of this project is to present a low-pH grout and confirm that it is suitable for the intended use of sealing wide fractures in the final repository.

Status and realization: A project will be carried out during 2007 to evaluate the current status of low-pH grout based on experience at Posiva in relation to requirements on grout strength and rheology for the sealing project at Äspö, and including some laboratory investigations. This work is fully funded by SKB and will be carried out by Chalmers. Further work will depend on the possibility of demonstrating the grout type and results in the sealing project as well as experience and results obtained by Posiva, see R20 project below.

Superplasticizers and other organic cement/concrete admixtures

Scope and purpose: The project concerns an evaluation of the long-term consequences for repository performance of the use of organic cement/concrete admixtures. The focus of this study is both on the release of organics from cement samples as well as on the effects of these compounds on radionuclide sorption under near-neutral groundwater conditions.

Status and realization: Work started in 2005. Preliminary evaluation models and preliminary acceptance or disqualification of superplasticizers are expected in 2008. The work is funded and managed jointly by SKB, Posiva, Nagra and NUMO and is being carried out by Saanio & Riekkola Oy, and Gothenburg and Helsinki Universities.

Procurement of grouting works

Scope and purpose: The purpose is to improve the tendering documents for grouting works so that they will better reflect current knowledge and understanding regarding both technical aspects and the importance of incentives. It includes a study of a set of current contracts and aims at a proposal for improved formulations.

Status and realization: Work started in 2007 and is planned to be finished by 2008. The project is jointly funded through SveBeFo. It is being carried out by Ramböll and Golder with the active support of a reference group of representatives from contractors, consultants and clients in which SKB will take part.

Grouting equipment

Scope and purpose: SKB main concerns regarding grout equipment are suitability and worker health and security in view of new grout types, high sealing demands and high pressures.

Status and realization: Work to specify and develop equipment for the at Äspö sealing project is under way. Further equipment development needs should be identified and specified by 2008–2009 based on experience from Äspö.

Observational method for grouting

Scope and purpose: A study will be executed aimed at developing the use of the observational method for grouting works.

Status and realization: A tentative interpretation of the method used for grouting is included in the current report. A detailed interpretation that is integrated and reflected in the design process and the excavation cycle is desired in 2008. It is expected that requirements on the formal application and overall requirements on the process will be stricter than in other rock construction projects. Refinement and adjustments of the interpretation of the method will thus be necessary during the first stages in the execution of the final repository project. This work is closely connected to the ongoing SveBeFo projects with a focus on different issues related to observational method.

Design process

Scope and purpose: A possible process and requirements for the detailed design should be described. The grouting design process is necessarily an iterative process, both between different stages and within the excavation cycle, and clear processes must be ensured for design, verification and documentation of grouting for the final repository facility that are in line with the observational method. The actual design process should be based on current understanding and experience from research and current underground projects.

Status and realization: Possible process and related requirements under discussion. The proposed design process and requirements should serve as a basis for the underground design premises for the detailed design.

Grouting of highly permeable fracture zones

Scope and purpose: A retrospective study should aim at analysing the process and experiences collected during grouting of the fracture zones at Äspö HRL in the view of the understanding from new research.

Status and realization: A compilation is made during design step D1 /Chang et al. 2005/. The retrospective study has not yet started, but should be completed in 2008.

Grouting of shafts

Scope and purpose: Grouting of shafts presents a special problem due to low accessibility and applicable solutions are highly dependent on the excavation technique. A retrospective study should aim at analyzing the process and experience collected during grouting of the shafts at Äspö HRL, based on the understanding gained from recent research. Experience from other shaft grouting is to be included. Within design step D2, grouting concepts will be studied for different shaft excavation methods, taking into account the predicted conditions at the different sites.

Status and realization: The study and the design activities in step D2 will start in 2007. The results will be available in 2008.

Educational efforts

Scope and purpose: The ultimate purpose is to ensure competence for the construction of the final repository. Before starting construction, SKB is, for practical reasons, mainly contributing to the understanding and knowledge parts of this competence. For example, SKB has performed a detailed theoretical evaluation of silica sol as a grouting material, whereas the know-how and skill to use silica sol in production has been developed by other organizations in their infrastructure projects. SKB is also contributing to a general enhancement of competence by funding doctoral studies. SKB's input to technical universities is providing a basis for continuous research and is also producing specialists for the industry with a pronounced and deep interest in implementing new grouting understanding and developing their specialist skills.

Status and realization: Educational initiatives has been taken by different groups within the tunnelling industry, but so far no education has been realized. The ambition and outcome of any joint efforts will constitute the basis of a specific SKB educational effort to be carried out in conjunction with the start of the construction of the final repository facility.

8.3 Contributions from other projects

Contributions from other projects, from which results will be of value for SKB grouting activities are listed below:

Development and application of grouting theories to real grouting conditions

Scope and purpose: The objectives of this project are to further develop analytical solutions for grout spread and apply the theories to real grout data in order to study their applicability.

SKB's interest: A stop criterion for grout spread is of central interest for controlled grout injection.

Status and realization: The project is being carried out in co-oporation with the project described below "From grouting theory to practical application". Different case stories are being studied. The basic idea is that it is the spread and penetration of the grout that should govern the stop criterion. A report to be presented in 2008. The work is being carried out at KTH in cooperation with Chalmers.

R20 programme Onkalo

Scope and purpose: This programme is carried out to prepare for the sealing works in the rock mass below the sub-horizontal zone R20 in the Posiva Onkalo facility. The objective is to prepare a practical grouting process that fulfils the requirements arising from long-term-safety considerations. The programme includes long-term safety related investigations regarding grouting materials as well as further development of grouting materials and methods.

SKB's interest: Results and applicability for SKB conditions are of importance for any further SKB efforts.

Status and realization: The project is under way. The R20 report and the actual construction through the R20 zone is scheduled for 2008.

Erosion of grout and fracture fillings

Scope and purpose: The objectives are

- to achieve an understanding of the erosion of grouts and fracture fillings in rock fractures caused by streaming water and/or grout,
- to determine requirements on the rheology and strength of grouts in order to obtain good sealing of rock fractures with regard to possible erosion by streaming groundwater,
- to predict grout penetration problems caused by the erosion of fracture fillings.

SKB's interest: The project will provide vital information to SKB on the choice and design of grouts for tunnels with high water pressures and hydraulic gradients, which cause grout erosion.

Status and realization: The project will result in a Chalmers doctoral thesis in 2008.

From grouting theory to practical application

Scope and purpose: The project aims at a deeper understanding of the combination rock mass – grouting process – construction industry. The objective is to build a knowledge platform for development of an efficient grouting process and thus also efficient tunneling. This will be based on an analysis of how our state-of-the-art understanding of the grouting process can be transformed into practical economic guidelines for grouting engineers.

SKB's interest: Since SKB anticipates extensive grouting operations for the future repository, guidelines on how to organize and handle this are of great importance.

Status and realization: The project is a licentiate project at Chalmers that has just started and aims at a licentiate thesis in 2009.

Drip sealing of tunnels

Scope and purpose: Dripping of water from the crown of road and railway tunnels is a serious and costly problem in Sweden with few effective remedies. The objectives of the project are:

- to achieve an understanding of the groundwater conditions in and close to a grouted tunnel ceiling,
- to predict drip leakage and icicle formation from the tunnel ceiling,
- to establish successful technical and economical strategies for sealing and drainage of tunnels in fractured rock in order to avoid water dripping and icicles.

SKB's interest: In repository tunnels, drip and spot leakage are a problem for the backfill and buffer. Understanding the mechanisms behind these phenomena and their occurrence is therefore of importance for SKB.

Status and realization: As a part of the project, a full-scale field test is currently being conducted in a railway tunnel. The project will result in a Chalmers doctoral thesis in 2010.

Characterization of rock mass for grouting

Scope and purpose: Post-doctoral research with the general main objective of developing and verifying:

- Methods for estimating transmissivity and aperture distributions.
- Conceptual models describing a grouting situation.

SKB's interest: The arrangement is of importance to SKB since it creates a resource for supervision and expert advice for the SKB projects at Chalmers. It also creates a resource for dealing with new issues in the field.

Status and realization: Results will be presented in papers for international conferences and journals. The Chalmers work is funded as a personal grant. The project is being carried out in close cooperation with the project "Characterization" mentioned above.

Durability of grouting materials

Scope and purpose: The durability of cement and particularly silica sol is important but also questionable for infrastructure tunnels. An approach to longevity assessments based on the thermodynamic stability of the grouting materials in combination with common groundwaters will be applied. The objectives are:

- To assess breakdown mechanisms and their timespans for cement and silica sol grouts.
- To identify environmental factors affecting the longevity of the grout.
- To provide a basis for assessing practical time spans for durability of grouts in the rock fractures.

SKB's interest: Although the longevity of the grouting is not a primary question for the safety of the repository, the tunnels and caverns of the system will be open for considerable time. This means that the durability of the grouting is of importance.

Status and realization: The Chalmers project just got started and a first stage will be reported in the autumn of 2008.

Observational method

Scope and purpose: This is a project package that aims

- to give a basis for how rock mass characterization can be applied in the context of the Observational method,
- to show how this facilitates a data-worth analysis that can build a basis for optimization of design, construction and functioning controls,
- to further develop the theoretical probabilistic base of the observational method,
- to further develop the observational method as a practical tool for rock design.

SKB interest: SKB has declared that the observational method will be used as a method in the design and execution of the final repository facility.

Status and realization: The new Eurocode for geotechnical constructions will be effective in 2009. The project consists of three doctoral projects on the application of the Observational method started at Swedish technical universities Chalmers, KTH and LTU in 2006 and jointly funded through SveBeFo. The project package does not specifically concern grouting, but will lead to a general increase in know-how to benefit from the method. The project will give valuable input to the above mentioned project "Observational method for grouting" and will result in three doctoral theses in 2010.

Programme for rock engineering controls

Scope and purpose: Work within the SKB spent fuel project that aims at presenting a description of control and verification programs regarding investigations, environment and technical systems. The programme for rock engineering controls includes grouting.

SKB's interest: Control and verification programs are an integrated part in assurance of the project goals during construction.

Status and realization: The results are to be included in the application to construct the final repository facility.

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Appendix 1

Terminology

Some of the terms and concepts used in this report are explained below. The list comprises terms and concepts that are specific for SKB or for grouting or the rock construction process, or for other reasons need to be explained or defined in order to describe the discussed concepts in a stringent way.

English	Swedish	Definition, comment
Access, access shaft or access tunnel	*Tillfart*	Link between repository area and ground surface, used for transporting material and/or personnel.
Additive, admixture	*Tillsats*	In this report no difference is made between additive and admixture.
Batch	*Sats*	Quantitiy of grout mixed at one time.
Bingham fluid	*Bingham vätska*	A substance which possesses both viscosity and cohesion.
Cement based grout	*Cementbaserat bruk*	A grout in which the primary bonding agent is cement.
Characterization for grouting	*Karakterisering för injektering*	Rock mass characterization aiming at the specific grouting features and behaviour.
Characterize	*Karakterisera*	Define the important characteristics of a phenomenon.
Class	*Klass*	Group with similar properties.
Classification	*Klassificering, klassindelning*	Arrangement of objects in different groups for the purpose of getting a better overview. Covers the whole range of outcomes and results in mutually exclusive classes.
Conceptual model	*Konceptuell modell*	A model which demonstrates understanding and defines the geometric framework in which the problem is solved, the dimension of the modelled volume, descriptions of the processes included in the model, and the boundary conditions.
Deposition holes	*Deponeringshål*	Chambers for deposition of canisters containing spent nuclear fuel.
Deposition tunnel	*Deponeringstunnel*	Tunnel from which deposition holes are bored.
Design step	*Designsteg*	Design activity with a complete design product, based on results from an investigation stage.
Design work	*Projektering*	Activities including layout, sizing and description of the final repository as a basis for construction, operation and closure. All the work of preparing system and preparing documents and a facility description.
Detailed investigations	*Detaljundersökningar*	Measurements, samplings, tests and observations carried out during the construction and operating phases *to verify and update site descriptions* in order to permit adjustment of the final repository facility to the prevailing conditions and as a basis of the analyses required for future permit applications.
Deterministic	*Deterministisk*	Determined by preceding causes or other given conditions, allowing only one answer.
Fan length	*Skärmlängd*	The length of the boreholes drilled in a grouting fan.
Fracture transmissivity	*Spricktransmissivitet*	The ability of an individual fracture to conduct water.
Geotechnical behaviour	*Geotekniskt beteende*	Covers ground behaviour and system behaviour.
Ground behaviour	*Ground behaviour*	From a grouting point of view: seepage, without grouting measures.
Grout	*Injekteringsmedel*	A pumpable material (suspension, solution, emulsion or mortar), injected into soil or rock, which stiffens and sets with time.

English	**Swedish**	**Definition, comment**
Grout injection	*Injektering*	The actual pumping of grout into the rock fractures.
grout spread	*Bruksspridning*	distance travelled by the grout from the injection point.
Grouting class	*Injekteringsklass*	Objects with properties that according to the result of design work can be grouted using the same grouting measures. The grouting class is defined by indicators ad their values. The grouting class can also include the grouting measures, and can then be referred to as design class.
Grouting design work	*Injekteringsprojektering*	
Grouting fan	*Injekteringsskärm*	The pattern of boreholes drilled into the rock in which grout is to be injected.
Grouting measures	*Injekteringsåtgärder*	Work carried out during construction aiming at achieving the sealing requirements. Includes any checks carried out in direct connection with the actual grouting injection.
Grouting pressure	*Injekteringstryck*	A pressure applied during the grouting process and measured at defined locations (usually at the pump or the borehole collar). Often set based on the groundwater pressure plus an excess pressure.
Grouting result	*Injekteringsresultat*	Result from the grouting operation. Includes sealing result, grout take, time use etc.
Hydraulic aperture	*Hydraulisk vidd*	Theoretical fracture width evaluated from a hydraulic test and assuming parallel fracture and plane-parallel flow.
Indicator	*Indikator*	Condition on which classification is based.
Inflow	*Inläckage*	Ingress, seepage.
Investigations	*Undersökningar*	Measurements, surveys, samplings tests and observations aimed at determining properties and mechanisms.
Low-pH grout	*Låg-pH bruk*	Any grout, cement-based or solution grout, that gives a leakage with a pH lower than 11.
Method	*Metod*	Planned procedure for achieving a given result.
Methodology	*Metodik*	Scientific approach for gaining knowledge or solving problems in a given discipline.
Monitor	*Registrera, övervaka*	Watch, keep track of, or check usually with a predefined time interval and for a specific purpose. Monitoring results in records in a database.
Newtonian fluid	*Newtonvätska*	A true fluid that exhibits constatnt viscosity at all rates of shear. A Newtonian fluid has no yield point.
Observational method	*Observationsmetoden*	Method where the design is reviewed during construction in accordance with Eurocode 7.
Observe	*Observera*	See and notice, watch carefully.
Operation	*Operation*	Execution of a task aimed at achieving a given goal.
Penetrability	*Inträngningsförmåga*	The ability of a grout to penetrate the ground, quantified by bmin and bcrit.
Penetration length	*Inträngningslängd*	Theoretical distance travelled by the grout from the injection point.
Phase	*Skede*	Period of time limited by well defined events.
Prediction	*Prognos, förutsägelse, prediktion*	Prognosis.
Probabilistic	*Probabilistisk*	Based on probability.
Reference design	*Referensutformning*	Description of design valid from a defined time that is to be used as premise and basis for comparison for further development of the described item and development and design of items that depend on the described item.

English	**Swedish**	**Definition, comment**
Rheology	*Reologi*	The rheology of a grout describes its flow properties, which influence how far it can spread in the rock mass.
Rock cavern	Bergrum	Underground excavation intended to contain chambers for personnel and visitors, technical systems, other equipment or for loading/unloading that is required for construction and operation.
Rock caverns in the service and handling area	*Centralområdets bergrum*	Underground chambers necessary for operation of the deep repository.
Rock mass characterization	*Bergkarakterisering*	Investigations and analyses that result in a description of the rock mass conditions giving values to the various rock mass features and assessing possible behaviour of the ground.
Rock mass Classification	*Bergklassificering*	Division of the rock mass into classes or groups as a basis for specifying measures.
Rock mass conditions	*Bergförhållanden*	Values of the various rock mass features and possible behaviour of the ground.
Rock engineering design work	*Bergprojektering*	The rock engineering design work consists of the site-specific design of the facility openings and the rock construction works.
Rock engineering checks	*Bergtekniska kontroller*	The measurements, samplings and tests that take place *in direct connection with* the other activities included in rock works. Rock engineering checks can take place before an activity is initiated in order to provide a basis for how it is to be executed and to check that the right material is used, and during and after execution in order to check the result with respect to material properties, execution and function.
Seal	*Täta*	Measures to prevent inflow.
Sealing result	*Resulterande täthet*	Tightness as a result of a sealing operation. Can e.g. be expressed as remaining inflow, as sealing effect – i.e. reduction in inflow divided by inflow before sealing, or as resulting conductivity.
Silica sol	*Silica sol*	Grout consisting of colloidal silica particles dispersed in water.
Site description	*Platsbeskrivning*	The site description presents a balanced description of a site (geosphere and biosphere) and its regional environs with respect to current state and naturally ongoing processes. It is based on a digital site model. Included in the background material for a permit application.
Site descriptive model, SDM	*Platsmodell*	Interpreted information on the site that is presented in a 3-D site model. Part of site description.
Site Engineering Report, SER	*SER*	A stage specific report that presents an engineering description of the rock mass. SER is based on the site descriptive model (SDM) and presents ground types that will be encountered during construction. It synthesizes the site description into design values that are used I repository design.
Site investigations	*Platsundersökningar*	The measurements, samplings, tests and observations that are performed in the site investigation phase for the purpose of serving as a basis for the facility layout and the analyses required in the licensing process.
Sol	*Sol*	A system containing tiny, freely suspended particles in a medium that may be a liquid or a gas. The particles are in the size interval 1 nm up to 1 micron and are thus of colloidal character.

English	**Swedish**	**Definition, comment**
Solution grout Any grout characterised by being a solution, i.e. having no particles (other than impurities) in suspensions	Lösningsbaserat injekteringsmedel	Any grout characterized by being a solution, i.e. having no particles (other than impurities) in suspension.
Split-spacing	*Split-spacing*	The procedure by which additional holes are located at half the distance from previously drilled holes.
Stage	*Etapp*	A clearly defined part of a phase. E.g. the site investigation phase, the Initial site investigation stage.
Stakeholder	*Intressent*	Party who has (legitimate) interests and right to make demands.
Step	*Steg*	A clearly defined part of a stage. E.g. design step D2.
Stop criterion	*Stoppvillkor*	Defines the conditions or requirements at which grouting may or must be stopped.
Strategy	*Strategi*	Long-term general approach. General plan involving the gradual application of different methods, each of which leads to an interim goal, and which in combination lead to a goal specific for the strategy, e.g. “strategy for sealing of the final repository”.
Suspension	*Suspension*	A system consisting of a finely divided solid substances suspended in a liquid. Particle size roughly 1 micron – 1 mm.
System behaviour	*Systembeteende*	From a grouting point of view: “interaction between ground behaviour and grouting measures”, i.e. seepage, after grouting measures.
Tollgate	*Tollgate*	Superordinate decision point in a project, at which formal decisions are made by the project sponsor concerning the aims and execution of the project.
Tunnel	*Tunnel*	Underground passage intended for transport (personnel, vehicles, materials) and services (supply, ventilation).
Underground Design Premises, UDP	*Projekteringsanvisningar, UDP*	A stage-specific control document for the rock engineering design work.
Validation	*Validering*	Confirmation, by the provision of objective evidence, that the requirements for a *specific intended use or* **application** have been met.
Verification	*Verifiering*	Confirmation, through the provision of objecive evidende, that *specified requirements* have been met.