

# DESIGN APPROACHES FOR GROUTING OF ROCK FRACTURES; THEORY AND PRACTICE

Jalaleddin Yaghoobi Rafi

Cover photo:

Background – Grouting at the curtain of Gotvand Dam, Iran.

Small photos – Grouting at the rock bedding of Laxede Dam, at Harads, Sweden.

# **DESIGN APPROACHES FOR GROUTING OF ROCK FRACTURES; THEORY AND PRACTICE**

## **Injektering av bergsprickor - Design metoder i teori och praktik**

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This report is a representation of the Licentiate Thesis (TRITA-JOB LIC 2021, ISSN 1650-951X) published by The Royal Institute of Technology (KTH), Stockholm, 2013.

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## Preface

Sealing of tunnels and caverns is an important activity within rock engineering and construction, especially in an urban environment and other areas which are sensitive to an affected groundwater. Dam structures founded on rock also need to be sealed, and in both cases, this is widely done by rock mass grouting. Rock grouting is a cost and time consuming process and design improvements should give direct positive effects of these works.

This research aims at verifying the so-called "Real Time Grouting Control Method" (RTGC method) and also the possibilities to identify hydraulic jacking based on this theory. This is done by case studies from tunnels and dams. The report describes different methods for empiric based grout design and its advantages and disadvantages are discussed. Also, an analytical solution based on theories for a new stop criterion on grout penetration length and to control deformation in fractures and hydraulic uplift is presented.

The present licentiate thesis was performed by Jalaledin Yaghoobi Rafi at the Division of Soil and Rock Mechanics at the Royal Institute of Technology - KTH, Stockholm, Sweden with Håkan Stille and Stefan Larsson as supervisors. A reference group followed the project and contributed with valuable advice and discussions. This group consisted of Rolf Christiansson (Swedish Nuclear Fuel and Waste Management Co - SKB), Mats Holmberg (Tunnel Engineering), Thomas Dalmalm (The Swedish Transport Administration), Lars Hässler (Golder Associates), Tommy Ellison (Besab) and Per Tengborg (Rock Engineering Research Foundation - BeFo). The research project was financed as a result of a common call by BeFo, The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning - Formas and The Development Fund of the Swedish Construction Industry - SBUF.

Stockholm in December 2013

*Per Tengborg*

## Förord

Tätning av bergtunnlar och bergrum är idag en betydelsefull aktivitet inom bergbyggnad, speciellt i stadsmiljö och andra områden som är känsliga avseende påverkan av grundvatten. Dammkonstruktioner grundlagda på berg behöver också tätas och i båda fallen används injektering av bergmassan. Berginjektering är en kostnads- och tidskrävande process i byggskedet och designförbättringar bedöms kunna ge direkta positiva effekter vid dessa anläggningsarbeten.

Föreliggande forskningsarbete syftar till att bekräfta den så kallade "Real Time Grouting Control Method" (RTGC-metoden) och vidare att verifiera möjligheten att upptäcka hydrauliskt upplyft (jacking - öppning av bergsprickor) med denna teori. Det utförs med hjälp av genomförda projekt från tunnlar och dammar. Rapporten beskriver olika metoder för empiriskt baserad design av injektering och dess för- och nackdelar diskuteras. Vidare redovisas en analytisk lösning baserat på teoretiska samband för nytt stoppkriterium utifrån inträngningslängd och för att kontrollera deformation i sprickor/hydrauliskt upplyft.

Detta licentiatarbete utfördes av Jaleddin Yaghoobi Rafi vid avdelningen Jord och Bergmekanik vid Kungliga Tekniska Högskolan - KTH, Stockholm med Håkan Stille och Stefan Larsson som handledare. En referensgrupp har följt projektet och bidragit med råd och diskussioner. Referensgruppen bestod av Rolf Christiansson (SKB), Mats Holmberg (Tunnel Engineering), Thomas Dalmalm (Trafikverket), Lars Hässler (Golder Associates), Tommy Ellison (Besab) och Per Tengborg (BeFo). Projektet har finansierats av BeFo, Formas och SBUF som ett resultat av en gemensam utlysning.

Stockholm i december 2013

*Per Tengborg*

## Sammanfattning

Cementbaserat bruk är vanligt förekommande i syfte att täta sprickor i berget och minska bergmassans permeabilitet. Dessutom utgör injektering av bergmassan vid tunneldrivning en viktig aktivitet i drivningscykeln. Stora mängder injektering används också vid tätning av berggrunden i samband med byggandet av dammar grundlagda på berg. Med hänsyn till den tid och kostnad som injekteringen utgör för dessa typer av projekt är det nödvändigt att kunna förbättra och optimera designmetoderna för injektering.

Vid en framgångsrik injektering är målet att uppnå den eftersträlvade tätningen av sprickorna och samtidigt förhindra rörelser i berget på grund av injekteringstrycket. Empiriska metoder har utvecklats i syfte att bestämma tillåtna injekteringstryck, lämpliga egenskaper för injekteringsbruk och stoppkriterier. Det finns emellertid otidigheter i hur de ska användas och deras förmåga har ifrågasatts. I dessa metoder har antaganden och kriterier baserats på tumregler och erfarenhet från tidigare projekt. De största osäkerheterna i anslutning till dessa metoder är emellertid kopplade till brukets spridning i sprickan under injekteringen och om sprickan vidgas.

I avhandlingen beskrivs ett teoretiskt underbyggt angreppssättet som är baserad på en analytisk lösning, vilket möjliggör en uppskattning av inträngningslängden för injekteringsbruket i sprickan i realtid, d.v.s. parallellt med att injekteringen utförs. Vidare kan teorin uppskatta trender för flödet av injekteringsbruket. I samband med utvecklingen av denna teori har gränser för elastisk vidgning av sprickorna och brottgränsen för lyftning av bergmassan tagits fram. Detta möjliggör både identifiering av när uppsprickning påbörjas och uppskattning av sprickans vidgning i realtid.

I detta arbete har det teoretiska tillvägagångssättet som kallas för "Real Time Grouting Control Method" validerats genom fallstudier. Egenskaper för använda material, injekteringstryck och flödesdata tillsammans med karaktäristiska geologiska egenskaper har samlats in från projekt utförda i sedimentära bergarter (Gotvand Dam i Iran och THX Dam i Laos) och hårt kristallint berg (Citybanan i Sverige). Teorin har gjort det möjligt att studera flödet av injekteringsbruk och vidgning av sprickor i sedimentärt berg. För projekt utförda i hårt kristallint berg med övervägande vertikala sprickor bekräftar teorin att användandet av högre injekteringstryck är möjligt, vilket kan minska den erforderliga injekteringstiden.

I arbetet har ingen hänsyn tagits till eventuella variationer i brukets egenskaper under injekteringen. Vidare har ingen hänsyn tagits tillvariationer av sprickans aperatur. Trots dessa antaganden har lovande resultat med att verifiera uppskattningen av brukets spridning och risken för lyftning av bergmassan under injekteringen uppnåtts med den använda metoden.

## Summary

Currently, cement base grout is used widely for sealing of the rock fractures in order to decrease the permeability of rock mass. Grouting procedure is one of the main tasks in cycle of rock excavation. In addition, huge amount of grout should be used during dam construction in order to seal the bedding and embankment walls. Therefore, considering the effect of grouting in duration and cost of the project, improving the design methods seems essential.

In successful grouting the goal is to achieve the required sealing of fractures while avoiding ground movement due to applied pressure. Empirical methods have been developed to decide the pumping pressure, grout mix properties and stop criteria in order to fulfill requirements of successful grouting but there are ambiguities in using them and performance of them have been questioned. In these methods, assumptions and criteria are based on rules of thumbs and experiences from previous projects. The main uncertainties connected to these methods are identifying amount of grout spread and state of the fracture.

Theoretical approach is an analytical solution which provides the chance for estimation of penetration length of the grout in real time. Furthermore, void filling fracture aperture and trend of the grout flow are estimated. As the development of this theory, elastic and ultimate jacking limits have been established based on the estimated penetration length. Therefore, it is possible to identify jacking of the fracture and estimate the state of the fracture in real time.

In this research work, performance of this theoretical approach which is called “Real Time Grouting Control Method” has been validated through case studies. Properties of the used material, data for pressure and flow in addition to geological characteristics have been gathered from projects in sedimentary rock (Gotvand Dam in Iran and THX Dam in Laos) and hard rock (City Line Project in Sweden). This theory made it possible to observe overflow of grout and jacking of the fractures in sedimentary rock. In place of hard rock with mostly vertical fractures, this theoretical approach confirms usage of higher pressure which will shorten the grouting time.

In this research work, variation in properties of the grout mix during grouting has been neglected. Moreover, orientation of the fracture and its deformation due to injection pressure are not considered. Despite these assumptions, the results were promising and performance this approach in estimation of grout spread and identifying jacking of the fracture has been verified.



## List of publications

**Paper I:** Rafi, J, Stille, H, Bagheri, M, 2012. Applying “Real Time Grouting Control Method” in Sedimentary Rock, in *4th International Conference on Grouting and Deep Mixing*. 16-18 February, New Orleans-USA.

**Paper II:** Rafi J, Stille H, 2013. Controlling jacking of rock considering spread of grout and grouting pressure, Accepted to be published in *Journal of Tunneling and Underground Space Technology*.

**Paper III:** Rafi J, Tsuji M, Stille H, 2013. Theoretical Approaches in Grouting Fractures of the Rock Mass: Theories and Applications. Accepted in *the 47th US Rock Mechanics / Geomechanics Symposium*. 23-26 June, San Francisco, CA, USA.

**Paper IV:** Rafi J, Tsuji M, Stille H, 2013. Theoretical approaches in grouting design: estimation of penetration length and fracture deformation in real time, Presented in *Bergmekanikdagen*, 11 March, Stockholm-Sweden.



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# 1. Introduction

## 1.1 Background

The goal of grouting is to make it possible for the grout to penetrate enough to seal fractures and fissures and reduce the permeability up to a certain amount. Maximum boundary is to avoid over spread of grout material which guaranty the optimized performance of grouting work i.e. keeping the project in time and avoiding extra cost. A grouting method could in general consist of five main activities: (1) drilling; (2) grouting; (3) waiting; (4) probe holes/water loss measurements; and (5) re-grouting (Dalmalm, 2004).

According to Houlsby (1990), to perform grouting work, set of main steps should be followed.

*Investigation:* in this step, geology of the area and permeability situation are investigated. These data are the inputs for the grouting design. Extensive investigation reduces uncertainties and result in accurately tailored design to the condition which can save money in long term. In this step properties of joints are studied. Spacing, width and inclination of joints and soundness and strength of rock are among the important geological factors. For controlling seepage, according to Houlsby (1990) knowledge of permeability is essential and it should be described how much seepage can pass through, under standard pressure head. The most important outcome of this investigation is size of cracks. Lugeon test is the most common way to quantify the permeability of rock mass.

*Design of grouting:* in this stage, with an overview from the data obtained from investigation area, spacing and length of boreholes, properties of required material and injection pressure are decided. Also, decisions are made to fulfill criteria of successful grouting. According to Houlsby (1990) estimation of grout quantities and cost of grouting is another important step in design process.

*Execution:* after investigating the field and designing grouting work, the executive procedure can be started. Without any theoretical approach, execution is mostly based on rules of thumb and decisions are made according to observations during the process. The main work in this phase is preparing machineries and facilities, preparing grout mix material, drilling boreholes and injecting grout material into fissures and fractures of the rock mass.

*Compilation:* refusal point has been discussed and several methods and techniques have been suggested (for example Houlsby, 1990 and Lombardi, 1993). Achieving maximum certain pressure, maximum certain injected volume or production of pressure and volume (P.V) are among popular refusal points. Based on theories developed by Gustafson & Stille (2005), it is possible to estimate penetration of the grout mix analytically in real time, thus required penetration length can be set as the stop criterion. The main part of this research work is about evaluation and verification of this theory.

*Assessment:* the procedure should be assessed to identify if grout has spread enough around the borehole and not more than required. The other considerable issue is the stresses induced to the rock mass due to grouting which may change the flow regime due to induction of new fractures and increasing the size of existing fractures. Prolonging the procedure, the induced excess pressure

may lead to larger deformation and in worse case cause damages to the on ground structures. Also, the increase in the size of fracture aperture will lead to lower penetration length than expected which will affect sealing efficiency of the grouting work.

This research study has focused on evaluation and verification of the theories for estimating the state of grout spread and fracture in real time. Refusal point has been synchronized with penetration length of the grout considering the limit of acceptable deformation. Performance of grouting work has been assessed by analyzing pressure and flow data which are indicator of physical grout interaction in the fracture. Furthermore, pumping pressure, borehole setting and material properties can be optimized by using this approach. This study has an impact on grouting works and may lead to reduce costs and shortening duration of grouting process.

## *1.2 Previous studies*

In successful grouting the goal is to have enough spread of grout around the borehole with no undesirable ground movements. To achieve this goal, pumping pressure and refusal criterion are decided based on rules of thumbs and experiences from similar projects. The specification of the maximum pressure is set to avoid undesirable deformations. Also, to avoid over spread of grout, a certain maximum limit for the injected volume is considered. In order to avoid long and undesirable pumping, refusal criterion connected to minimum flow is normally set as well.

Grout intensity number (GIN), introduced by Lombardi (1993), set limitation on product of pressure and volume to avoid expansion of energy which can open up the fractures and may lead to hydraulic uplift. The product of pressure and volume should therefore not exceed a given GIN value in order to avoid such problems.

In mentioned empirical methods, the reason to use volume instead of the theoretically correct penetration was practical (Stille et al. 2012). Recent efforts by Gustafson and Stille (2005) have solved the equations of grout spread by simplifying the existing voids in rock mass to channels or discs which make it possible to estimate grout penetration length and predict grout flow in a fractured rock mass and in real time. This will facilitate the analysis and make a significant improvement for managing grouting operation. According to Gustafson and Stille (2005), for each simplified geological model (1D and 2D models), spread of grout with specific properties and specific pumping pressure in specific time is a unique number. It means that the relative grout penetration, which is defined as the ratio between the actual penetration and the maximum penetration, is the same in all fractures (Kobayashi, et al., 2008).

Kobayashi and Stille (2008) described the use of penetration length as stop criterion as follow: “grouting is completed when the grout penetration of the smallest fracture to be sealed is above a certain minimum value (target value) or before the grout penetration for the largest fracture aperture reaches a certain maximum value (limiting value)”. Application of this method validated through case studies with data from tunnels in hard rock of Sweden and pre cambrium rock and depicted in several different publications (Stille (2010); Tsuji, et al. (2012); Fransson, et al. (2012); Rafi (2010)).

To go further, the estimated penetration length has been used to anticipate ground movements. In studies performed by Brantberger, et al. (2000), Gothäll & Stille (2009) and Gothäll & Stille (2010), grout pressure correlated with grout spread and stresses induced in rock mass have been studied and formulated. The analytical solution for estimation of grout spread provides an interesting opportunity for developing the earlier works by using the estimated penetration length to predict deformation of fractures in real time.

Ultimate and elastic limits have been defined based on spread of grout mixture and properties of the rock mass (Stille et al., 2012). This approach enables defining an acceptable deformation limit, thus it is possible to decide the refusal based on required penetration length and the defined limit for deformation.

### *1.3 Scope of research*

In these studies, the objective was validation of Real Time Grouting Control Method as well as verifying possibility to identify jacking based on this theory with data from dams and tunneling projects. For this purpose, application of Real Time Grouting Control Method has been established and software based on this model with better interface and easier functionality has been developed. Performance of this method has been validated through different case studies.

In the studies related to Gotvand Dam project, grouting data and cement material were collected during site visit. Properties of the grout material were obtained by testing the grout mixture in laboratory in Stockholm. In case of THX Project and City Line Project, properties of grout material and recorded pressure and flow data were obtained from the project consultant. Grouting works at some of the boreholes were analyzed and performance of this theoretical approach was validated. Furthermore, to verify the performance of the theoretical approach in identifying jacking, ultimate and elastic jacking limits based on the estimated grout spread have been established and success of grouting work in different boreholes has been examined. Moreover, a methodology proposed to optimize pumping pressure (optimum pressure gives the required spread of grout in shortest time with controlled ground movement) by considering required penetration and acceptable deformation. This study shows robustness of this method in optimizing the pumping pressure, refusal point, borehole setting and material properties which can affect performance of grouting work and cost and duration of the project.

### *1.4 Outline of thesis*

This thesis contains an overview introduction which addresses the procedure of grouting work, followed by the literature review of existing procedure and approaches in practicing grouting work in which, by highlighting obstacles of current practice, the requirement for an analytical approach has been discussed. This analytical solution has been described and evaluated through the case studies in next sections. The structure of this thesis is as below:

## Chapter 2

The properties of the joints as well as the requirement of penetrability and its effect on grouting are discussed and design elements which should be decided before grouting and be monitored during grouting are described. Furthermore, empirical design approaches which are instruction of how to set up the design elements in connection with each other to achieve the desired result (enough sealing efficiency in shortest time with the least damage) are depicted and the ambiguities and difficulties of them are discussed. Finally it is shown that uncertainties connected to the empirical design approaches can be reduced or eliminated if the behavior of the grout is studied analytically.

## Chapter 3

The theoretical approach which is an analytical solution to establish new stop criteria based on penetration length and to define new limits for controlling fracture deformation and hydraulic uplifts are discussed briefly.

## Chapter 4

Geological properties of the rock in studied projects as well as the properties of the used material and stop criteria in each project are shown.

## Chapter 5

This chapter contains the summary of the main results from different studied cases.

## Chapter 6

In final chapter, the general outcome of the project, limitations with the theory and the future works are discussed.

Results of this research work have been Published and presented in form of scientific papers as below:

In paper I, performance of Real Time Grouting Control method in sedimentary rock has been evaluated. In Paper II, this analytical solution has been implemented to estimate fracture deformation and identify risk of jacking based on the calculated penetration length. In papers III and IV, by using this theoretical approach, performance of grouting work in respect to fracture deformation at City Line project has been examined.



## 2. Current knowledge and practice

### 2.1 Investigation

#### Geology

As the most commonly developed of all structures, *Joints* properties affect the spread of grout and stability of rock mass. Roughness of joint walls, coating and filling, size, continuity, presence and shear strength of the joint are among these factors. Due to uncertainties in geological condition, Palmström & Stille (2010) suggest to establish a site engineering model to consider all the possible geological characteristics of the site and improve the understanding of geology during investigation and construction.

The better understanding from the geology of the area leads to better decisions. According to Palmström & Stille (2010) engineering properties of rock mass depend far more on the system of geological discontinuities within the rock mass than on the strength of intact rock. However, they mentioned that this does not mean that the properties of the intact rock material should be disregarded in the characterization. In case of widely spaced joints or weak intact rock, the properties of the intact rock may strongly influence the gross behavior of the rock mass.

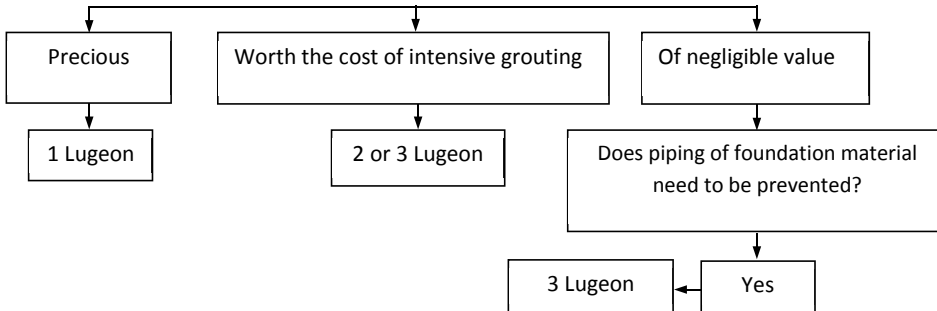
To precise the assumptions about properties of joints, different facilities and methods have been developed. Mapping, core drilling and logging are the field observations still used in many projects. To get more information about the size and distribution of fractures, Ivanetich, et al. (2012) suggest using Televiewer which is utilizing camera to monitor the wall of the borehole and produce high resolution images. District fracture network which integrates fracture characterization data within a 3D computer simulation is another tool to simulate the flow (Carter, et al., 2012).

The other important characteristic of the joint is the aperture size. According to Fransson, et al. (2012) fracture aperture describes behavior of grouting as well as determining penetrability and penetration length. As a methodology for prediction of fracture geometry, Fransson (2001) used principal steps to characterize and verify the boreholes. It starts with geological mapping which leads to distinguishing the orientation of fractures. Probability of conductive fractures obtained from frequency of fractures, information of the probe hole and transmissivity data in fixed intervals. The model then is simplified by considering the mean and standard deviation of conductive fractures. Thus probable interval and values of transmissivity, specific capacity and hydraulic aperture can be obtained.

#### Permeability

Permeability is defined as the ability of rock to transmit fluids where a pressure gradient exists and experiments have shown that the permeability of rock masses is primarily dependent on discontinuities (for example see: Wei Jiang, et al. (2009)). According to them, aperture, frequency, orientation and roughness of discontinuities are affecting transmissivity of rock. The transmissivity and the corresponding hydraulic aperture are important parameters since the aperture influences both the penetration length of grout and the volume injected, i.e. the grout take (Gustafsson & Stille, 1996).

Design of grouting work depends on the purpose of the grouting i.e. amount of required sealing efficiency. Houlsby (1990) has considered the value of water, requirement for avoiding piping and type of the dam in distinguishing conductivity requirement (Fig .1).



**Fig. 1.** Guid to the need for grouting at a dam (After Houlsby 1990)

According to Stille (2012) the required conductivity as well as required sealing efficiency determine difficulty of grouting work (table 1).

**Table 1** Degree of difficulty as function of required sealing effect and conductivity of the grouted zone (After Stille, 2012)

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

Moreover, pre investigations and observations during grouting work will have larger process in more difficult grouting. In uncomplicated case it is enough to only measure of water ingress to the tunnel while in difficult situation grouting work should be observed with real time application (RTGC). The proposal has been depicted in table 2.

**Table 2.** Proposal for pre-investigation and observations during grouting work depending on degree of difficulty (After Stille, 2012)

<i>Degree of difficulty</i>	<i>Pre investigation</i>	<i>Observations during grout work</i>
Uncomplicated grouting	<ul style="list-style-type: none"> <li>Establish major geological regimes</li> </ul>	<ul style="list-style-type: none"> <li>Measurement of the ingress of water to the tunnel</li> </ul>
Fair grouting	<ul style="list-style-type: none"> <li>Establish major hydro geological regimes and representative values of hydraulic conductivity</li> </ul>	<ul style="list-style-type: none"> <li>Measurement of the ingress of water to the tunnel</li> <li>Controlling stop criterion with theory of grout propagation</li> </ul>
Difficult grouting	<ul style="list-style-type: none"> <li>Establish the hydro geological properties of the regimes like section transmissivity based on WPT</li> <li>study of fracture transmissivity</li> </ul>	<ul style="list-style-type: none"> <li>Measurement of the ingress of water to the tunnel</li> <li>Pre-sounding and water pressure test (or inflow measurements)</li> <li>Controlling stop criterion by applying RTGC</li> </ul>
Very difficult grouting	<ul style="list-style-type: none"> <li>Establish the hydro geological properties of the regimes like section transmissivity based on WPT</li> <li>Study of fracture transmissivity (detailed study of the regimes with core drilling, pressure build up tests and fracture transmissivity measurement can be an alternative)</li> </ul>	<ul style="list-style-type: none"> <li>Measurement of the ingress of water to the tunnel</li> <li>Pre-sounding and water pressure test (or inflow measurements)</li> <li>Controlling both stop criterion and grouting process by applying RTGC</li> <li>Control hole after grouting</li> </ul>

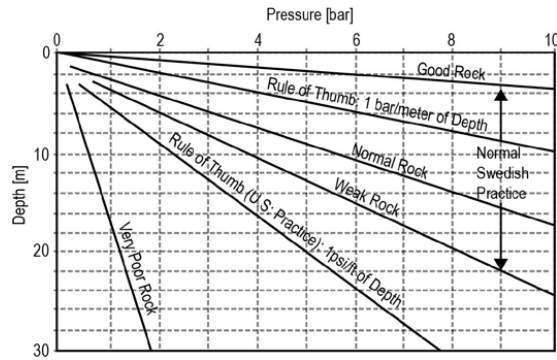
## 2.2 Design elements

Designing the grouting work is to choosing pumping pressure, material properties and refusal point in the way to achieve the required sealing efficiency with the least damages. Different methodologies have been proposed to decide design variables. In this chapter, the concept of each variable and its effect in grouting process has been discussed. In the next chapter, the practical methodologies to decide these elements have been depicted.

### Injection pressure

Deciding the injection pressure in grouting projects has been the point of discussion (Houlsby (1990) ; Lombardi (1997); Gothäll & Stille (2009); Stille, et al. (2012)). The grouting pressure should be designed in the way to not be higher than the minimum rock stress, in order to avoid jacking of joints (Gustafsson & Stille, 1996) as well as fulfilling penetration requirements. Grout mixture in a given fracture will move faster with increasing pressure but too high pressure will give jacking. Depth of fracture (distance from the surface), fracture orientation and amount of injected grout mix are important factors in deciding the pumping pressure.

The maximum applicable grout pressure depends on stiffness of the rock mass and the depth of the fracture. According to Houlsby (1990) the pressure should be adjusted to the maximum limit the foundation can take in order to get maximum penetration. Based on him, the pressure should be limited concerning the quality of rock mass and depth of the fracture. Based on this approach, different graphs have been developed to decide the applicable pressure (Fig.2) .



**Fig. 2.** Grouting pressure according to practice in Sweden and the USA (Weaver 1991). Both rock quality and depth of grouting are important factors in determining grouting pressure.

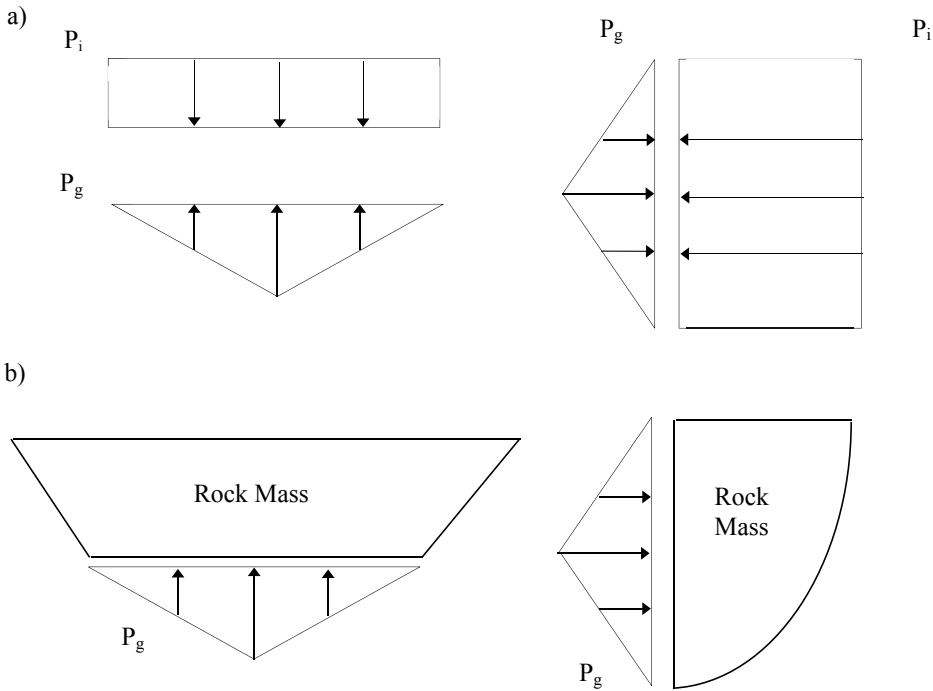
Stille, et al. (2012) explained that since the good rock mass has both smaller fractures and larger stiffness, in this case higher pressure can be used. In fractures close to the surface and where ground movement is limited, low pressure should be applied. In fractures in deeper zone, (Lombardi & Deere, 1993) suggests using higher pressure to open up the fractures and even induce new fractures in weak rock and fill them fully. This will be only valid in largest fractures and according to Stille, et al. (2012), since the elastic deformation may go back when the pressure is revealed, the smallest fractures can then be unsealed.

Orientation of the fracture is important since it affecting the stresses. In situ stresses in the rock mass are important factors affecting design of grouting. Hoek & Brown (1980) showed that unless at shallow depth, vertical stresses are in fair agreement with weight of the rock at a particular depth. Terzaghi & Richart (1952) suggested lateral stresses to be one third of vertical stresses in a typical rock with Poisson ratio of 0.25. Later, there were reports of measuring horizontal stresses of several times the vertical stresses in Scandinavia (Hast, 1958). Considering inability of rock to support large stress differences, it was suggested that the ratio of horizontal to vertical stress will be close to one over a period of geological time. From the measurements performed by Hoek & Brown (1980), this ratio ( $k$ ) varies as below:

$$\frac{100}{z} + 0.3 < k < \frac{1500}{z} + 0.5 \quad (1)$$

Where  $z$  is the depth below the surface. Thus, at the depth less than 500 meters, horizontal stresses are significantly greater than vertical stresses while in deeper zone (over 1 kilometer) the ratio tends to 1. This result has been explained by Hoek & Brown (1980) that the highly existed horizontal stress lead to fracturing, plastic flow and time dependent deformation in the rock which tend to reduce the difference between horizontal and vertical stresses.

From discussion above, in horizontal fractures, lower pressure can lead to dilation of the fracture which may not affect the vertical ones.



**Fig. 3.** Grouting in horizontal (left) and vertical (right) joints. a) is the stress situation and b) is the failure at ultimate limit.

At small penetration length and since pressure diminish rapidly as it spreads away from the borehole, the total uplift force may be in such cases much lower than the overburden even if the pumping pressure exceeds the overburden (Lombardi & Deere, 1993). Thus in order to achieve faster and better penetration in fine fractures, high pumping pressures can be used (Gothäll & Stille, 2010).

### Stop criteria

Deciding the stop criteria to fulfill the requirements of grouting work is a challenging task. Experiences with grouting have shown that grout has to be injected to a full stop ("refusal") in order to obtaining a successful result. At the point of refusal, the injection pressure is balanced by the shear stress towards the fracture walls. Higher pressure should be applied to continue grouting spread. On the other hand, injection of larger volume of grout in larger fracture may not be necessary and would be waste of grout material. Thus the stop criteria should be set in the way to fill up the smallest fracture while not over spreading in largest ones. According to Fransson (2008), the penetration length for smallest fracture is sufficient to theoretically fill the fracture between boreholes including and overlap to increase the chance of sealing. Therefore limiting grouting volume (or the grout spread, as will be discussed later) is one of the stop criteria.

Stopping the procedure at a certain maximum pressure to avoid jacking of the fracture is the other limiting edge. In geology with tight rock, there would be no grout take in many of the boreholes therefore grouting time should be limited in boreholes with a certain minimum take as well. Deciding the stop criteria would be more efficient if enough information from grouting procedure and geology of the area is available. The theoretical approach which enables estimation of grout spread and jacking in real time (chapter 3), provide the possibility for defining a robust stop criteria.

### Material properties

Both measurement of grout mix properties and choice of material are challenging issues in designing grouting work. According to Håkansson, et al. (1992) rheological properties of cement grout are sensitive to measurement techniques. Resulted values for yield stress and viscosity depend on the instrument and the rheological model.

Different approaches have been proposed for choosing the grout mixture properties. It is suggested by Lombardi & Deere (1993) to use only a single mix for the entire grouting work to provide a single Bingham fluid with known properties and also simplify the grouting procedure and reduce errors. They mentioned advantage of using stable thicker grout during grouting as less sedimentation, less bleeding, greater stability and finally less risk of hydro fracturing due to fast drop of pressure away from the grout hole as a result of grout cohesion. During service time thicker grout will give less shrinkage, higher mechanical strength, less porosity, lower permeability, greater chemical resistance and higher durability of grout curtain of dam. Thus the injected thin grout which will also fill larger fractures may not fulfill all grouting requirements.

The other approach is to start grouting with thinner material and thicken it to establish pressure and fill the fracture (see Houlsby (1990); Bonin, et al. (2012)). Difficulty in applying this method is about deciding how to change the grout to get the desired performance.

Applying changes in mixture properties in regards to the geology i.e. considering penetrability properties of the grout mix is another approach (Eriksson & Stille, 2003). Penetrability meter device developed at division of soil and rock mechanics at royal institute of technology (Eriksson & Stille, 2003) is used to find how the grout material can penetrate in the fractures. In this measurement method, minimum and critical apertures have been defined as ultimate boundaries indicating in which apertures the grout can penetrate and where the filter cake can be developed. To fulfill penetrability requirement, Funeag & Gustafson (2008) suggest usage of a Newtonian fluid such as silica beside the cement base grout to enter and seal small fracture apertures.

Penetrability properties depend on grain size, grain size distribution, super plasticizer, w/c ratio, chemical reaction, geometry of aperture and amount of mixture. Variation of penetrability properties directly affects spread of grout (Eklund & Stille, 2007). These properties can be adjusted based on requirements of penetration and deformation by alteration of material or grouting pressure or both together. In case of fractures with smaller apertures ( $b < b_{\min}$ ), there would be no grout take and increasing pressure may lead to hydro-fracturing. Thus changing penetrability properties in the way to decrease the minimum aperture is preferred. On the other hand the fracture with larger aperture ( $b > b_{\text{critical}}$ ) may let infinite volume of grout to flow i.e. no filter cake may form. Thus other methods should be used to seal these fractures. Pressure in grout-

able fractures ( $b_{\min} < b < b_{\max}$ ) should be adjusted to not increase the aperture size over the critical limit which may not only reduce the sealing efficiency of the grouted fracture but it also may lead to remaining of unsealed smaller fractures after grouting.

### Borehole spacing

Houlsby (1990) describes closure grouting as a method based on observations and filed data. Primary boreholes are fairly apart and secondary boreholes are casted in between. Lugeon test and grout take are criteria to decide about drilling tertiary and quaternary boreholes. This method is called split spacing and is useful in grouting curtain of dams. In successful grouting operation an overlap of grouting of the fractures is required and in result the first stop criterion can be set in the way that the penetration of the smallest grout-able fractures shall reach at least up to halfway between the boreholes (Gustafson & Stille, 2005). Thus, in this approach borehole spacing can be used as a tool besides grouting pressure and material properties to reach desired spread.

### Grouting time

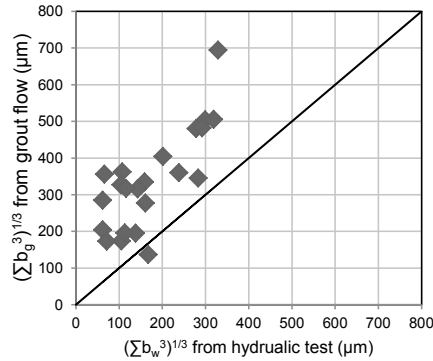
Dalmalm & Stille (2003) have suggested grouting time to be regarded during the design of grout work. In their research work, to optimize the grouting process, the grouting time is correlated to the rock mass joint system situation. In this respect, in blocky rock mass with wide joints, grouting for long time lead to over spread of grout while in crushed rock mass with narrow joints there is low risk of over spread and increasing grouting time improve the sealing efficiency of performed job. Interesting result could be achieved by correlating the injected grout volume and spread with time. for instance in the studied case by Dalmalm & Stille (2003) since most of the volume was taken in short time, decreasing grouting time and drilling more boreholes have been suggested as optimum design.

Later, by developing analytical solution (Gustafson & Stille, 2005) and (Stille, et al., 2012), grouting spread and state of the fracture could be estimated in real time, thus, as depicted in this research work, grouting time has been considered as the stop criterion where enough penetration length is achieved in boundary of desired fracture deformation.

### Fracture aperture

One of the important characteristics of the joint that affect grouting design is the aperture size. According to Fransson, et al. (2012) fracture aperture describes behavior of grouting as well as determining penetrability and penetration length. Since transmissivity has correlation with cubic of the aperture size, thus, a small change in fracture aperture size will have significant effect on conductivity of the rock mass. This implies the importance of monitoring fracture dilation

The measurement method of the fracture aperture affects the result. Large difference of hydraulic aperture and void filling aperture at larger transmissivity at Portuguese dam has been depicted by (Carter, et al., 2012). It has been demonstrated by Kobayashi, et al. (2008) that estimated grout aperture based on theoretical method (considering the void filling by Bingham fluid, see section 3.1) is larger than corresponding hydraulic aperture. The same study performed by Tsuji, et al. (2012) with data from City Line project and similar results were obtained (Fig. 4).



**Fig. 4.** Comparison of fracture aperture size obtained from the Lugeon test and the Real Time Grouting Control method which consider filling the voids with Bingham material using data from the City Line project. It is illustrated that the latter measurement method estimates a larger fracture aperture size (After Tsuji, et al., 2012).

### 2.3 Empirical Design Approaches

In previous section, design variables and their effect on grouting process were discussed. Different methodologies have been established to adjust these elements and fulfill successful grouting criteria. Below, some of these methods which are used worldwide in different projects are depicted and merits and disadvantages of them are discussed.

#### Rules of thumbs

Without any theoretical approach, execution of grouting is mostly based on rules of thumb and decisions that are made according to observations during the process. Houlsby (1990) suggests starting with thinner mix and lower pressure, and check for leakage, rock movement and loose standpipe. If none happened, pressure can be increased and the thicker mix can be used. It means that pressure and material properties are adjusted step by step. In this approach the aim is to getting as much cement in, as fast as possible. Pressure is increased up to maximum pressure with the thickest mix the hole will take. Grouting should be carried out until refusal is reached. As an empirical rule, grouting is completed when the grout flow is less than a certain value at maximum pressure or the grout take is above a certain value.

According to Houlsby (1990), pressure should be maximized as soon as possible before the grout become stiff and by decreasing the pressure, grout take should decrease as well. Thus the grout take-time (V-t) graph will have decreasing manner. This graph can be used as an assessment tool in which constant or increasing trend of grout take during the time while the pressure is decreasing can be indicator of rock movement or leak. There are limitations in using this method which are discussed as below:

- Geological interpretation



To decide the maximum pressure, depth of the fracture as well as rock mass properties has been considered (see for example Fig.2). The problem is introducing the geological properties to the defined qualities in graph.

- Unknown spread at refusal point

The other impotent shortcoming of this method is the ambiguity about the spread of grout. Since a certain maximum volume is considered, it is not known if the minimum required spread has been achieved. In case of larger fractures, there would be risk of overspread which is not detectable.

- No information about deformation of fracture

The same limitation goes to the deformation of fracture which is not detectable. Despite empirical rules for choosing the maximum pressure to avoid jacking, the state of fracture at refusal point is not known.

### Aperture Controlled Grouting (ACG)

In attempt to improve practical method, another approach, namely *Aperture Controlled Grouting*, has been introduced. Studying geological issues in more detail, applying changes in grout mixture and using monitoring tools during grouting procedures are focused in this technique. In this method, according to Carter, et al. (2012) after deciding volume based on void filling space and chosen hole spacing, grout rheology is adjusted to match fracture characteristics and achieve pressure build for refusal at the required take. This method can be considered as an update to Australian method suggested by Houlsby (1990) where grout mixes are thickened in sequence using a decision chart (Bonin, et al., 2012). Using modern and near-colloidal grouts rather than thin grout and improvement in deciding mixture thickening sequences are mentioned by Bonin, et al. (2012) as the updates.

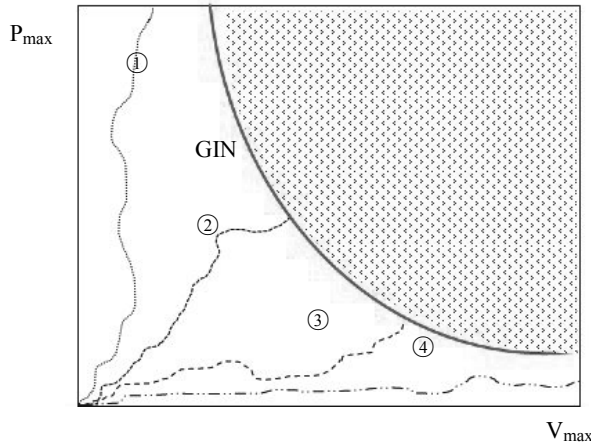
The major advantage of ACG method according to Bonin, et al. (2012) is that the grouting criteria are based on fully capturing all of the geological and hydrological information of relevance to grouting the formations of concern by utilizing electronic monitoring system. According to Carter, et al. (2012) grouting to only the required volume necessary to be injected for that stage can optimize the closure and cost standpoints.

Based on the injection decision flowchart of ACG, grouting starts with thinner mix to penetrate in the smaller fractures and is thickened to close up large fractures. The difficulty in applying this method is changing the mixture during grouting which is not practical. Furthermore carrying out DFN (Discrete Fracture Network) studies are time taking and costly. Although using the DFN , regardless of the effort to build the model and rate of uncertainty in the resulted model, is an step forward to define characteristics of discontinuities, still the ambiguities about state of grout spread and fracture at refusal point are remaining.

### Grout Intensity Number (GIN)

To control the energy induced in the fracture, production of pressure and volume is restricted. This limit which is called Grout Intensity Number has been proposed by Lombardi & Deere (1993) and

trims the rectangle of maximum pressure-maximum volume which was proposed in empirical methods (Fig.5). Therefore, in tight rock mass with small fractures, the maximum pressure is build up with low amount of grout take (path 1). On the other hand, in largest fractures, large amount of grout is injected (Path 4). In other fractures, GIN limit controls the applied pressure by considering injected volume (Path 2 and 3). Lombardi & Deere (1993) propose gradually rising pressure and control it based on injected volume. Single steady grout material has been suggested to be used to confirm sealing of the grouted zone (see section 3.3). Quality of the performed grouting in split spacing system can be evaluated by analyzing these grout paths. According to him, as the grouting reduce from hole series to hole series, the inject volume should be reduced i.e. the path of grouting should shift to left side.



**Fig. 5.** GIN limit curvature trims the rectangle of  $P_{\max}$ - $V_{\max}$ . Due to size of the fractures, grouting is stopped at different points.

Despite this method has been used in several different projects and still it is very common to be practiced, performance of this method has been questioned (see Ewert (1996); Rombough, et al.(2006); Shuttle, et al. (2007)). Some of the main difficulties in using this method are listed below:

- Nature of GIN Limit

The nature of GIN limit is unknown. Since the grout is stopped at intersection of grouting path with this limit, the state of fracture is not known. Thus it is not obvious if it is safe to continue grouting up to this boundary and to what extent it can be exceeded. In other word, since GIN curve does not provide any information about the extent of fracture dilation, the safety margin in intersecting this limit is not known.

- Selection of GIN number

Since the GIN limit not provides any information about the grout spread, selection of this number is not easy task. In practice, a GIN number selected by benchmarking similar projects and after assessing the results from the trial test, this number is adjusted.

## *2.4 Uncertainties with current approaches*

In previous sections, geological and design related issues which are affecting the result of grouting work were discussed. It was depicted that the main uncertainty related to geology refers to estimation of fracture aperture size. Furthermore identifying the required sealing efficiency is important in designing and process of grouting work. Design elements were discussed as well and it was shown that due to lack of enough understanding about grout behavior, the criteria for deciding these elements may not fulfill the requirements of successful grouting. Empirical design approaches suggest deciding the grouting pressure, material properties and stop refusal point based on rules of thumbs. The main improvement in ACG method is modeling of the fractures with more investigation and details and using computerized monitoring. In GIN method, suggested limit is not physically understandable.

However it is not possible to investigate the ground to such extend to overcome geological uncertainties but there are uncertainties connected to the empirical design approaches, which can be eliminated by better understanding of grout behavior through an analytical solution. According to Kobayashi & Stille (2007) since empirically based stop criteria (as well as grouting pressure and grouting time) are determined without a theoretical basis and are not related to grout penetration, the grouting result may be inadequate or uneconomical. Thus it seems essential to have a tool for estimation of state of grout and fracture analytically.

Theoretical approach which is dealing with mechanical behavior of grout in the fracture makes it possible to estimate the penetration length and trend of grout flow as well as fracture dilation in real time based on the initial inputs from laboratory (material properties) and field data (geology of the area and injection pressure). Thus, by considering the criteria as reaching a certain grout spread with no ground movement, the initial estimated design elements can be decided. In next chapter this analytical solution has been explained.



### 3 Analytical approach for grouting design

In practicing grouting of the fractures, mathematical and numerical models can supplement empirical methods by simulating grout propagation which increase our understanding of grouting mechanics and developing new methods (Hässler, et al., 1992). To estimate the grout flow, an equation derived by Hässler (1991) considering inclination of the channel with several different Bingham fluids. In his model channel network concept has been chosen, since it leads to comparatively simple mathematics without taking away possibilities of great variability both in single joints and between joints. The mathematical model implemented in simulated program. Later the analytical solution introduced by Gustafson & Stille (2005), which gives a robust stop criteria based on required penetration length of mixture. It confirms the requested sealing efficiency while avoiding loss of material and extra process time. Through the efforts by Brantberger, et al. (2000); Gothäll & Stille (2009) and Stille, et al. (2012) monitoring of fracture dilation based on the estimated grout spread could be possible.

In this chapter, this analytical solution which is named as “Real Time Grouting Control” method is explained briefly. In next chapters, in addition to describing the geological situation of the projects and input data, the results have been discussed.

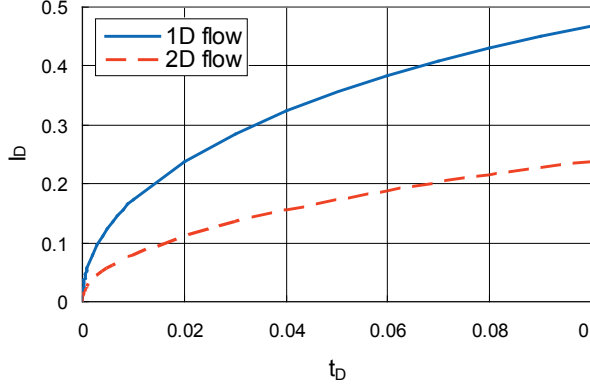
#### 3.1 Penetration estimation

According to Gustafson & Stille (2005) and Kobayashi & Stille (2007) “Real Time Grouting Control method” is a theory to formulize grouting in order to estimate the spread of grout and predict flow trend. the input data are rheological properties of the cement base grout mix which are viscosity and shear stress, geological data (which are mainly the aperture size and depth of the fracture) and also the injection circumstances and adjustment such as pumping pressure, ground water pressure, borehole filling volume and injected grout volume.

By correlating the injected volume with grouting time, Dalmalm & Stille (2003) expressed the spread of grout in term of time and fracture geometry. Characteristic grouting time ( $t_0$ ) is defined by considering rheological properties of grout mix as well as grouting pressure. Furthermore, since rock mass properties may vary several times in the project and as far as it is not possible to fully model the whole geology, to achieve a design method, Concept of dimensionality has been introduced (see Hässler (1991) and Gustafson & Stille (2005)). In one dimensional case, fractures are like channels and grout directly flows in parallel lines while in two dimensional case, grout flows in a disk around the borehole. The slope of the curve at logarithmic scale graph of injected volume versus grouting time is considered as the indicator for distinguishing dimensionality in every moment.

Relative time which is the ratio of grouting time to characteristic grouting time ( $t_D = t/t_0$ ) has been correlated with relative penetration ( $I_D$ ) for one and two dimensional flow in a unique graph (Fig.6). the relative penetration for constant pressure has the same time scale for all fractures with different apertures intersected by a borehole. This means that at a certain  $I_D$ , the grout has reached the same percentage of its maximum penetration length in all fractures at a certain time (Fransson, et al., 2007). In other word, relative penetration shows grout advancement regardless of the

aperture size and demonstrates to what extent of its maximum penetration, grout can spread ( $I_D = I/I_{max}$ ).



**Fig. 6.** Relative penetration as a function of relative grouting time on normal x-axis (Gustafson and Stille, 2005).

Since the maximum penetration length is directly correlated to the fracture aperture size, understanding about different measurement methods of the fracture aperture is important. According to Stille, et al. (2012), the fracture aperture can be determined by measuring volume and time and assessed dimensionality. The factors  $\sum b_g^3$  for the 2D case and  $\sum w b_g^2$  for the 1D case can be determined by curve fitting through the estimated scattered resulted from following equations (see Kobayashi, et al. (2008)):

$$\sum w b_g^2 = \frac{dI_D}{dt_D} \cdot \frac{1}{t_0} \cdot \left( \frac{\Delta p}{2\tau_0} \right) / Q \quad (2)$$

$$\sum b_g^3 = 2\pi \cdot I_D \cdot \frac{dI_D}{dt_D} \cdot \frac{1}{t_0} \cdot \left( \frac{\Delta p}{2\tau_0} \right)^2 / Q \quad (3)$$

Considering Pareto distributed transmissivity of fractures (Fransson & Gustafson, 2005) the largest fracture dominates the water inflow and the penetration of grout (Stille, et al., 2009). In other way, flow is governed by aperture cubed ( $Q \sim \sum b^3$ ) which means that few number of fractures with larger aperture stand for most of the flow. Thus the cubic root of the estimated factor in Eq.7 can be a good estimation for fracture aperture in 2D case. It should be noted that in 1D case, the width of the fracture must be known.

In this theory it is assumed that fractures are non-deformable and fluid is non-compressible. Also the pressure change in the groundwater ahead of the front of the grout can be neglected due to distance from the borehole and the viscosity of the grout being larger than that of water (see for example (Fransson, et al., 2007)).

In next section, estimation of fracture deformation due to injection pressure and based on grout spread has been explained. Since in estimation of penetration, the aperture size is assumed to be constant this means that the solution discussed in next section is valid as long as no deformation happen.

### 3.2 Jacking

According to Gothåll & Stille (2009) one of the limitations of the network model is to not considering mechanical properties of the fracture. According to them the grouting pressure would have some effects on the rock mass and fracture void space. Considering the induced stresses in the rock mass which were discussed as production of pressure and injection volume by Lombardi & Deere (1993), the effort has been made to correlate the GIN value with spread of grout. In this model, “Contact points of the fracture” (which later demonstrated by the concept of dimensionality) and the “geometry of the lifted rock” (which is described by the angle of the lifting cone) were considered to determine the risk of hydraulic uplift (Brantberger, et al., 2000). Based on this research work, the ultimate grouting pressure possible to be applied in a mainly horizontal fracture defined in terms of penetration length as below:

$$P_n \leq P_{n,ultimate} = 1 + \frac{1}{I_n} + \frac{1}{3I_n^2} \quad (4)$$

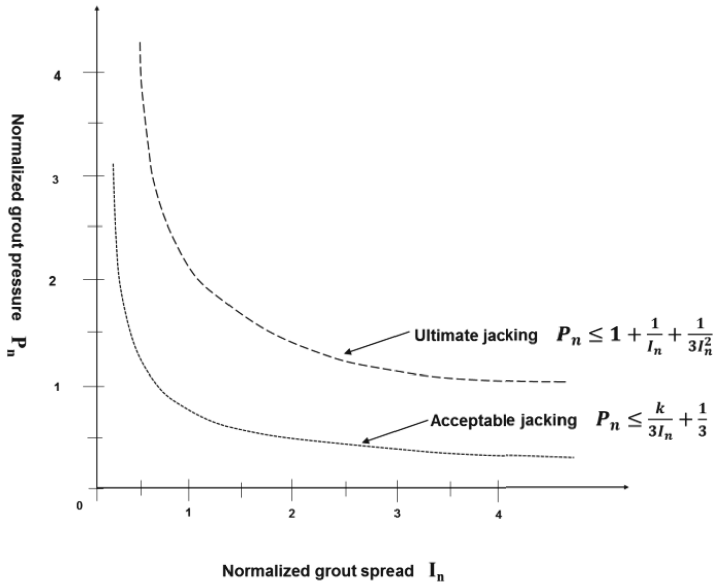
Where  $P_n$  (critical pressure/effective grout pressure) is normalized penetration and  $I_n$  is normalized pressure (Grout spread/depth of the fracture). According to Stille, et al. (2012), considering the elastic properties of the rock, fracture will be deformed at much smaller pressure. This deformation is elastic and is recoverable in case the pressure is revealed and the grout mix can be pumped out. If an acceptable opening of the fracture can be defined, by considering the properties of the rock mass, the maximum allowable pressure is defined as below:

$$P_n \leq P_{n,acceptable} = \frac{k}{3I_n} + \frac{1}{3} \quad (5)$$

In which

$$k = \frac{3}{4} \cdot \frac{E}{(1-\nu^2)} \cdot \frac{\delta_{acc}}{\rho gh^2} \cdot \frac{P_g}{P_e} \quad (6)$$

$P_e$  is the grouting pressure reduced with the initial normal stress,  $E$  is the young's modulus of the rock mass and  $\nu$  is the Poisson ration.  $h$  is the depth of the fracture to the free surface.  $P_{n, acceptable}$  determines the maximum allowable pressure to achieve the required penetration in boundary of acceptable deformation. The elastic and ultimate jacking limits are depicted in figure 7.

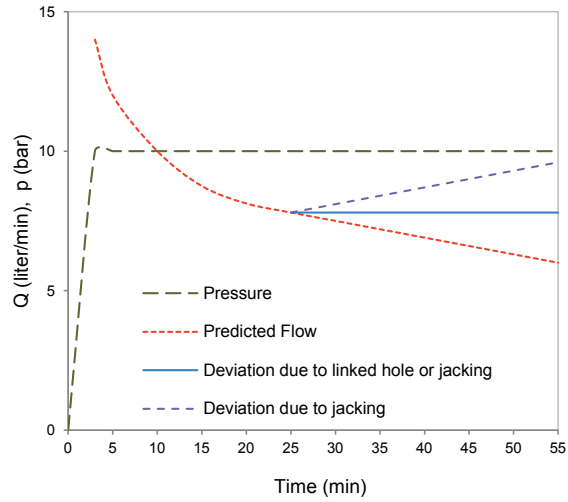


**Fig. 7.** Maximum normalized pressure as a function of normalized grout spread for both the ultimate limit state (Eq. 1) and the acceptable limit state (Eq. 2). The curves are calculated for  $P_w = 0$  (After Stille et.al 2012).

### 3.3 Assessment

In this research work, results are evaluated theoretically by comparing the estimated flow trend from the theory with the recorded data which describes the process physically. LOGAC flow meter is used to register injection pressure and grout flow during the procedure. Well convergence of these flows confirms the efficiency of the solution. According to Lombardi & Deere (1993), contacts of the grout with fracture walls increase during spreading, thus the decrease of flow in applying constant pressure is expected. At holes linked to more porous area or in case of leakage, in applying constant pressure the grout flows constantly or even with increasing trend. It happens also where fracture aperture increases i.e. jacking of the fracture (Fig.8). Therefore to evaluate the performance of the theoretical approach in estimation of fracture dilation, the deviation point of recorded and predicted flow is compared with the corresponding time at which the path of normalized pressure-normalized spread reach the elastic jacking limit.





**Fig. 8.** Jacking to be detected by grout flow in principle. If jacking occurs, the increase in grout flow should be observed. Constant flow in constant pressure indicates linked hole or jacking (Tsuiji, et al., 2012). Conversion factors 1 bar = 0.1 MPa and 1 liter/min =  $1.67 \times 10^{-4}$  m<sup>3</sup>/s.



## 4 Studied Projects

In this research work, the theoretical approach has been verified with data from different projects. Data from Gotvand Dam project has been used to evaluate performance of the analytical solution in estimation of penetration length and fracture dilation (Paper I and II). Furthermore, grouting works in THX Project has been examined in respect to Jacking phenomena (Paper II). In the papers III and IV, Data from City Line project has been used. Below, Geological characteristics of each project as well as the used material and considered stop criteria have been given.

### 4.1 Gotvand Dam Project

#### Geology

At Gotvand project, a rock fill clay core dam has been constructed on the sedimentary rock. The geology of the region is consists of two different formations: “Bakhtiari” formation which is situated in upper level and the “Agha Jari” formation which is laid beneath (rafi 2010). These formations consist of lime stone, sand stones and in upper levels, conglomerates. At the top level, there is a layer of dislocated rock mass which is the most permeable section. Density of rock is  $24 \text{ kN/m}^3$  and modulus of elasticity is 4 GPa. The goal is to reduce conductivity to less than  $3 \cdot 10^{-7}$  which is corresponding to water loss in control holes of 3 Lugeon.

#### Material

Grout with water cement ratio of 2 has been used. This high ratio selected since the geology is sedimentary rock and grout mixture can penetrate smaller fissures.  $d_{95}$  of the cement is  $32 \mu\text{m}$ , yield stress is 0.35 Pa and viscosity is 0.0043 Pas. Regarding to the results in Paper I, this mixture has been penetrated far away. Sealing efficiency of this material is a point of question as well (see Paper I)

#### Stop criteria

The gradient of pressure and flow is considered as stop criterion in grouting works of Gotvand dam project and grouting is stopped when the flow is less than a minimum value in a defined pressure. The order of setting pressure according to consultant document is as below:

- During the first 10 minutes of grouting the exerted pressure gradient is 0.5bar/min and the manner continue if the flow is more than 8lit/5min.
- If the flow is lower than 8lit/5min the exerted, increase pressure gradient to 1 bar/min.
- If the flow is near zero, increase the pressure Gradient to 2-3bar/min.

## 4.2 THX Project

### Geology

At THX project, which is about building a concrete dam, 10 rock core obtained and analyzed with aim of representing the geological logs thus describing the lithological characteristics of the rock mass and evaluating the rock cores in terms of strength, weathering and degree of fracturing (consultant documents). Density of rock mass is  $26 \text{ kN/m}^3$  and modulus of elasticity is 4 GPa. In this research work cases from the right bank of the dam situated between chainage 60 to 190 have been studied. According to consultant documents, sandstone and conglomeratic sandstone prevalence in the dam foundation. Mudstone is mainly found in the foundation in the upper parts of the right bank, abutments and the central part (table 3).

**Table 3.** geological properties in THX Project

<i>From Chainage</i>	<i>To Chainage</i>	<i>Main Lithology</i>
60	190	Mudstone/Sandstone layers
190	220	Sandstone
220	300	Sandstone/Conglomerate layers
300	400	Mudstone/Sandstone layers
400	545	Sandstone with mudstone layers

### Material

In THX dam project, thicker gout mix in compare with Gotvand project has been used. Grout has been mixed with the water cement ratio of 0.75 which gives yield stress of 0.7 Pa and viscosity of 0.02 Pas.

### Stop criteria

GIN method has been used to distinguish refusal point. In studied cases, the GIN value of 1000 has been used.

## 4.3 City Line Project

### Geology

In the City Line project in Stockholm (Citybanan), currently grouting is conducted in the service tunnels at Stockholm city station. The dominant rock types are mainly gray granite or reddish gray gneiss with minor feature of pegmatite or amphibolite. Thus mechanical property of the rock is expected to be modulus of elasticity of 40000 MPa and density of  $28 \text{ KN/m}^3$ . The hydrogeological pre-investigation shows the rock mass conductivity varying between  $10^{-7}$  and  $10^{-8}$  m/s and the ground water level is considered to be equal to the ground surface level as elevation is close to the sea level in the Stockholm area. The ground water head of the area ranges between 32

and 33m. Furthermore, the fracture mapping shows that vertical fractures are dominant in the studied tunnel. Grouting is performed in fans of boreholes with inclination of between 10 to 20 degrees and the length is often between 20 and 25 m in general.

#### Material

The Injecteria 30 is used as the cement and mixed with the water in the ratio of 0.8. The rheological properties of the final product are yield stress of 6 Pa and viscosity of 0.02 Pa.s.

#### Stop criteria

According to the documents from consultant the following practical criteria are applied in grouting of this borehole.

Grouting is normally conducted with planned pressure for 20 minutes. Grouting is completed when any of the following stop criteria is achieved within that time:

- (a) When the grout flow is less than 1 liter/min and sustained for 5 minutes.
- (b) When the grouting volume is above 500 liters (exclude hole filling volume), change the grout mix to  $W/C = 0.5$  and after the thick grout volume is above 150-200 liters.



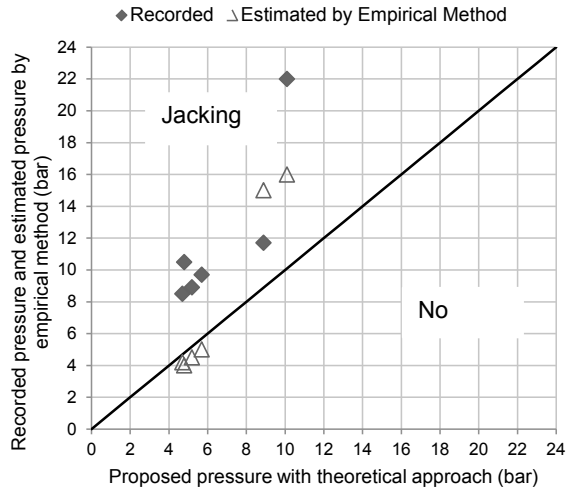
## 5 Discussion of the results

The grouting works is categorized as difficult since in all studied cases the goal is high reduction in conductivity and therefore there is a need to use more precise procedure in design and execution. It has been depicted that using empirical methods in studied projects resulted in unsuccessful grouting. There were over spread of grout in studied cases in Gotvand Project and jacking has happened in fractures of THX Project. However, in City Line project, the theory confirms usage of high pressure which decreases the grouting time.

In studied cases with data from the sedimentary rock of Gotvand Dam (Paper I), there is a well convergence of the recorded and predicted flow trends which indicate well performance of the analytical method. In this study, size of the largest existing fracture based on flow of grout has been estimated. This fracture is dominant for most of grout flow and penetration length of grout has been estimated in this fracture. Results indicate overflow of grout in the studied cases since the used grout is very thin and grout has been injected for a long time. Shorter penetration length is achieved with a thicker mix in the same time. It has been shown that by using penetration length as the stop criteria, grouting time and material properties can be optimized. Considering long duration of grouting at each borehole, using this theory can shorten the grouting time at curtain of this dam.

In the other research work (Paper II), jacking of the fracture has been studied. In this purpose, elastic and ultimate jacking limits have been established based on the estimated grout spread. Studied cases with data from sedimentary rock of Gotvand Dam and THX Project confirm well performance of this approach. In all the studied cases, Deviation of recorded and predicted flow happens about the same time at which deformation of the fracture starts (see section 3.3). Uncertainties in measurement of the pressure as well as the depth of the fracture (the distance of the surface to the largest fracture which will jack) are among the reasons for the small difference. As a further study, a methodology for deciding grouting pressure based on the required penetration length has been proposed. From the results it could be concluded that recorded pressures are higher than the one proposed by the theoretical approach. The empirical approach was found conservative in some cases (Fig 9).

In the studied case at City Line project (Paper III and IV), considering a single horizontal fracture in depth of 30 meters below the surface, the high applied pressure resulted in small deformation in the assumed fracture. Geology of the studied area consists of mostly vertical fractures, and as discussed before, much larger pressure is required to jack these vertical joints. Thus the theory confirms usage of high pressure which shortens the grouting time while monitoring the grouting work with theoretical approach is suggested.



**Fig. 9.** Comparing the pressure proposed by the empirical method and also the recorded pressure during grouting with the ones obtained from the proposed methodology at the studied boreholes. Applied pressures are higher than the one proposed by the theoretical approach and lead to deformation of fractures. The empirical approach is conservative in some cases. Conversion factors 1 bar = 0.1 MPa.



## 6 Conclusion

Theoretical approach in grouting design which is called “Real Time Grouting Control Method” has been studied in this research work. Performance of this approach regarding estimation of grout penetration length has been validated through the cases from 3 different projects. Furthermore, the possibility of using the estimated penetration length for identifying jacking of the fracture has been verified. It has been shown that performance of grouting work can be controlled and design variables can be optimized based on the predicted values for grout spread and fracture deformation, which are provided by this method.

Uncertainties connected to geological properties of the rock mass can be mentioned as the main obstacle in implementation of this theory. A single horizontal fracture has been assumed to be dominant for the grout flow. Furthermore, variation of the fracture aperture size as well as material properties has been neglected. Despite assumptions and simplifications, the results are promising.

Currently this theory has been applied in different geologies and performance of it has been verified. To enable using this approach as a tool in future grouting works, there is a need for more case studies in projects with different geological properties which make it possible to improve and customize this analytical solution to be installed on grouting machineries. Studying pros and cons of elastic deformation of fracture will optimize the stop criterion. Furthermore, examining the empirical approaches closely in compare with theoretical approach provides better understanding about obstacles of current practices and will be helpful in developing the theory. Applying this theory in to highlight and decrease ambiguities in grouting works is another aspect of future work.

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**Paper I\*:** Rafi, J, Stille, H, Bagheri, M, 2012. Applying “Real Time Grouting Control Method” in Sedimentary Rock, in *4th International Conference on Grouting and Deep Mixing*. 16-18 February, New Orleans-USA.

**Paper II\*:** Rafi J, Stille H, 2013. Controlling jacking of rock considering spread of grout and grouting pressure, Accepted to be published in *Journal of Tunneling and Underground Space Technology*.

**Paper III\*:** Rafi J, Tsuji M, Stille H, 2013. Theoretical Approaches in Grouting Fractures of the Rock Mass: Theories and Applications. Accepted in *the 47th US Rock Mechanics / Geomechanics Symposium*. 23-26 June, San Francisco, CA, USA.

**Paper IV:** Rafi J, Tsuji M, Stille H, 2013. Theoretical approaches in grouting design: estimation of penetration length and fracture deformation in real time, Presented in *Bergmekanikdagen*, 11 March, Stockholm-Sweden.

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# **BERÄKNING AV BRUKS SPRIDNING OCH SPRICKDEFORMATIONER; REALTID FÖR STYRNING AV INJEKTERINGFÖRLOPPET**

## **Theoretical approaches in grouting design: estimation of penetration length and fracture deformation in real time**

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*Masakuni Tsuji, KTH*

*Håkan Stille, KTH*

### **SAMANFATTNING**

Analytiska lösningar för uppskattning av injekteringsbrukets inträngning i realtid har utvecklats (Gustafson och Stille 2005). Denna metod ger ett robust stoppkriterium baserat på brukets inträngning i sprickan. Metoden har validerats genom tillämpning i ett flertal olika projekt med olika typer av berggrund, såsom hård kristallin berggrund och sedimentär berggrund. Resultaten bekräftar att erforderlig tätningseffekt uppnås med bruk- och tidssåtgång som sannolikt ligger när den optimala.

Genom att ersätta den injekterade volymen injekteringsbruk (vilket för närvarande görs i dagens empiriska metoder) med den uppskattade inträngningen av bruket gör det även möjligt att uppskatta sprickans mekaniska spänningstillstånd i realtid. I tidigare studier har metodens tillämpning studerats. I denna studie har metodens effektivitet i en av Citybanans tunnlar utvärderats. För detta syfte har gränser för brott- och elastiska deformationstillstånd i den injekterade sprickan beräknats tillsammans med sprickans tillstånd i realtid. Trots att höga injekteringstryck används visar analysen att sprickans beräknade deformationer är lägre än de som krävs för ett uppspräckningsbrott. De deformationer som inträffar i sprickan kan i vissa fall vara fördelaktiga då de kan öka inträngningen och minska injekteringstiden.

### **SUMMARY**

Analytical solution for estimation of grout penetration in real time has been introduced (Gustafson and Stille 2005). This method gives a robust stop criteria based on required penetration through the fracture of grout mixture. This method has been validated through application in several case studies with data from tunnels in hard rock, pre-Cambrian rock and sedimentary rock. It confirms the requested sealing efficiency while avoiding loss of material and extra process time.

Substitution of injected grout volume (currently used in empirical methods) with the estimated grout spread provide an interesting opportunity to estimate state of fracture in real time as well. In previous studies applicability of this method in estimation of penetration length has been verified. In this study, efficiency of this approach at one of the tunnels in Citybanan project is examined. For this purpose ultimate and elastic jacking limits based on the spread of the grout has been established and state of the fracture in real time has been determined. Despite high applied pressure, the

estimated state is much lower than ultimate jacking limit although the fracture has been opened up. This deformation can be beneficial since it would increase penetrability and shorten grouting time.

## **INTRODUCTION**

Selection of grouting pressure in order to have adequate grout spread while avoiding undesirable deformations is point of interest. Jacking of the fracture due to injection pressure will be beneficial since penetrability increase and the required spread will be achieved in shorter time. On the other hand larger induced pressure will cause larger deformations which affects sealing efficiency of grouting works. Continuing the process with this pressure may lead to uplift of the rock mass and cause damages to the on-ground structures.

At empirical method, grout spread and jacking are controlled by limiting injection pressure in tight rock and grout volume in larger fractures (Houlsby, 1990). To avoid jacking, Lombardi & Deere (1993) introduced limitation on production of pressure and volume to control the induced energy in the fracture. There are difficulties and ambiguities in practicing empirical methods which among them, lack of information about the amount of grout spread as well as fracture deformation due to injection of grout material are considerable.

The objective of this article is to verify performance of the theoretical approach which is an analytical solution for estimation of grout penetration length and state of fracture in real time. Advantages of practicing this method in compare with empirical methods have been discussed and applicability of the method at grouting works of Citybanan project has been examined.

## **GROUTING SPREAD**

Different strategies and stop criteria have been proposed in order to control injected volume of grout while achieving required penetration length. Houlsby (1990) suggests stopping injection when a fairly substantial amount of cement has been injected. But in this case it is not known if the grout has been spread enough around the borehole. Considering a certain low flow rate or certain maximum pressure would not fulfill the spread requirements either. Analytical solution has been proposed by Gustafson and Stille (2005) which enables estimation of penetration length in real time. This theory which is called “Real Time Grouting Control Method” first developed in channels (Hässler, 1991) by considering properties of Bingham Fluid. Grout flow in the fracture has been simplified to flow in channels where grout spread in parallel lines (on dimensional flow) or flow in a disk around the borehole (two dimensional flow).



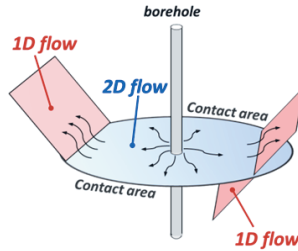


Figure 1 Dimensionality of the grout flow

Fracture aperture is estimated based on the flow of Bingham fluid in the fracture (void filling aperture). Since transmissivity of the rock mass is correlated to the cubic size of aperture, a fracture with the largest aperture is dominant for most of the flow. Thus 70-80% of sum of the apertures is considered as the largest existing aperture.

To solve the numerical approach in analytical solution, relative time and penetration are defined by Gustafson & Stille (2005) according to dimensionality of fractures. Thus at every moment, based on characteristics of the material and applied pressure, relative penetration for each dimensionality is available (figure 2). Relative penetration is independent of fracture aperture and is the same for every fracture. It implied the ratio of grout spread to maximum possible penetration length. Since the relative penetration and the fracture aperture are available, flow of grout mix at every interval is predicted.

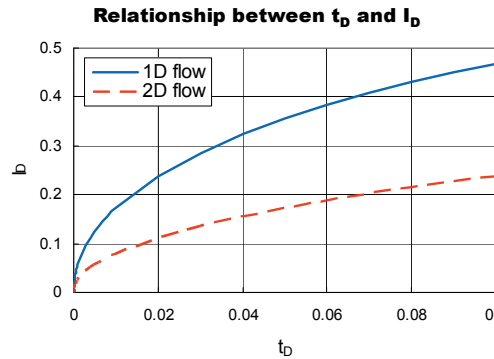


Figure 2 The relative penetration as a function of the relative grouting time in normal x-axis (Kobayashi, et al., 2008).

## GROUTING PRESSURE

As a rule of thumb, the overburden pressure is principally considered in selection of pumping pressure to limit potential for uplift or displacement. Furthermore the rock strength, apparently independent of depth, should be the limiting factor for pressure (Weaver, 1991). Empirical methods propose usage of moderate pressure in stressed rock, called as penetration grouting by Houlsby (1990), which is helpful to avoid disruption while in deeper levels of ground (displacement grouting), higher pressure which open up the fractures to facilitate penetration of grout is suitable. For this purpose graphs for selection of the proper pressure based on quality of rock mass and the depth where fracture situated in have been established (for example figure 3. ). The difficulty of using this method is categorizing geology of the grouting zone according to suggested qualities in these graphs.

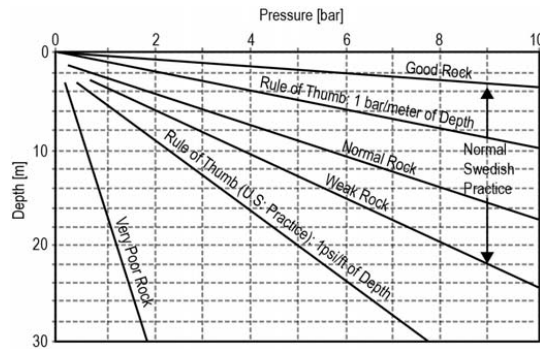


Figure 3 Grouting pressure according to practice in Sweden and U.S. (Weaver 1991). Both rock quality and depth of grouting are important factors in determining the grouting pressure.

As it is mentioned by Houlsby (1990), the energy regarded to combination of volume and pressure should be controlled, Lombardi & Deere (1993) introduced Grout intensity number (GIN) as a curvature trimming rectangle of maximum pressure-maximum volume (fig 4). It implies that in tight rock mass where there is low grout take, high pressure up to maximum limit is applicable while in larger fracture where grout spread in far distances, lower pressure must be applied to avoid undesired deformations or even uplift of the rock. In practicing this method, state of the fracture when GIN curve arrives is not known. Furthermore the amount of spread at this point is indefinite. Thus there are ambiguities in selection of GIN number and applicability of this method has been questioned (Ewert, 1996; Rombough, et al., 2006; Shuttle, et al., 2007).

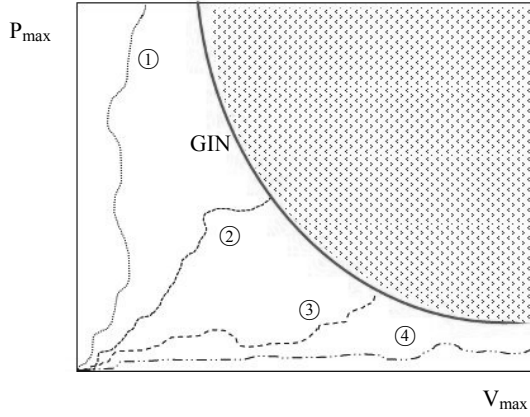


Figure 4 GIN limit curvature trims the rectangle of  $P_{\max}$ - $V_{\max}$ . Due to size of the fractures, grouting is stopped at different points. (from ① to ④, larger fractures are grouted. Dotted zone is the danger zone)

The reason to use volume instead of theoretically correct penetration in empirical methods was practical. (Stille, et al., 2012). As a development to GIN method, Brantberger, et al. (2000) correlated GIN value with spread of grout. Since the grout pressure acting as a cone on the fracture, it should be at least 3 times the overburden to lift the rock mass above (figure 5).

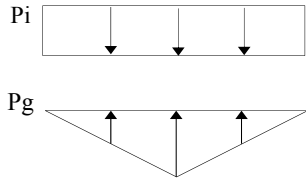


Figure 6 A cone of pressure acting on walls of the fracture

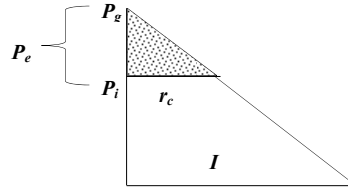


Figure 5 Excess pressure ( $P_e$ ) is due to the difference of grouting pressure and critical pressure (Dotted zone).

The normalized pressure is defined as  $P_n = P_g/3P_i$ , thus the ultimate jacking occurs at  $P_n > 1$  where deformations are permanent. This is valid in the larger grout spread. When the

penetration length is small in compare with the depth of the fracture below ground surface, due to the geometry of the lifted cone, much larger pressure is applicable.

It has been shown by Goth  ll & Stille (2009) that when the grouting pressure ( $P_g$ ) exceed the critical pressure ( $P_1$ ), The exceeding pressure  $P_e$  loading the rock mass in radius of  $r_c$  (figure 6) and the grouted fracture will open up. In other word, as soon as the  $P_n < 1/3$ , the fracture starts to dilate. The deformation at this point is elastic and is recoverable if the injection pressure is released and the grout mixture can be pumped out.

In case of allowing larger deformations, higher pressure is applicable. Both serviceability and ultimate limit states have been depicted in figure 7. Over the acceptable jacking limit, dilation of the fracture is larger than acceptable deformation but it is recoverable. It continues up to ultimate jacking limit where beyond that, deformations are permanent i.e. rock will be uplifted.

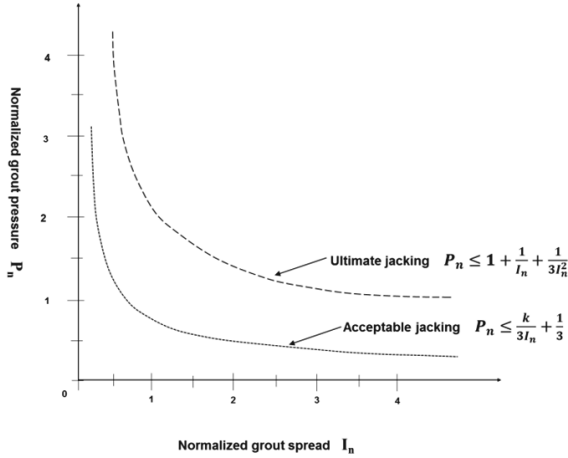


Figure 7 Relation between relative pressure and relative penetration related to ultimate jacking and acceptable jacking (Stille, et al. 2012). (K is the stiffness of the loaded area.)

## METHODOLOGY

Substituting injected grout volume with penetration length provides an interesting chance to develop Real Time Grout Control method in order to estimate state of the fracture in real time. This method is practiced through two processes 1) estimation of the grout spread and 2)

establishing serviceability and ultimate limits based on the estimated grout spread to predict state of the fracture and decide pumping pressure.

At first process, pumping pressure and grout flow which are recorded by Logac system in addition to properties of the grout material are inputs for estimation of the grout spread. Relative penetration is obtained through figure 2 and by determining fracture aperture size penetration length of grout in real time is estimated. Stop criteria considered as “reaching a certain maximum spread in largest fracture and certain minimum spread in smallest fracture” (Kobayashi, et al., 2008). Therefore, by considering the required penetration length, grouting time at which the procedure should be stopped is achieved. Convergence of predicted grout flow with the recorded one is an indicator to verify efficiency and accuracy of this process.

To establish elastic and ultimate jacking limits, the estimated penetration length in first process as well as geological properties of rock mass, depth of the fracture aperture under the ground surface and decided acceptable deformations are used. Examining the state of fracture in this span as well as adjusting the initial design inputs (Pumping Pressure, Material Properties and Refusal Point) is of interest. The procedure at “Real Time Grouting Control Method” to estimate spread of the grout and state of the fracture in real time has been depicted in figure 8

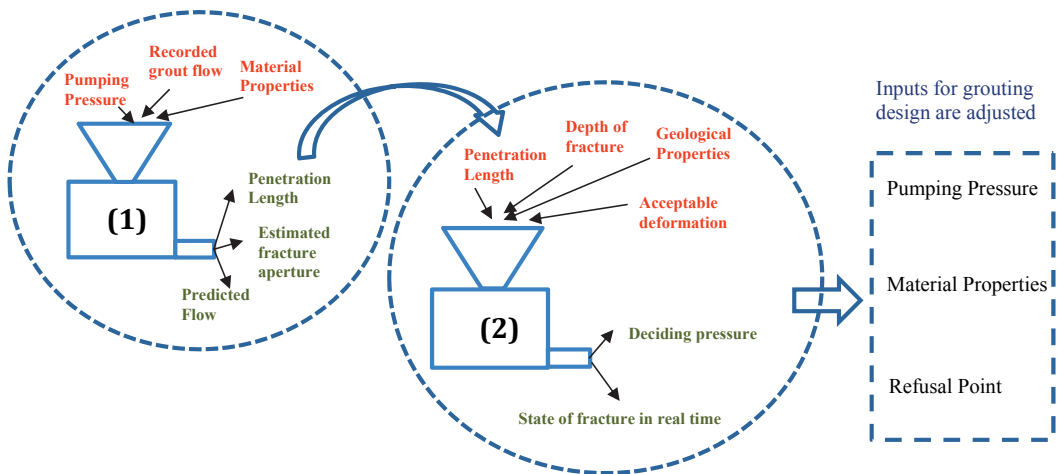


Figure 8 Procedure of Real Time Grouting Control method is practiced in two processes. Penetration length which is outcome of the first process is used for the estimation of state of the fracture. By this procedure, initial design inputs are adjusted.

To verify efficiency of this theory at estimation of the grout spread and defining stop criteria based on the theory, case studies have been performed with data from different projects

(Fransson, et al., 2012; Tsuji, et al., 2012; Stille, 2010; Rafi & Stille, 2012). In this study grouting work at one of the tunnels of Citybanan project has been examined to study the complete procedure.

## **CITYBANAN PROJECT**

### **Project configuration**

In the City Line project in Stockholm (Citybanan), currently grouting is conducted in the service tunnels at Stockholm city station. Grouting is performed in fans of boreholes with inclination of between 10 to 20 degrees and the length is often between 20 and 25 m in general. The tunnels are excavated in hard rock of Stockholm with Modulus of elasticity of 40000 MPa.

### **Material properties and stop criteria**

The Injecteria 30 is used as the cement and mixed with the water in the ratio of 0.8. The rheological properties of the final product are yield stress of 6 Pa and viscosity of 0.02 Pa.s. According to the documents from consultant the following practical criteria are applied in grouting of this borehole.

1. Grouting is normally conducted with planned pressure for 20 minutes. Grouting is completed when any of the following stop criteria is achieved within that time:

a) when the grout flow is less than 1 lit/min and sustain for 5 minutes.

b) When the grouting volume is above 500 liters (exclude hole filling volume), change the grout mix to W/C= 0.5 and after the thick grout volume is above 150-200 liters.

### **Analyzing grouting work**

To verify efficiency of Real time grouting control method, grouting at the borehole number 4 in fan 1522 is examined. It is assumed that largest fracture which is dominant for most of the grout is horizontal and situated in the middle of the borehole. Based on the drawings from consultant, this fracture is at the depth of 30 meters under the ground surface. Refusal point has been arrived at the maximum injected volume.

Injection pressure and flow of grout has been registered during the grouting work (figure 9). High constant pressure has been applied for around 10 minutes. The amount of pressure has been decreased and continued constantly up to refusal point. As expected, grout flow in decreasing trend up to 3 minutes. Largest fracture aperture has been estimated based on the grout flow in this zone as 0.1 mm. At this point sudden increase of flow can indicate opening of new fractures (hydro fracturing) in this tight zone. According to Houlsby (1990), the signs indicate that rock has probably moved are sudden increase in grout take for no apparent reason or sudden loss of the pressure in the hole. Therefore, jacking may start at the moment when

recorded and predicted flow data are deviating and continue as long as grout flow in a trend other than predicted one. The sharp increase at around ten minutes with no big drop afterwards can be due to existence of connected fractures where the mixture can flow in large amount. Flow of the grout has been estimated with the initial estimated fracture aperture and in first 3 minutes, it converges with the recorded flow. Extension of the predicted flow implies that the grout take has been much larger than the expected amount. The grout flow is steady or even increase while the grout pressure is approximately constant. It means that the fracture aperture may opening up i.e. jacking has happened.

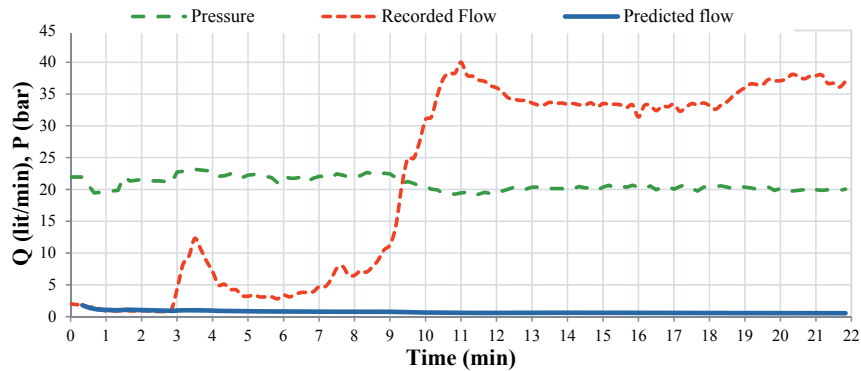


Figure 9. Recorded grout pressure and flow and predicted flow obtained from analytical solution. Hole filling period has been excluded.

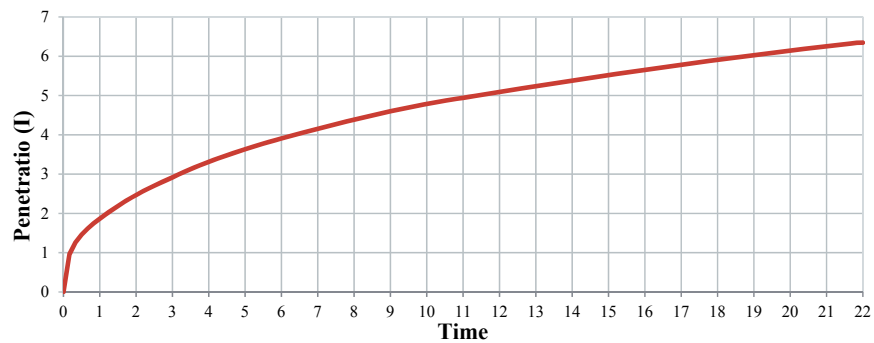


Figure 10 Penetration length of grout in assumed single horizontal fracture.

Critical pressure ( $P_i$ ) is the overburden of the rock mass and would be 8.4 bar which is considerably less than the applied pressure. Thus it is mostly possible for the fracture to open up. To examine the state of the fracture during grouting, penetration length of the grout in real time has been estimated (figure 10) and ultimate jacking limit has established in span of 11 to 22 minutes (figure 11). It should be noticed that the estimated penetration length is based on the initial estimated fracture.

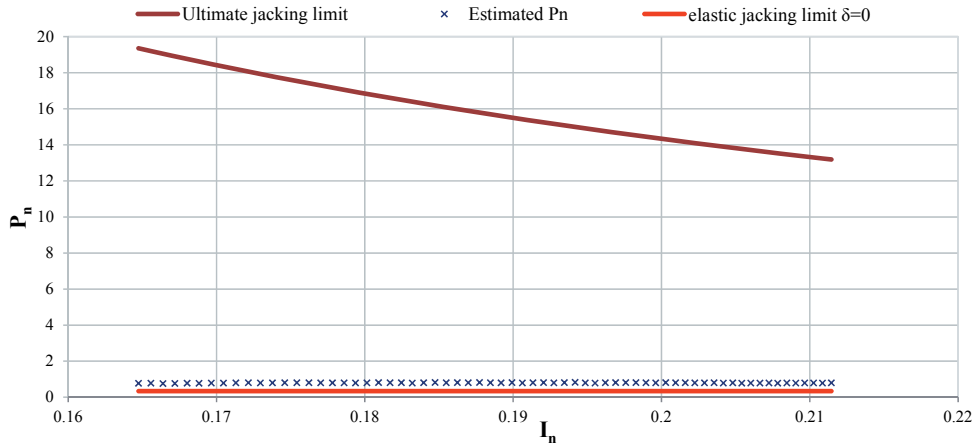


Figure 11 Estimated state of the fracture in compare with ultimate and elastic jacking limits.

From figure 11 it is depicted that the grouting has been stop much sooner than arriving the ultimate limit i.e. since the fracture has been situated at deeper part, ultimate jacking would not happen in short spread. Due to the larger applied pressure in compare with the overburden, the fracture has opened up, but since the deformation is elastic, in releasing pumping pressure, this deformation will be recovered if the grout can be pumped out.

Due to existence of tectonic stresses that are in result of tectonic activities, the total horizontal stress is much higher than the stress induced by gravity (Palmström & Stille, 2010). “k” value is used as the ratio of horizontal stress to vertical stress and at shallow and moderate depth values of k are high (Hoek & Brown, 1980). Thus it is reasonable to apply a grouting pressure much higher than overburden. Since no deformation may happen in vertical fracture, in applying the pressure for long time, grout may flow out of the fracture (leakage). In the studied case, fracture has been dilated (horizontal fracture) or grout has been flowed out (vertical fracture), thus the pressure is needed to be reduced or grouting should be stopped sooner.



## CONCLUSION

It was demonstrated that theoretical approach is robust method in estimating the spread and the state of the fracture in real time. Thus it allows grouting with highest possible pressure up to the point where spread requirements are fulfilled and no undesirable jacking happens. Estimating theoretically correct spread and formulating jacking limits based that will clarify ambiguities of the empirical methods.

Development of Real Time Grouting Control method in order to establish jacking limits and to estimate state of the fracture based on the grout spread was discussed and application of this theory was validated with data from a grouting work at Citybanan project. In this case, by considering grouting at a horizontal fracture, theoretical approach could estimate dilation of the fracture. Since the depth of the fracture from the surface is large in compare with penetration length, there is a large gap between elastic and ultimate jacking limits. Therefore the energy induced by applied pumping pressure in the fracture in span of the grout spread is much less than the energy that is required for the uplift. However the applied pressure is larger than the overburden and the fracture has been dilated. This elastic dilation may be beneficial as it can improve the penetrability and shorten the grouting time.

In developing this method, there were uncertainties connected to the geology and the material properties. Variation in rheological properties of the grout mix has been neglected. The variation of fracture aperture due to jacking has been neglected as well. Furthermore, discontinuities connected to the studied borehole have been simplified to one single horizontal fracture which is dominant for most of the grout flow. In case of vertical fractures, since horizontal stresses are much larger than the stresses due to overburden, elastic and ultimate jacking limits are larger and no deformation may occur. In Citybanan project, there are many vertical fractures under high horizontal stress, thus applying high pressure while using this theory to modify grouting procedure in real time (reducing pressure or stopping grouting when jacking or leakage occurs) is the optimum design.

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ISSN 1104-1773