Study of Pumping Pressure and Stop Criteria in Grouting of Rock Fractures

JALALEDDIN YAGHOOBI RAQI

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KTH Royal Institute of Technology
School of Architecture and the built Environment
Department of Civil and Architectural Engineering
Division of Soil and Rock Mechanics
SE -100 44 Stockholm, Sweden
Summary

Today practice of grouting is based on empirical approaches in that, pumping pressure and stop criteria are determined by benchmarking similar projects. Considering a maximum limit for grouting pressure would allow applying a relatively high pressure that may lead to jacking of the fracture or even uplift of the rock mass. On the other hand, keeping the pressure lower than the overburden, in order to avoid any deformation, will prolong grouting process. Determination of pumping pressure is more complicated considering the induced energy to the rock fracture due to combination of the injected volume and pumping pressure. In other word, pressurizing large volume of the injected grout with a low pumping pressure establish the same force inside the fracture as the high applied grouting pressure on small injected volume do. Therefore, an stop criterion to limit grouting volume along with grouting pressure, which is a hyperbola trimming maximum pressure-maximum volume limits and named as grout intensity number (GIN), has been defined. However, in using this stop criterion and at completion point, the state of the fracture and the distance that grout spread inside the fracture are unknown. As a theoretical approach, examining the flow of the Bingham fluid in network of fractures led to development of a numerical model and later an analytical solution, which enabled estimation of distance that grout spread in the fractures in real time. Finally, theoretical curves to limit elastic and ultimate jacking were established to limit grout pressure in correlation with depth of grout penetration by considering the state of the fracture.

Despite empirical and theoretical developments, determination of optimum grouting pressure is still challenging. In this study, In addition to examining performance of the analytical solution in estimation of grout spread and distinguishing onset of fracture jacking, the goal is coming up with recommendations for selection of optimum grouting pressure, by examining mechanism of elastic jacking. For this purpose, negative aspects of fracture deformation, which are increase of grouting time and remaining transmissivity, were quantified and discussed against its positive effect on increase of penetrability. By that, application of a relatively high pressure was recommended in order to opening of the fracture to a permitted level, with purpose of increasing penetrability while considering negative effects of elastic jacking. The stop criterion is defined as the grouting time of achieving the required distance of grout spread at the highest applicable grouting pressure.

In examining empirical methods, in grouting of fractures in deep levels, pressure-depth graph suggests usage of higher pressure in compare with the estimated pressure by theory while GIN method is conservative. In further studies GIN was estimated analytically and applying a relatively high grouting pressure in order to opening the fracture, up to attaining the hyperbola, and continuation of grouting with decreasing trend, in order to bringing the fracture back to its initial size at refusal, were proposed. Complexity of using this methodology in compare with theoretical approach was discussed.

As the future work, there is a need to verify the results in the field, and to confirm well performance of this analytical solution in different geologies. Examining variation of grout mixture properties during grouting program as well as significance of simplification of geological pattern to a single horizontal fracture, in that grout flow radially, are among other future studies that can develop this theoretical application further.
Sammanfattning

Dagens praxis vid injektering är baserat på empiri. Pumptryck och stopkriterier bestäms genom jämförelser med likartade projekt. Ibland har detta medfört att bergsprickorna har öppnats och även att lyftning av berg massan har skett. I vissa fall har användning av låga tryck, lägre än bergets vertikal tryck, medfört långa pumptider.

Bestämning av pumptrycket är komplex eftersom den energi som förs in berget även beror på brukets spridning dvs., den inpumpade volymen och använt injekeringstryck. Samma energi kan erhållas med högt tryck och liten spridning som med lågt tryck och stor spridning. Detta har lett till förutom att begränsa det maximala trycket och den maximalt inpumpad volymen även begränsa användningen av kombinationen av höga tryck och stora volymer. Detta har kallts GIN- metoden som dock även den är erfarenhetsbaserad.

Genom utveckling av beräkningsmodeller av brukspridningen har möjlighet getts att beräkna spridningen. Först utvecklades numeriska modeller för att beräkna spridningen av Bingham vätskor i ett nätverk av sprickor. Senare har analytiska lösningar tagits fram som möjliggör att i realtid följa förloppet. Detta i kombination med mekaniska modeller för både elastisk vidgning av sprickor och bärighetsbrott i bergmassan har möjliggjort studier av vilket injekeringstryck som kan användas utan att skapa önskade effekter.

Utmanningen har varit att studera vilket pumptryck som är optimalt. Detta har varit målsättningen med denna studie. Utgångspunkten har varit att applicera de teoretiska landvinningarna på verkliga projekt för att verifiera modellerna för att sedan använda dessa för en diskussion om optimalt pumptryck. I detta innebär att studera dels de negativa effekterna av att sprickorna öppnar sig såsom längre pumptid och ökande vattenföring i sprickorna utanför den injekterade zonen dels den positiva effekten av att bruket lättare kan tränga in i sprickorna.

Studien visar att flödeskurva väl följer det teoretiska förloppet så länge ingen vidgning av sprickorna sker. Vidare visar studien att när den uppmätta flödeskurvan avviker från den teoretiska visar den mekaniska modellerna att vidgning av sprickan har skett.

Vad gäller val av optimalt tryck har tre olika modeller studerats. Låga tryck, lägre än det initiala normaltrycket över sprickan, ger ingen negativ inverkan men ett långsammare flöde, ett tryck över det initiala ger kvarvarande deformationer som kan vara oönskade medan ett tryck som successivt minska ned under det initiala får sprickan att sluta sig medan inträngningen har underlättats i början av förloppet. Större öppning än ca två gånger den öppning som bruket kan tränga in i synes mindre meningsfullt eftersom inträngningsförmåga ej förbättras därefter.

I jämförelse med empiriska regler för pumptryck ger analysen att dessa ger för höga värden på djupet. GIN metoden är konservativt om GIN-värdet bestäms utifrån krav på brukspridning. Empiriskt bestämda GIN-värden kan vara på osäkra sidan. Stopkriterier byggda på inträngningen verkar vara det mest optimal att använda.
Preface

The work for this thesis has been carried out at the division of Soil and Rock Mechanics at KTH Royal Institute of Technology. This thesis is based upon four publications, which are appended at the end of the thesis. This project has been performed under the supervision of Professor Håkan Stille and Professor Stefan Larsson at the division of Soil and Rock Mechanics and with financial support of Rock Engineering Research Foundation (BEFO).

No need to say that this has not been a solo project and it would not be possible without the support and companion of Professor Håkan Stille, people in KTH Soil and Rock Mechanics Division, FORMAS, BEFO, Trafikverket, SKB, and above all, my Lovely family.

Thank you all!

Jalaleddin Yaghoobi Rafi
October 2014, Stockholm
## Notations

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<th>Description</th>
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<tr>
<td>( \rho )</td>
<td>Density of water</td>
<td>kg/m³</td>
</tr>
<tr>
<td>( g )</td>
<td>Gravitational acceleration</td>
<td>m/s²</td>
</tr>
<tr>
<td>( b )</td>
<td>Fracture aperture size</td>
<td>m</td>
</tr>
<tr>
<td>( h_0 )</td>
<td>Water head at ( x=0 )</td>
<td>m</td>
</tr>
<tr>
<td>( h_L )</td>
<td>Water head at ( x=L )</td>
<td>m</td>
</tr>
<tr>
<td>( \mu_g, \mu_B )</td>
<td>Viscosity of Bingham fluid</td>
<td>Pa·s</td>
</tr>
<tr>
<td>( t )</td>
<td>Groutin time</td>
<td>sec</td>
</tr>
<tr>
<td>( L )</td>
<td>Channel length</td>
<td>m</td>
</tr>
<tr>
<td>( \tau_0 )</td>
<td>Shear stress</td>
<td>Pa</td>
</tr>
<tr>
<td>( I_D )</td>
<td>Relative penetration</td>
<td></td>
</tr>
<tr>
<td>( I )</td>
<td>Depth of penetration (1D), Radius of grout spread (2D)</td>
<td>m</td>
</tr>
<tr>
<td>( I_{\text{max}} )</td>
<td>Maximum grout penetration</td>
<td>m</td>
</tr>
<tr>
<td>( t_0 )</td>
<td>Characteristic time</td>
<td>Sec</td>
</tr>
<tr>
<td>( t_D )</td>
<td>Relative time</td>
<td></td>
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<tr>
<td>( V_{\text{tot}} ) (1D)</td>
<td>Total injected volume in 1D case</td>
<td>m³</td>
</tr>
<tr>
<td>( w )</td>
<td>Width of channel</td>
<td>m</td>
</tr>
<tr>
<td>( Q(1D) )</td>
<td>Unidirectional flow (1D)</td>
<td>m³/s</td>
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<tr>
<td>( V_{\text{tot}} ) (2D)</td>
<td>Total injected volume (2D)</td>
<td>m³</td>
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<tr>
<td>( Q(2D) )</td>
<td>Radial flow (2D)</td>
<td>m³/s</td>
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<tr>
<td>( \Delta P )</td>
<td>Pressure difference</td>
<td>MPa</td>
</tr>
<tr>
<td>( P_{\text{allowable}} )</td>
<td>Allowable grouting pressure to avoid deformation larger than ( \delta_{\text{acc}} )</td>
<td>MPa</td>
</tr>
<tr>
<td>( P_w )</td>
<td>Ground water pressure</td>
<td>MPa</td>
</tr>
<tr>
<td>( P_g )</td>
<td>Grouting pressure</td>
<td>MPa</td>
</tr>
<tr>
<td>( P_i )</td>
<td>virgin normal stresses</td>
<td>MPa</td>
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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>$P_e$</td>
<td>Excess pressure</td>
<td>MPa</td>
</tr>
<tr>
<td>$P_n$</td>
<td>Normalized pressure</td>
<td></td>
</tr>
<tr>
<td>$I_n$</td>
<td>Normalized penetration</td>
<td></td>
</tr>
<tr>
<td>$k_i$</td>
<td>Geometry of the lifted rock mass</td>
<td></td>
</tr>
<tr>
<td>$k_2$</td>
<td>Relative area of contact in the joint</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of grout</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$h$</td>
<td>Vertical distance</td>
<td>m</td>
</tr>
<tr>
<td>$\Delta a(r)$</td>
<td>Fracture deformation at distance of 'r' from borehole</td>
<td>m</td>
</tr>
<tr>
<td>$\Delta a(j)$</td>
<td>Fracture deformation at the intersection of fracture and borehole</td>
<td>m</td>
</tr>
<tr>
<td>$E$</td>
<td>Modulus of elasticity</td>
<td>MPa</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>Poisson’s ratio</td>
<td></td>
</tr>
<tr>
<td>$\delta_{acc}$</td>
<td>Acceptable fracture deformation</td>
<td>m</td>
</tr>
<tr>
<td>$Q_t$</td>
<td>Inflow of water into the tunnel</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>$H$</td>
<td>Head of ground water</td>
<td>m</td>
</tr>
<tr>
<td>$T$</td>
<td>Transmissivity of rock mass</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>$l$</td>
<td>Length of borehole</td>
<td>m</td>
</tr>
<tr>
<td>$r_t$</td>
<td>Radius of tunnel</td>
<td>m</td>
</tr>
<tr>
<td>$t_d$</td>
<td>Thickness of grouted zone</td>
<td>m</td>
</tr>
<tr>
<td>$T_g$</td>
<td>Transmissivity of grouted rock mass</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Skin factor</td>
<td></td>
</tr>
<tr>
<td>$d\theta$</td>
<td>Propagation angle</td>
<td>Radian</td>
</tr>
<tr>
<td>$r_c$</td>
<td>The distance from the borehole along which the excess pressure acts</td>
<td>m</td>
</tr>
<tr>
<td>$\Delta V_{inj}$</td>
<td>Injected grout volume at any given time step</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>The excess volume developed due to excess pressure at any given time step</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$\Delta V_b$</td>
<td>Volume of the initial fracture that is filled at any given time step</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$Q$</td>
<td>Flow of grout</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Given time step</td>
<td>sec</td>
</tr>
<tr>
<td>$b_{ultimate}$</td>
<td>Fracture aperture size at ultimate state of fracture.</td>
<td>m</td>
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Reference List
1 Introduction

1.1 Background

One of the major obstacles in underground excavation is inflow of water into the excavated area through rock fractures. This can disturb construction of tunnel and cause problems during operation. In construction of dams also, rock fractures beneath the foundation and in the abutments could lead the water to downstream of the dam and decrease the catchment size of the dam. The pressurized water also induces a large force to the foundation of the dam and in severe case, may lead to uplift of the whole construction. Therefore, sealing of these fractures by injecting grout material from drilled boreholes is one of the major tasks to that, a significant share of time and cost of the project is allocated.

In the practice of grouting of fractured rock, the main issues are determining pumping pressure, stop criteria and properties of the grout. In empirical approaches, suggestions are based on similar precedent projects. Houlsby (1990) suggests determining grouting pressure by considering the distance of the fracture to the surface as well as limiting the injected volume in order to preventing overspread of grout. However, applying a high pressure on a large amount of injected volume induces a large energy inside the rock mass that may result in uplift of the rock mass. Thus, Lombardi and Deere (1993) proposed combination of the grouting pressure and the injected grout volume (P·V) as Grout Intensity Number (GIN), which is a hyperbola trims the rectangle of Houlsby’s recommended maximum pressure and maximum volume.

Despite significant effect of the GIN method in improving performance of grouting, difficulties in applying that were reported, among them estimation of the GIN is the main issue. Conrad (2012) suggested to select an initial GIN based on experience, literature and understanding of the geology and to apply variation in that in order to reduce the risk of rock mass displacement. Even if it is possible to control the induced energy, lack of control on grout propagation makes the use of this method complicated (Steyn, 2012). Nevertheless, as mentioned by Lombardi (1996) GIN is not simply a magic number to be freely selected and fundamental design parameters for grouting works have to be defined based on precise theoretical considerations or experiments.

To overcome these obstacles, grout propagation in the network of the fractures was simulated and a numerical model was introduced by Hässler (1991) based on the proposed behavior of Bingham fluid by Dai and Bird (1981). Later, by simplifying the geological model, an analytical solution was proposed by Gustafson and Stille (2005), which enables estimation of the distance that grout spread in real time. Therefore, stop criteria based on grouting time at which grout spread to the required distance in different fractures could be established. With aim of developing GIN method, Brantberger, et al. (2000) suggested substitution of the estimated depth of grout penetration with volume. In other studies, Gothäll and Stille (2009) examined mechanism of fracture deformation closely and Stille, et al. (2012), proposed a limit based on
depth of grout penetration. Therefore, the depth that grout spread in the fracture as well as the state of the fracture could be determined in real time.

1.2 Scope and objective

The objective of this study is to evaluate and to develop further the function of the theoretical approach in grouting of rock fractures, and to investigate it closely versus current empirical practices. Optimizing grouting design parameters (pumping pressure and stop criteria) by identifying mechanism of grout propagation and fracture deformation is another goal of this research work. Furthermore, by developing practical applications, the aim is to bring this analytical solution close to practice and to come up with design recommendations.

In order to evaluate the efficiency of the theoretical application, performed grouting works at Gotvand dam project in sedimentary rock of Iran, THX project in sedimentary rock of Laos and City line project in hard rock of Sweden have been examined, by estimating the distance that grout travels in the fracture and predicting the flow of the grout. The input data are pumping pressure and grout flow, collected through grouting in the field, as well as rheological and penetrability properties of the grout mix, which are obtained by laboratory tests. In order to examine the state of the fracture, elastic jacking curve has been established based on the depth of grout penetration, and the grouting time corresponding to the onset of the elastic jacking has been distinguished.

With purpose of developing this approach, the mechanism of the elastic jacking has been investigated and cons and pros of that have been discussed. The aim is examining the significance of the elastic deformation, by quantifying the negative consequences of the elastic deformation, which are increase of grouting time as well as transmissivity, also by considering the positive role of that in increase of penetrability. In this procedure, the elastic jacking curve has been established and corresponding grouting pressure has been determined by assuming the required depth of penetration as well as the permitted deformation. Finally, grouting pressure has been adjusted, by considering the increase of the transmissivity. Stop criterion is defined based on the grouting time corresponding to the required depth of grout penetration at this grout pressure.

In examining empirical methods, and with aim of getting deeper understanding about the GIN method, it has been studied against the theoretical approach and an analytical solution for selection of the GIN and determination of the completion point has been proposed.

This study is a step forward to understand the mechanism of grout-fracture interaction and to determine pumping pressure, which is highly beneficial in difficult grouting situations, where high reduction of conductivity is required. Furthermore, this study shows how to put this theory in practice in order to estimate initial design parameters, evaluate performed grouting work or use it online to control the grouting progress.
1.3 Outline of thesis

In this thesis, current grouting practices are reviewed in chapter 2 and limitations of the empirical methods are discussed. This clearly demonstrates the need for a robust tool to confirm the quality of the performed grouting work.

In chapter 3, background of this theory and its development, which have been mostly carried out in Royal Institute of Technology (KTH), accompanied by a through description of the theoretical approach are demonstrated. Furthermore, the analytical solution for estimation of GIN in order to achieve the required depth of penetration while avoiding jacking of the fracture is illustrated.

The criteria to stop grouting considering the depth of grout penetration is depicted in chapter 4, followed by the procedures for applying the theoretical approach in design and practice. The outcomes and major findings are discussed in chapter 5. The thesis is finalized with conclusion and proposals for future works that can bring the proposed application to the field.

The results of this research work have been published in form of journal papers as listed below:


Paper D: Rafi J., Stille H., 2014. Applicability of using GIN method, by considering theoretical approach of grouting design. Submitted to Journal of Hydrologic Engineering (ASCE). The first paper (Rafi et al.(2012)) is about evaluating the grouting work, which has been performed in Gotvand dam project, and investigating the efficiency of the used stop criteria in that project. The conclusion was that grouting procedure could stop sooner. Furthermore, the penetrability properties of grout mix could be improved. The Paper B by Rafi and Stille (2014) is allocated to examining deformation of fracture due to spread of grout, where the ability of the theoretical approach in distinguishing the onset of jacking has been evaluated. However, the remaining question was that to what extent the fracture is allowed to be dilated. Thus, the study continued to examine the basic mechanism of rock jacking and consequences of fracture deformation. In this study, that was discussed in paper C by Rafi and Stille (2014), a practical procedure was proposed to optimize the grouting pressure in order to fulfill the requirements of the successful grouting. In last paper (Rafi and Stille (2014)), GIN method, which is one of the most commonly applied empirical methods in the field, has been investigated close to the theoretical approach, and complexity of using it, especially in grouting of shallow fractures, has been discussed.

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1 This Article has been refered as Rafi et al.(2012)
2 This Article has been refered as Rafi and Stille (2014)
3 This Article has been refered as Rafi and Stille (2014)
4 This Article has been refered as Rafi and Stille (2014)
2 Review of today practice of grouting pressure and stop criteria

As a practical solution to avoid unwanted deformations, Houlsby (1990) suggested that the maximum allowable pressure should be based on the depth of the fractures and the rock conditions. Similar recommendations can be found in many textbooks (see for example Weaver, 1991). See Fig. 1. With this approach, the main limitation is the uncertainty about the state of the fractures and the grout propagation after grouting, i.e. whether or not the ground has been propagated in the desired distance or any damages in system of fractures have been occurred. Frequently, the initial decisions on grout mixture and borehole spacing are imprecise, so that the use of engineering experience and judgment is an important factor.

In other approach, which has mainly been suggested for grouting in favorable rock condition for underground utilization and is called Norwegian method, pre-exca vation grouting is used to control the water inflow in urban and subsea tunnels (Grov and Woldmo, 2012). According to them, in this approach the applicable pumping pressure may reach to 100 Bars, if required. However, knowledge of minimum in-situ component to avoid uncontrolled hydraulic jacking is required. Furthermore, in applying this high pressure, they emphasize on requirement for strict compliance criteria. The ground water control is assured either from control holes or by artificial, pressurized water injection adjacent to underground openings. In this approach, in addition to requirement for defining allowable inflow criteria as well as employing adequate drilling and grouting equipment, Grov and Woldmo (2012) highlighted the importance of the experience obtained from the particular project, and following up residual inflow to the tunnel and surface monitoring, which allows modification of grouting scheme.

U.S. practice in contrast has routinely grouted at lower pressure than necessary (Wilson, 2012). According to USACE report (1984) maximum pressures of 0.0055 MPa/m of overburden and 0.011 MPa/m of rock material are applicable, for poor or unknown subsurface condition. According to Bruce (2007), Selection of maximum grouting pressure must be made on a project-specific basis. His suggestion is using an effective pressure greater than the in situ water pressure to cause flow of grout into the fracture while considering occurrence of the hydraulic jacking. This fracture dilation, as he mentioned in (Bruce, 2011), can readily and quickly be recognized by experienced personnel who use modern real time monitoring equipment and thus injection pressure can be reduced. In this approach, the effort is to bring each grouting stage to the absolute refusal by progressively varying the rheology of the grout, with the goal of reducing apparent Lugeon value to zero gradually, at the target refusal pressure i.e. zero flow over at least a 5-min period (Bruce, 2007). For this purpose, he proposed usage of multicomponent grout mix. Grouting starts with a relatively thinner mix and the viscosity is varied by changing the water cement ratio to finalize grouting with a thick material. Bruce (2011) counts employment of computer monitoring control, as well as usage of apparent Lugeon theory and Lugeon testing, which assure satge refusals and low residual permeabilities,
as strong points of US grouting practice. However, recorded data are not analyzed in real time to estimate initial values for grouting parameters (grouting pressure, material properties). Also, at completion, there is no clue about the distance that grout has been propagated.

Lombardi and Deer (1993) recognized that the rock becomes “tighter” in successive phases of grouting, i.e. at least partial filling of at least some of the fractures occurs so that the rock mass permeability will be reduced. Consequently, they introduced the procedure of using a progressively lower volume of grout at a progressively higher pressure to grout the finer fissures. They proposed that, when grouting in this manner, the product of grout pressure and volume should not exceed the given value at the design stage, which they called the Grouting Intensity Number (GIN), otherwise the induced pressure might cause hydro jacking or hydro fracturing.

This method was a significant development in order to control the grouting procedure by changing the pressure while using single stable mixture. According to Lombardi and Deere (1993) in the pressure-volume graph, the path of grouting will touch the GIN curve in different points depending on the quality and tightness of the rock mass i.e. the fracture aperture size. They used this in deciding distance of boreholes in the application of split spacing method (Fig.2). Although GIN method was a significant progress aiming towards more effective and economic grouting, there are limitations and ambiguities connected to that. Lombardi (1996) has described the intensity as the approximation of the energy produced in the rock mass. It is difficult to correlate this energy to mechanical behavior of the fracture and thus recognizing if the deformation is either recoverable or permanent when the GIN hyperbola arrives.

Without knowing the nature of GIN, selection of that would be challenging and still there is no exact method unless benchmarking similar precedent projects. Later, instead of one limiting hyperbola, El Tani (2012) defined a terminal zone that varies between two energy boundaries i.e. span of two GIN numbers. Deciding about these boundaries is even more complex. According to Lombardi (1996), the correct GIN value to be used is the result of a good balance between the natural rock condition and the design requirements. Choosing of this number needs knowledge of grout-ability parameter. This factor can be estimated in several ways and according to

![Fig. 1. 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.](image-url)
Lombardi (1996), an observational method is the best approach for the estimation since the mathematical method is useful only in simple cases due to large amount of assumptions and the experimental method needs huge amount of measurements. Not only determination of GIN but also the initiating grouting pressure i.e. grouting path, is challenging. Evert (2003) mentioned that using GIN principles might be inappropriate that choosing higher pressure or lower volume than required, will lead to jacking or incomplete filling of the fractures.

The uncertainty connected to selection of GIN makes it difficult to set up stop criteria based on that. According to Lombardi and Deere (1993), grouting should be stopped in attaining one of the limiting boundaries of the maximum pressure, maximum volume, or the hyperbola. However, El Tani (2012) suggested to continue grouting after attaining the hyperbola with decreasing pressure along that to the point where no gout flow. This point is on the so-called ZFP curve (zero flow paths), which is the combination of pressure and volume, at which the grout flow is zero (refusal). Thus grouting is completed at the intersection of ZFP and GIN hyperbola (Figure 1). In his discussion, the path of grouting that can fulfill successful grouting criteria, which are achieving the required depth of penetration in shortest time and in desired span of fracture deformation, is not a concern. This method has been used in many projects, despite some ambiguities and limitations. Since there is no mechanically based theory for choosing the GIN value, the applicability of this method has been questioned (Ewert, 1996; Rombough et al., 2006; Shuttle et al., 2007).

In discussed empirical approaches, different grouting pressures regarding to completion point are employed. Setting a maximum pressure may result in jacking of the deformation, in combination with the large volume of injected grout, although the concept of stop pressure to achieve zero grout flow may increase grouting time. Furthermore, requirement for variation in grouting pressure or mixture make it difficult to propose initial design values. Thus, the focus of this study is to introduce a procedure for determination of grout pressure and stop criteria, by examining the mechanism of the grout propagation and fracture deformation. In next chapter,
the research work that has been started more than 20 years ago is reviewed and possible development of that by considering occurrence of fracture deformation is discussed.
3 Theoretical approach

3.1 Estimation of depth of grout penetration

The first attempts to look at grouting theoretically goes back to work of Hässler (1991), who developed a numerical model where advancement of grout in the fracture was simulated, by considering the geometry of the plug of Bingham material and its velocity during grouting process. The goal of this simulation as mentioned by Hässler, et al. (1992) was to supplementing existing empirical methods, which were developed through the experience of grouting personnel, as well as increasing understanding of grouting mechanics. According to them in simulating spread of grout in fractures, the rock should be considered as a discrete medium since grouting usually affect a limited volume of rock due to its high viscosity. Therefore, in numerical solution, the fractures were simulated as channel networks and the grout flow is formulated based on the grout velocity, the rheological properties and the head of pressure. In result, a system of equations was established by using the fact that the sum of inflow is equal to sum of out flow for each intersection. In his thesis, Hässler (1991) expressed a function for estimating the size of grout plug iteratively where both the grout velocity and the grout head at the ends of the channel are known, in the presence of an identical Bingham material (Fig.3).

The velocity of grout in the fracture was formulated based on the size of plug (Z) as below:

\[
\frac{dX}{dt} = \frac{\rho_w g b^2 (h_0 - h_L)}{12 \mu_B(t) L} \left(1 - 3Z + 4Z^3\right)
\]

Where Z is

\[
Z = \min\left(\frac{\tau_0(t)}{b \rho_w g \left|\frac{(h_0 - h_L)}{L}\right|}, \frac{1}{2}\right)
\]

Fig.3 Grout penetrating a fracture (After (Gustafson, et al., 2013))
This equation is solved successively for a number of time steps or front positions during grouting procedure. Thus, by considering suitable time steps, the velocity at each section and the corresponding position of fronts are estimated. The procedure is repeated with new initial values until convergence of the results.

Håkansson, et al. (1992) used this model to describe how the spread depends on rheological properties of grout and later Saedi, et al. (2013) discussed the effect of the different parameters such as orientation and persistence of fractures on the grout propagation by a similar numerical model. Dalmalm & Stille (2003) showed how measurement of the grout flow and grout pressure could be used to interpret the depth of the penetration around a tunnel by semi-empirical methods. Later Gustafson, et al. (2013) introduced an analytical solution for estimation of spread of grout in a disk around the borehole, which here has been called two-dimensional flow or radial flow. The solution was obtained already in 2005 but was unpublished until 2013. Grout propagation in two-dimensional flow followed by one-dimensional flow (which is also called as unidirectional flow) has been depicted schematically in Fig.4.

According to them, flow can take place only in a part of fluid in case of Bingham material that means a stiff plug is formed in the center of the flow channel surrounded by a plastic flow zone and grow to the the size of the aperture at refusal. Based on Hässler’s work, they correlated the size of the plug to the ratio of depth of grout penetration to maximum grout penetration length (\(I/I_{\text{max}}\)), and named it as relative penetration (\(I_D\)), as below:

\[
I_D = \frac{I}{I_{\text{max}}} = \frac{2Z}{b}
\]  

(3)

Where the maximum grout penetration (\(I_{\text{max}}\)) is resulted from a force balance of difference between grouting and resisting water pressure (\(\Delta P = P_g - P_w\)), and shear stress with wall of the fracture, with aperture size of b, as below:

\[
I_{\text{max}} = \frac{\Delta P \cdot b}{2\tau_0}
\]  

(4)

This relative penetration is formulated based on relative time (\(t_D\)), which is the ratio of the grouting time to the characteristic time (\(t_D = t/t_0\)), and define the advancement of grout independent of the fracture size that grout penetrates into (Eq.5 and 6).
Theoretical approach

\[ t_0 = \frac{6\mu_g \Delta P}{\tau_0^2} \] (5)

\[ t_D = \frac{l_D}{3(1 - l_D)} + \frac{2}{9} \cdot \ln \left[ \frac{2(1 - l_D)}{2 + l_D} \right] \] (6)

Since \( l_D \) cannot be solved explicitly from Eq.6, Gustafson and Stille (2005) proposed the approximate equation as below:

\[ I_D = \sqrt{\frac{t_D^2}{4(1 + t_D)} + \frac{2t_D}{1 + t_D} - \frac{t_D}{2(1 + t_D)}} \] (7)

And by defining \( \theta = t_D/(2(1+t_D)) \), \( I_D \) is expressed as below:

\[ I_D = \sqrt{\theta^2 + 4\theta} - \theta \] (8)

They proposed a better approximation for correlating relative time and relative penetration by simplifying the geometry of the grout flow in parallel fractures to unidirectional flow in channels, one dimension (1D), and radial flow around the borehole, two-dimension (2D), respectively (Eq.9 and Eq.10).

\[ \theta_{1D} = \frac{t_D}{2(0.6 + t_D)} \] (9)

\[ \theta_{2D} = \frac{t_D}{2(3 + t_D)} \] (10)

Kobayashi, et al. (2008) proposed an approximation for the case of the radial flow to overcome the poor accuracy of the previous equations at small \( t_D \).

\[ I_D = 0.7032 \cdot \exp(0.9072 \cdot \log(t_D)) \quad t_D < 0.2413 \]
\[ I_D = 0.3643 \cdot \log(t_D) + 0.6266 \quad 0.2413 < t_D < 2.7546 \] (11)
\[ I_D = 1 - 0.4522 \cdot \exp(-1.7098 \cdot \log(t_D)) \quad t_D > 2.7546 \]

The relative penetration is independent of fracture aperture and only shows grout advancement based on its rheological properties, pressure head and grouting time. In idealizing the radial movement of Bingham’s material between non-deforming parallel plates, El Tani (2012) emphasized the hypothesis that a visco-plastic material flows everywhere or remains rigid everywhere in complex geometries, proposed by Lipscomb & Denn (1984). Thus he assumed that the thickness of plug does not depend on the radial coordinates and by that, he generalized movement of unidirectional flow to radial flow, where the visco-plastic material does not deforming and some parts can move rigidly with constant flow. This assumption may lead to different results from the one obtained by Gustafson and Stille (2005). In practice, radius of grout spread is a small fraction of the maximum penetration and the difference of these concepts would be very small at small relative time and corresponding small relative penetrations \( I_D \). As an example, in grouting with pressure of 1MPa, and grout material with yield stress of 7 Pa and
viscosity of 0.03 Pa·s, different solutions of obtaining the relative penetration at the range of relative time smaller than 0.2 are almost the same (Fig. 5).

Since relative penetration is calculated in given time steps, penetration of grout in a certain fracture aperture is estimated at any given time by using Eq. 3 and Eq. 4. The injected volume and consequently the rate of grout flow are estimated stepwise by plugging the estimated penetration length in Eq.12.

\[
V_{tot}(1D) = I_D(1D) \cdot \sum wb \cdot I_{max,b} = I_D(1D) \cdot \sum wb \cdot \frac{\Delta P}{2\tau_0}
\]

\[
Q(1D) = \frac{dI_D}{dt_D} \cdot \frac{1}{\tau_0} \cdot \frac{\Delta P}{2\tau_0} \cdot \sum wb^2
\]

\[
V_{tot}(2D) = I_D^2(2D) \cdot \pi \cdot I_{max}^2 \sum b^3 = I_D^2(2D) \cdot \pi \cdot \frac{\Delta P}{2\tau_0}^2 \cdot \sum b^3
\]

\[
Q(2D) = 2I_D \cdot \frac{dI_D}{dt_D} \cdot \frac{1}{\tau_0} \cdot \pi \cdot \frac{\Delta P}{2\tau_0}^2 \cdot \sum b^3
\]

Fig. 5 in short depth of grout penetration, where grout spread is a small percentage of the maximum possible penetration length, correlations of relative penetration-relative time for an identical grout material at 10-bar pressure and by considering different propagation concepts of Bingham fluid, are almost the same.
Theoretical approach

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

The remaining questions are determining dimensionality of grout flow and estimating fracture aperture size. The importance of the dimensionality according to Gustafson and Stille (2005) is that it dominants the pattern of the boreholes i.e. for two-dimensional planar fractures, limited number of boreholes hit most of fractures while in one-dimensional case, larger number of boreholes should be drilled. Furthermore, relatively longer grouting time is required to achieve the same depth of penetration in two-dimensional pattern. To determine the flow regime, the slope of logarithmic curve of injected volume versus grouting time is used (Eq.13). In plotting the curves of this parameter versus the relative time, it stands on 0.8 for radial flow and 0.45 for unidirectional flow.

$$\frac{d \log V}{d \log t} = \frac{Q \cdot t}{V}$$  \hspace{1cm} (13)

From Fig.6 the estimated depth of penetration when grout travel in large distance would differ considerably, depends on the assumption of the dimensionality.

Estimation of fracture aperture size is challenging and it affects the estimated depth of penetration directly. Several efforts have been made regarding estimation of fracture aperture size. One of the popular methods is water loss measurement. The estimated aperture with this approach is called hydraulic aperture. Lugeon value, which is defined as water loss in liter per meter per meter for the applied pressure of one MPa, is obtained through field tests. Since this value in interchangeable to transmissivity, Hydraulic aperture is estimated by cubic law as Eq. 14.

$$T = \frac{\rho g}{12 \mu} \sum b^3$$ \hspace{1cm} (14)

Barton, et al. (1985), suggested an empirical equation for estimating the initial mechanical aperture based on joints, rock strength and joint roughness. They also proposed correlation of equivalent smooth wall aperture and conductivity as an indirect approach for estimating aperture size. Hakami and Larsson (1996) measured the aperture size by statistical analysis of microscopic images from exposed fracture profile. The results indicated that the mean aperture
of the studied fracture is 1.4 times larger than the hydraulic aperture. Dershowitz, et al. (2003), correlated the void filling aperture to transmissivity with empirical coefficients. These coefficients indicate that hydraulic aperture corresponds to purely parallel and smooth plates. According to the filed results, they found these coefficients larger for fractures with other characteristics and thus concluded that void the filling aperture is larger than the hydraulic aperture. Carter, et al. (2012), illustrated that in larger transmissivity, the void filling aperture is significantly larger than the hydraulic aperture, i.e. the cubic law (Eq.14) underestimates the aperture size largely. Through a case study in City Line project, which has been performed by Tsuji, et al. (2012), it has been confirmed that the estimated apertures based on flow of Bingham fluid in the fracture are larger than the obtained ones from water pressure test. The reason is the lower velocity of the grout flow, which let the voids between the contact points of the fracture getting filled. Form the scattered data in Fig.7, a multiplier of 1.2 to 3 is required to change the hydraulic aperture to the void filling aperture.

In present study, size of fracture aperture is estimated based on flow of Bingham flow through Eq.12 (see Gustafson and Stille, 2005). The estimated aperture size is the average of the spaces and is larger than the estimated aperture size by water pressure test. It should be noted that several fractures may intersect the grouting borehole and are grouted simultaneously. The aperture sizes of these fractures are not the same in most of the cases, and since flow of grout has correlation with sum of cubic of apertures (Eq.12), the largest fracture is dominant for most of the grout flow. Hernqvist (2014), who showed that most of the transmissivity is due to the largest un-grouted fracture, has confirmed this. Therefore, in the studied cases in this thesis, the assumption is that 80 percent of the flow pass through the largest fracture aperture and by that, fracture aperture size could be estimated by Eq.12.

![Fig. 7](image-url) Fig. 7. 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).
Discussed analytical solution is valid as long as the fracture aperture size is constant. However, applying a grout pressure larger than the existing stresses in rock mass may lead to dilation of fracture, which affects the radius of grout spread and sealing efficiency of grouting program. In next chapter, cons and pros of these deformations are discussed and considerations for optimizing grouting pressure are explained.

### 3.2 Jacking of the fracture

- **Elastic and ultimate jacking limits**

Grouting in rock fractures may change the stress situation in rock mass, and if the grouting pressure exceeds the in-situ stresses (so called critical pressure), fractures start to open up (Gothäll and Stille, 2009). By continuing grouting, this deformation becomes larger and may lead to uplift of the rock mass. Lombardi & Deere (1993), showed that not only the grouting pressure but also combination of the pressure and volume of injected grout generates the energy that deforms the fractures of the rock mass. In an attempt to develop GIN method, Brantberger, et al. (2000) defined GIN value based on the depth that grout penetrates into the fracture. By that, they formulated the allowable grouting pressure ($P_{allowable}$) that takes into account the overburden pressure, the geometry of the lifted rock mass ($k_1$) and the amount of contact areas ($k_2$) in the fracture.

$$P_{allowable} < \frac{3 \cdot \rho gh \cdot k_1}{k_2}$$ (15)

Where $\rho$ is density of rock mass and $h$ is the vertical distance of the ground surface to the point where the grout hole intersects the fracture. The lifted rock mass is in a cone shape thus, the parameter that considers the geometry of the rock mass ($k_1$) is defined based on the height of the cone ($h$) and the depth of penetration ($I$) as Eq.16.

$$k_1 = 1 + \frac{h}{I} + \frac{1}{3} \cdot \left( \frac{h}{I} \right)^2$$ (16)

Grout pressure needs to become three times the overburden to lift the rock since it acts in a cone shape on the fracture’s wall. Thus the ratio of grouting pressure to three times of the overburden ($P_g/3\rho gh$), which is called normalized pressure ($P_n$), is equal to 1 or larger when the rock mass is lifted. Therefore, ultimate jacking limit over that the rock mass is lifted has been devised by Brantberger, et al. (2000) as Eq.17, in that the normalized penetration ($I_n$) is the ratio of the depth of grout penetration to the vertical distance from the surface to the intersection of the borehole and the fracture ($I_n=I/h$). $P_w$ is the underground water pressure. From Eq.17, relatively larger grout pressure is applicable at relatively smaller depth of grout penetration, and as grout penetrates further, relatively smaller pressure is allowed.

$$P_n + \frac{P_w}{\rho gh} \leq 1 + \frac{1}{I_n} + \frac{1}{3I_n}$$ (17)

The reason to use injected grout volume in GIN method instead of the theoretically correct depth of penetration was practical. With development of Real Time Grouting Control method, the estimated depth of penetration in real time can be plugged in Eq. 17, by that the grouting
Chapter Three

pressure to reach the desired depth of penetration in shortest time while avoiding uplift of the rock mass can be obtained. However, according to (Gothäll and Stille, 2009), fracture will be dilated at much smaller pressure, theoretically when the grouting pressure exceeds the critical pressure \( P_n > 1/3 \). They proposed contact pressure hypothesis in order to describing the complex behavior of a fracture due to grouting induced load. In this theory, the load that is transferred in the fracture has been considered as a reduction of the pre-loading of the contact asperities. Either no or only a very small deformation occurs at initial moment of pressurizing, until the asperities lose their contact. This corresponds to the unloading stress-opening curves for joints, observed through extensive experiments by Bandis, et al. (1983). However, contact asperities are unloaded as soon as the grouting pressure exceeds the critical pressure. Deformation of these asperities approximated by the deformation of an infinite half space that is loaded by a circular uniform load. Considering the rock mass with several contact points, the Bousinesque solution has been used, by that deformation in a large distance from the borehole has been obtained as Eq.18.

\[
\Delta a(r) = 4 \frac{P_e}{E} \cdot \frac{r_c^2 (1 - \vartheta^2)}{r} \quad (18)
\]

Where

\[
r_c = \frac{P_e}{P_g} \cdot l \quad (19)
\]

\( r_c \) is the distance that excess pressure \( (P_e) \) acts, and dissipates beyond that. Considering an infinite solitary fracture inside an infinite homogenous rock mass, the deformation along this distance would be constant (Eq.20) and is estimated by plugging \( r_c \) in Eq.18.

\[
\Delta a_j = 4 \frac{P_e r_c}{E} (1 - \vartheta^2) \quad (20)
\]

It shows that fracture deformation not only depends on the grout pumping pressure, but also on the existing stresses in the rock mass (referred here as the critical pressure, \( P_i \)), the quality of the rock mass (which is quantified by its stiffness), and the radius of grout spread around the borehole. At this stage, deformations are elastic and reversible if pumping pressure is released and grout can be pumped out. Continuation of the grouting procedure cause larger deformations and at the ultimate state and beyond that \( (P_n>1) \), deformations are permanent. Similar to the ultimate limit state, acceptable limit state has been defined by Stille, et al. (2012), in order to limit fracture deformations to a certain amount (Eq.21).

\[
P_n + \frac{P_w}{3 \rho gh} \leq \frac{k}{3I_n} + \frac{1}{3} \quad (21)
\]

Where

\[
k = \frac{3}{4} \frac{E}{(1 - \vartheta^2)} \cdot \frac{\delta_{accept}}{\rho gh^2} \cdot \frac{\Delta P_g}{P_e} \quad (22)
\]

Ultimate and acceptable Jacking limit states have been depicted in figure 8.
Theoretical approach

Fig. 8 Maximum normalized pressure as a function of normalized grout spread for both the ultimate limit state (Eq.17) and the acceptable limit state (Eq.18). The curves are calculated for $P_n = 0$ (after Stille, et al., 2012).

In Eq.22, considering a constant acceptable deformation, $k$ parameter is not constant, if grouting pressure varies during the procedure. Thus, by solving Eq.22 in Eq.21, and introducing constant parameter of $C$ (Eq.24), grouting pressure corresponds to a specific permitted deformation and required depth of penetration is determined as below:

$$P_n^2 - \frac{1}{3} P_n \left( 2 + \frac{C}{I_n} \right) + \frac{1}{9} = 0$$  \hspace{1cm} (23)

Where

$$C = \frac{3}{4} \frac{E}{1 - \nu^2} \frac{\delta_{acc}}{\rho g h^2}$$  \hspace{1cm} (24)

• Mechanism of fracture deformation

Now that the deformation of the fracture in real time can be estimated, the remaining question is to what extent of the fracture dilation is advantageous in order to confirm successful grouting i.e. what is the optimum pumping pressure. According to Houlsby (1990), in displacement grouting where higher pressure is used, larger area around the borehole is grout-able i.e. lower number of boreholes is needed to be drilled. However it arise uncertainty whether these few holes given access to all the cracks there. The proposal in the displacement grouting is opening the joint by applying a high pressure and injecting a thinner grout followed by compressing the grout when the pressure is released and fracture is closed, although he has questioned the practicality of this method. Lombardi and Deere (1993), suggest using higher grouting pressure in grouting of fine fractures, since grout spread in shorter distance in these fractures and thus the total uplift force is much lower than the overburden. Therefore, the dilation of the fracture would be an advantage and can improve the penetrability. Stille (2012), has discussed the increase of the grout take due to this jacking and has indicated the advantage of the minor jacking in facilitating the penetrability and improving the tightness of the rock mass.
Here, the effort is to examine and quantify influences of the elastic jacking on grouting program, and therefore to optimize the grouting design. The pros and cons of the elastic jacking of the rock fracture are summarized to improvement of the penetrability of the grout mix into the fracture, and increase in grouting time as well as remaining unsealed voids, respectively. Eriksson and Stille (2003), introduced “penetrability meter” device that characterize the grout mix by the aperture size it can penetrates into. According to their definition, no grout enters the channels with the apertures size less than the “minimum aperture” while grout can flow unaffected in the fractures with the aperture size larger than the “critical aperture”. For the apertures in the span of these boundaries ($b_{\text{min}} < b < b_{\text{critical}}$), a limited amount of grout can enter, due to filtration (Eriksson, et al., 2003). In this research work It is shown that the elastic jacking might be favorable in opening of the fractures up to the critical aperture size, which facilitate penetration of grout, however, deformations over this limit will not improve the penetrability anymore.

The main obstacle with the elastic jacking is probability of opening of previously grouted fractures, and consequently creating a void that may remain unsealed. Referring to cubic low (Eq.14), transmissivity is correlated with the cubic of the aperture size and thus a small increase in the aperture size will increase the transmissivity, which is the ability of the rock mass to transmit water (see e.g. Fransson, et al. 2007), and consequently affects the sealing efficiency of the grouting process. The target for sealing i.e. the amount of decrease in water inflow, is set based on the objective of the grouting and is different depends on the function of the structure. In dam constructions, flow of water in fractures of the rock mass is limited to the Lugeon value of one to three in order to avoid loss of water as well as reducing the risk of the uplift (Houlsby, 1990). In tunnels, based on rules of thumb the allowable water ingress during construction can be 50-500 liter per 100 meters while during operation it should be lowered to 5-20 liter per 100 meters (Palmström and Stille, 2010). In estimation of water leakage according to Palmström and Stille (2010), basic flow theory or numerical modelling is normally used, and the inflow of water before and after grouting is shown as Eq.25.

$$Q_t = \frac{2\pi TH (\tau)}{\ln \left( \frac{2H}{\tau} \right) + \left( \frac{T}{T_g} - 1 \right) \cdot \ln \left( 1 + \frac{T_d}{\tau} \right) + \xi}$$  \hspace{1cm} (25)$$

From that, the expectation is decrease of water flow after grouting due to the decrease in the transmissivity, while in some of the studied cases, grouting was not successful in fulfilling this purpose. In examining mechanism of jacking closely, the extent of the deformation outside the grouted zone due to load redistribution will open up previously grouted fractures, which may lead to remaining of un-grouted area if no grouting from adjacent boreholes is performed afterwards. This case is probable in establishing the curtain of the dams in split spacing technique, where grouting is performed through primary boreholes in first stage, before secondary boreholes are drilled and grouted, followed as necessary by tertiary and quaternary boreholes and so on. Thus, the current empirical recommendations of Lombardi and Deere (1993), which propose applying a high grouting pressure in final grouting set (Fig.2) in purpose of improving the penetrability in the finer fractures, may not be favorable.
Theoretical approach

Not only the fracture deformation may disturb the system of fractures and increase the water inflow, but it also affects the grouting time. The estimated depth of penetration will be decreased, since extra room is developed due to fracture deformation, and thus a part of grout is consumed to fill up this extra volume and only a part of grout travels forward. It means that it takes longer time for grout to travel the same distance. Mechanism of elastic jacking has been summarized in Fig. 9.

Fig. 9 Mechanism of elastic jacking
Looking closely to formulate this increase in grouting time, in case of the radial flow in a single fracture, the excess volume ($\Delta V$), which is developed due to the excess pressure ($P_e$) applied along the radius of grouted zone ($I$), will be cylinder shape with a radius of $r_c$ and a hyperbolic shaped extension, as depicted in Fig. 10. This excess volume is estimated by considering the geometry of the dilated fracture as follow:

$$\Delta V = \int_0^{2\pi} \int_0^{r_c} k r_c \, dr \, d\theta + \int_0^{2\pi} \int_{r_c}^{r} \frac{k r^2}{r} \, dr \, d\theta$$

(26)

Where

$$k = \frac{4}{3} P_e \left(1 - \phi^2 \right)$$

(27)

Thus

$$\Delta V = \pi \left(\frac{4}{3}\right) P_e r_c^2 \left(1 - \phi^2 \right) \left(2I - r_c \right)$$

(28)

To estimate the significance of this negative consequence of the elastic jacking i.e. the amount of prolongation in time, equilibrium of injected grout volume and the volume of void area after jacking at the given time step is established and solved based on the increment of the depth of the grout penetration in dilated fracture.

$$\Delta V_{inj} = \Delta V + \Delta V_b$$

(29)

In grouting with a constant pumping pressure in a constant aperture, the grout flow has decreasing trend due to increase of the contact between the grout and the fracture in constant pumping pressure. Variation of aperture size due to high-applied pressure makes it possible for grout to flow in a larger amount and in a more or less constant rate. It means that “$\Delta V_{inj}$”, the injected volume in deformed fracture, is the volume of the constantly flowed grout.

$$\Delta V_{inj} = Q \cdot \Delta t$$

(30)
“$V_b$” is the volume of the grout that flows in initial fracture with aperture size of “b” i.e. the volume of the grout that moves forward, which in case of radial flow is the volume of the disk of the grout spread around the borehole in radius of $I$ (Eq.31).

$$V_b = \pi b I^2 \tag{31}$$

Therefore, from discussion above, as grout spread further with equal increments at given time steps, larger volume in the fracture is created since this volume is correlated with cubic of radius of grout spread. Thus grouting time increases largely as radius of grout spread increases, since the injected volume is linearly correlated with the grouting time. Correlation of these volumes, radius of grout spread and grouting time has been fully demonstrated in Rafi and Stille (2014)\textsuperscript{III}.

3.3 Modifying GIN method based on the theoretical approach

Now that the grout propagation could be estimated in real time and interaction of grout and fracture in high pressure could be justified, GIN can be formulated based on spread of grout instead of injected volume. Thus, the depth of grout penetration as well as state of fracture in attaining the hyperbola is available. In Rafi and Stille (2014)\textsuperscript{IV}, the procedure with assumption of radial flow is described and here is summarized. Obtaining the pressure and the volume based on the maximum possible radius of grout spread (Eq. 4 and Eq.31 respectively), and plugging them to definition of GIN ($P \cdot V$), the following equation is devised.

$$P \cdot V = GIN = 2\pi \tau_0 I_{max}^3 \tag{32}$$

It implies correlation of GIN with maximum distance that grout can travel ($I_{max}$) as well as rheological properties of the used grout mix (yield stress of grout). This means that regardless of the aperture size and in grouting with a specific grout mixture, the hyperbola is attained at the point where grout has been spread to its maximum possible depth i.e. at zero flow rate. The aperture size of the single fracture at which the maximum penetration at intersection of grout path and hyperbola is achieved, is estimated as below:

$$b = \frac{V_{max}}{\pi \cdot (P \cdot \tau_0)^2} \tag{33}$$

Alternatively based on GIN:

$$b = \frac{V_{max}}{\pi \cdot \left(\frac{GIN}{2\tau_0 \cdot \pi}\right)^{2/3}} \tag{34}$$

To enable GIN method for considering the state of the fracture, by modifying Eq.17 and multiplying the injected grout volume in both sides, corresponding GIN to the ultimate jacking state is expressed as:
The hyperbola that limits the fracture deformation to a certain acceptable limit while the required depth of penetration is achieved at its intersection can be estimated with the same modification of Eq. 21, which results in Eq.36.

\[
\Delta P \cdot V < GIN = \rho g h \pi (b_{\text{ultimate}})(3l^2 + 3lh + h^2) = \rho g h \pi l^2 b_{\text{ultimate}} \left( 3 + \frac{3h}{T} + \left( \frac{h}{l} \right)^2 \right) \tag{35}
\]

In grouting several fractures simultaneously, the total amount of injected volume has correlation with sum of cubic of apertures (Eq.37).

\[
V_{\text{max}} = \sum_{i=1}^{n} V_i = \pi \left( \frac{2}{2\tau_0} \right)^2 \cdot \sum_{i=1}^{n} b_i^3 \tag{37}
\]

Furthermore, at any given time interval, the vector of the volume is the summation of the volumes in all fractures, \( V_{\text{total}} = \Delta V_1 + \Delta V_2 \). Therefore, disregarding density of material i.e. applying the same grout pressure at intersection of fractures with borehole:

\[
GIN = \Delta P \Delta V_1 + \Delta P \Delta V_2 \tag{38}
\]

That means the GIN for several fractures is summation of GINs of each fracture. Considering the correlation of injected volume with the radius of the grout spread (Eq.31), GIN for several fractures is defined by generalizing Eq.32 as below:

\[
GIN = 2\tau_0 \pi \sum_{i=1}^{n} (l_{\text{max},i})^3 \tag{39}
\]

Now that the physical model that describes the interaction of the grout and the fracture and the analytical solutions for examining that are discussed, in the next chapter, possible stop criteria considering grout spread and jacking of the fracture will be discussed and the procedure for determining the optimized grouting pressure will be depicted.
4 Application of theoretical approach

4.1 Introduction

In practice of grouting, the main parameters that are required to be determined are pumping pressure, stop criteria and properties of the Bingham material i.e. yield stress and viscosity. The goal is to select the optimum values to reach the desired depth of penetration in shortest time and with the least damages. With development of the theoretical approach that was explained in chapter 3, The depth of grout penetration in the fracture is estimated in real time, which provides the chance of establishing stop criteria based on grout propagation. Therefore, the time span during that grout travel a certain minimum distance in the smallest grout-able fracture and a certain maximum distance in the largest fracture can be the optimum stop criteria. This is reasonable since the fracture aperture and its trace are directly correlated and therefore, in finer fractures, grout needs to travel in shorter distance. However, longer time may be required to achieve even this short distance in compare with the required depth of penetration in larger fractures. Therefore, the stop criteria can be refined based on the result of the trial test and imposing limitation for grouting time and pumping pressure to achieve a minimum depth of penetration in fractures, also to avoid overspread in larger fractures. Re-grouting may be required in purpose of filling up finer fractures to a certain minimum distance ($l_{b\text{max}}$) if the limiting minimum depth of penetration in large fractures ($l_{b\text{max}}$) arrives first (Fig.11). It means that to avoid overspread of grout, grouting of relatively finer fractures need to be performed as re-grouting.

The other design parameter is pumping pressure that significantly affects the outcome of the grouting program and its determination is challenging. Grouting time is shortened by using high pressure while, especially in case of injecting relatively large volume of grout, it cause fracture deformation, which may negatively affects sealing efficiency of grouting program and in sever case, may leads to uplift of the rock mass. Therefore, in applying a pressure larger than critical pressure, not only the grout propagation, but also the fracture deformation may oblige to stop grouting process. In other word, at reaching the permitted deformation limit, grouting process should be stopped or grout pressure should be reduced. In theoretical approach, the optimum stop point is the time that the grout has been spread to the required distance at the pressure that opens up the fracture up to the permitted amount. For this purpose, the elastic and the ultimate jacking limits have been defined based on the spread of grout in the fractures (Eq.17 and 21). Fracture deformation is possible to be estimated at each section of the fracture (Eq. 18) and at any given time, considering the possibility of estimating the distance that grout travel in the dominant horizontal fracture in real time.
Additional stop criteria other than reaching the required spread of grout may be needed. There are the issues occurring during grouting work that may force stopping the procedure and should be included as additional stop criteria. These issues are related to possible grouting scenarios that are not covered by the basic stop criteria and shall handle events that may result in inadequate or uneconomical grouting or damage events (Holmberg, et al., 2013). The examples of these events are leakage of grout and existence of linked holes, tight hole that are not groutable, and occurrence of fracture jacking. In next section, the possible procedures for design and monitoring of grouting parameters are depicted.

4.2 Procedures for applying theoretical approach in design and practice

With aim of bringing this theory close to practice, procedures for following the theory in order to examine the performed grouting job or coming up with recommendations for grouting pressure and stop criteria are explained here. In practicing this methodology, different approaches are considered, depends on the requirements of the project. Offline method is suitable for preliminary estimation of design parameters (pumping pressure, completion time of grouting and material properties) or examination of performed grouting program. The procedure is described through two successive processes; 1) estimating the depth of grout penetration and 2) predicting the state of the fracture. In first process, pumping pressure and grout flow are recorded in time steps with Logac machine in the field. Rheological properties of the grout mixture, yield stress ($\tau_0$) and viscosity ($\mu$), are measured in laboratory and are assumed constant during the grouting period. By that, relative penetration of grout at any given time step is estimated (Fig.6, Eq.11). The maximum penetration length ($I_{\text{max}}$) is estimated by simplifying the network of fractures to a single dominant horizontal fracture (Eq.4).

There are uncertainties in estimating the depth of grout penetration, which are connected to geotechnical investigations i.e. assumptions for the dimensionality of the grout flow and the size of the fracture aperture are not certain. As mentioned by Rafi et al. (2012), since the grout flow is correlated to the cubic of the aperture size, few number of fractures with larger aperture size contribute for most of the flow e.g. a fracture with aperture of 1 mm stands for 1000 fractures with the aperture size of 0.1mm. Thus, the network of fractures can be simplified to one large...
fracture that is dominant for the most of the grout flow. It means that the maximum estimated fracture aperture would be equal to the third root of sum of cubic of apertures \( b_{\text{max}} = \sqrt[3]{\sum b_{g}^3} \).

For two fractures with equal apertures, the aperture size is smaller and can be approximated to 80% of the third root of sum of cubic of apertures \( b_{\text{max}} = 0.8\sqrt[3]{\sum b_{g}^3} \) and to 50% if ten of equal aperture size fractures are existing (Holmberg, et al., 2013). Dimensionality is distinguished by plotting the scattered data of \( Q \cdot t/V \) during grouting time, where cumulative values for time and volume are used. The flow is characterized as one and two dimensional if \( Q \cdot t/V \) parameter stands more or less on 0.45 and 0.8 respectively. Larger values indicate higher porosity and existence of larger void area. However, it is not always easy to assign one of these categories to the grout flow since trend of scattered data may vary in a large range. It means that flow dimensionality is changed as the grout proceeds in the fracture. It should be noted that in case of unidirectional flow, the width of the fracture is needed.

In formulation of the velocity in the fracture that results in estimation of depth of penetration (Eq.1 and 2), the assumption is usage of a single mix i.e. the mix properties remain constant during the whole procedure. Theoretical approach can give a rough estimation of the properties of this mixture in case of applying a certain constant grout pressure and aiming a certain depth of penetration into the fracture with a certain aperture size. As a practical solution, this fracture aperture size is roughly approximated by considering aperture size of the hydraulic fracture, which is obtained from water pressure test (refer to the discussion in chapter 3). With assumption of radial flow, the grout is assumed to travel up to 20% of the maximum possible penetration \( (I_D=0.2) \) in order to disregarding dimensionality parameter (refer to chapter 3 and Fig.6). Therefore, yield stress of grout is obtained from Eq. 3 and Eq.4. Viscosity of grout mix is approximated from Eq.5, by considering the corresponding relative time to 20% of the maximum penetration, where the outcome of the theoretical approach is in good convergence with other proposed methodologies (Fig.5). In the procedure depicted in Fig.12, the grout mix is designed by considering these rheological properties, plus the required penetrability properties (minimum and critical aperture).

Other than preliminary design of grouting parameters, Real Time Grouting Control method is a valuable tool in applying observational method (Stille, 2012) where performance of grouting work is evaluated with back analysis. In this approach, based on recorded pressure and flow data as well as injected grout volume, fracture aperture size and dimensionality of grout at different grouted holes are approximated.

Finally, by estimation of the corresponding time to the required depth of penetration, a stop criterion based on grouting time in the next section of grouting and in a similar geology is defined and it is revised as grouting project is going on i.e. the required grouting time is adjusted as more of grout sections are examined. Trueness of the assumptions for fracture aperture size and the dimensionality are evaluated by comparing the recorded and the estimated flow trends. Deviation of these data sets is either due to the wrong assumption of the dimensionality and the aperture size (where the trends are similar) or because of jacking of the fracture (in case of deviation of data sets with different trends as Fig.13).
**Chapter Four**

Decide grouting pressure

Hydraulic aperture from water pressure test

Decide required grout spread

\[ b_f \approx 1.8 - 2 \, b_{hyd} \]

\[ I_0 = 20\% \]

Selecting grouting time

\[ t_0(20\%) = t/t_0 \]

Eq. 5

Viscosit

**Yield stress**

\[ \tau \]

Eq. 3 and Eq. 4

Measure penetrability properties of grout

**Select Grout Mix**

**Fig. 12** procedure of estimating the properties of grout material to be used in order to fulfil the spread requirement.

**Figure 13** One can distinguish occurrence of fracture jacking from deviation of recorded flow and estimated flow.

Grouting Pressure

Recorded flow after Jacking

Estimated flow no jacking

P_g

P_i

Q

t_f

t_0

Time
On-line analysis of the data is a robust approach in compare with back analysis by that, depth of grout penetration is monitored in real time and during grouting procedure. However, as mentioned by Holmberg, et al. (2013), this approach requires that on-line analysis be an integral part of the grouting operation, which to date is not a market standard. Nevertheless, the possible procedure for this approach has been depicted in Fig.14. The recorded applied pressure and flow of grout at first time step, as well as rheological properties of grout material, which are obtained from laboratory tests, are the initial input data. By that, the fracture aperture size and the depth of the grout penetration are estimated at this time step (Eq. 12, Eq.4 and Eq.3 respectively). Comparing the recorded and the estimated flow provides the chance of adjusting the assumption about dimensionality, and distinguishing occurrence of fracture deformation. The same procedure is repeated in following time steps and the estimated size of the fracture aperture is adjusted at each round. This means that in online procedure, flow of grout at each time step provides information about the porosity of the rock mass, which is helpful to justify the estimation of the dominant fracture aperture. Furthermore, grouting is stopped as soon as the requirement of the grout propagation is achieved.

Development of the theoretical approach enables distinguishing deformation of fracture as grout spread further. The estimated depth of penetration combined together with the applied grouting pressure determine the state of fracture and since the spread of grout is monitored in real time, the state of fracture in real time is also possible to be estimated. Thus the second process of the application, which is examining the state of the fracture and therefore optimizing the grouting pressure to the permitted deformation, is developed (Fig.15).

by assuming the distance of the horizontal fracture to the surface (h) in addition to the geological properties (density of the rock mass, modulus of elasticity and Poisson’s ratio), as well as the permitted deformation, the ultimate and the elastic jacking limits are established (Eq.17 and 21). Coordinates of the scattered data in normalized pressure-normalized penetration graph specifies the state of the fracture. Thus, the scattered data of the estimated normalized depth of grout penetration (I_n) at different elapsed time is plotted against the normalized pressure (P_n) and is examined by considering the theoretical jacking curves by that, the onset of jacking is distinguished. Deformation of fracture is possible to be controlled by using a lower pressure or revising the stop criteria to shorten the grouting time i.e. decrease in depth of grout penetration.
Fig. 14 On-line application of estimating the depth of grout penetration by revising initial assumptions in each time step.
A more complex procedure should be followed in order to considering the elastic jacking of the fracture with purpose of using the benefit of the fracture opening i.e. improving the penetrability. Achieving the required radius of the grout spread to fill up the fractures between two boreholes while not exceeding the permitted deformation (defined based on penetrability requirements) are the main concerns in approximation of the grouting pressure. Real Time Grouting Control method provides the opportunity of estimating the initial fracture aperture size based on flow of grout and consequently calculating the corresponding grouting time to the required radius of grout spread at this fracture. However, since the applicable pressure has been approximated to be larger than critical pressure, in order to give the permitted fracture deformation, at injecting grout in a constant flow rate, the grouting time will be prolonged and the transmissivity outside the grouted area is increased due to extent of the fracture deformation. Quantifying these negative effects has been discussed by Rafi and Stille (2014)\textsuperscript{III}. In this process, the reduced increment of depth of penetration at any given time step and consequently prolongation of grouting time are estimated. Increase of transmissivity outside the grouted zone is estimated as well. Quantifying negative consequences of applying a high grout pressure parallel with considering its positive effect in filling of the fine fractures and shortening the grouting time provides enough information for optimizing the grouting pressure. In active design, the process is followed successively i.e. with applying the estimated pressure constantly, grouting is stopped.
as soon as the required radius of grout spread or the permitted fracture deformation are achieved. The procedure with assumption of radial flow has been depicted in Fig.16.
5 Major results and findings of the application

In previous chapters, the methodology for determining grouting parameters with theoretical approach was demonstrated and possible procedures to put it in practice were discussed. In this chapter, the goal is to demonstrate the main findings of the application of Real Time Grouting Control method and further developed methodologies.

Data from grouting at different geologies of sedimentary rock and hard rock at different projects have been used to examine discussed applications. Grouting at Gotvand dam project, which is located in south west of Iran, has been performed with the objective of creating a water-tightening curtain under the dam and in the embankment. Requirements of this project have been discussed by Rafi et al. (2012). In this project, the goal is to reduce conductivity to less than $3 \cdot 10^{-7}$, which corresponds to water loss of three Lugeon in control holes. The distance between the primary boreholes is 4 meter and secondary and tertiary boreholes are drilled between them in split spacing technique. According to the project records, the adopted procedure required the grout pressure to be increased at a rate of 0.5 bar/min during first 10 minutes of grouting, as long as the flow exceeds 8 liter/5 min. If the rate of flow fell below this limit, the exerted pressure gradient was to be increased to 1 bar/min. For flows occurring at a pressure near zero, the pressure gradient was to be increased to 2-3 bar/min. A thin grout with water cement ratio of two has been used. The yield stress and viscosity of the Bingham material are 0.35 Pa and 0.0043 Pa·s respectively.

As depicted by Rafi et al. (2012), Good convergence of the recorded and the estimated grout flow in the studied cases at Gotvand project validates the applicability of this analytical solution. This application modifies the porosity to a single horizontal fracture, simplifies grout flow model to unidirectional flow (1D) or radial flow (2D) around the borehole and neglects variation of rheological properties of grout mix. However, there were difficulties in interpretation of the recorded pressure and the flow curves as well as determining a constant fracture aperture size. Examination of performed grouting work in this project indicates overspread of grout. The stain of grout in lower gallery confirms that grout has been propagated far away from the required zone. The possible reason could be usage of a thin grout mix with high water cement ratio. Using the off-line application of Real Time Grouting Control method, showed that thicker grout with content of different cement type (INJ 30), not only decreases the depth of the grout penetration, but it also improves the penetrability properties of the grout by decreasing the minimum and the critical apertures. However, the results indicate that the thicker grout mix with the used pumping pressure might not spread far enough in the smallest fracture i.e. to the required distance (Fig.17). Thus, the initial determined values for the pumping pressure and the mixture properties should be revised.
In THX project, which is about construction of a hydro power plant with a concrete dam on sedimentary rock in Laos, grout has been spread in a distance of two to five times longer than required depth of penetration (equal to the distances of the grout holes, which are 6 and 3 meters for secondary and quaternary boreholes respectively). In this project, a grout mix with a water cement ratio of 0.75 has been used. Yield stress and viscosity were measured by means of laboratory tests (yield stress of 0.7 Pa and viscosity of 0.02 Pa·s). This relatively thin used grout mix travel the short required distance very quickly, so that it would have been useful to set a stop criterion to limit the spread of the grout.

Other than overspread of grout, a pressure larger than critical pressure has been used for grouting at the first 10 meter of rock below the ground level. In this project, considerations for estimating the grouting pressure and critical pressure were applied. In respect to critical pressure, to allow curtain grouting to be carried out simultaneously with the construction of the concrete dam, the curtain boreholes were grouted from a gallery inside the concrete dam. Thus, the weight of the part of the dam constructed at the time of grouting (15 meters) plus the overburden of the rock mass were considered as the critical pressure ($P_i$). on the other hand, As Rafi and Stille (2014) discussed it, head losses in the hoses and boreholes will lead to the pressure at the entrance to the fracture probably being less than the measured one at the grouting equipment at the surface. It means that measurement of the grout pressure is uncertain. From the results of the studied cases, it can be observed that the ratio between the grout pressure at the onset of elastic jacking and the overburden pressure is around 1.4 (Fig.18). In this study, the pumping pressure recorded at the grouting equipment has been considered.
Major results and findings of the application

Fig. 18 Pressure at onset of elastic jacking is close to overburden. The reason for the small difference is the assumption in location of the fracture and the inaccuracy in registered pressure. Conversion factors 1 bar = 0.1 MPa.

Efficiency of the theoretical approach in distinguishing the onset of the jacking was evaluated with data from Gotvand and THX projects (Rafi and Stille, 2014). For this purpose, the scattered estimated coordinates of \( P_n - I_n \) were plotted against the limit over that fracture starts to dilate (\( P_n > 1/3 \)). The results indicated that the intersection of the scattered estimated points and the elastic limit curve corresponds to the moment that grouting pressure exceeds the critical...
pressure. This confirms good performance of the theoretical approach in estimation of onset of elastic jacking. Furthermore, applicable pressure to avoid any fracture deformation was approximated and compared with the estimated grouting pressure through the graph suggested by Weaver (1991), which was depicted in this thesis as Fig.1. Rafi and Stille (2014)\textsuperscript{III} showed that in examined cases at Gotvand project, where fractures are situated in deep level, this empirical method suggests much higher pressure in compare with theoretical approach, while the pressure proposal for grouting of the shallow fractures in THX project is conservative (Fig.19).

As the stop criterion, GIN method was used in THX project and grout injection was stopped at the point where the path of the grout pressure-volume pumped met the 1000 bar liter/m GIN hyperbola. However, Rafi and Stille (2014)\textsuperscript{IV} showed that the used GIN is much larger than analytically estimated values. Analysis of the recorded pressure and the flow data confirms occurrence of jacking where fractures have been dilated up to 2-4 times of its initial size. This means that most of the deformations not only had no contribution in improving of the penetrability and were unnecessary but they also increased the grouting time especially in examined shallow fractures. Furthermore, applying the high pressure increased grouting time in the shallow fractures 30 to 40\% (Rafi and Stille, 2014)\textsuperscript{III}. Recorded data indicates that grouting has been stopped prior to achieving the hyperbola or at its intersection and thus, since no closure of fractures may have been occurred, the extent of the deformation out of grouted zone, especially in quaternary boreholes, may have been remained unsealed. The results showed by Rafi and Stille (2014)\textsuperscript{IV} indicate that, by setting a short required depth of penetration at completion point, a higher grouting pressure could have been applied than the pressure that was actually used.

Fracture deformation ($\Delta a_j$) and in result increase of transmissivity not only depends on the grout pumping pressure, but it also is proportional to the existing pressure in the rock mass that was mentioned here as critical pressure ($P_i$), quality of the rock mass which is quantified by its stiffness ($k$), and the radius of grout spread around the borehole ($I$). Rafi and Stille (2014)\textsuperscript{III} established Fig.20, which implies that regardless of the rock quality and the depth that gout penetrates, a higher relative pressure results in a larger fracture deformation. They also divided Eq.18 by Eq. 20, which leads to Eq. 40 from that, at a given relative pressure ($P_g/P_i$), the deformation will be smaller at a greater distance from the borehole. However, if larger relative pressure is applied, there will be less difference between the deformations in different sections of the fracture. Fig.21 shows that as the relative pressure increase, fracture deformation at a section corresponding to the radius of grout spread ($\Delta a(r=I)$) converges to the deformation in the zone influenced by the active excess pressure ($\Delta a_j$). This means that, by increasing the pressure, not only the deformation in the overloaded zone ($\Delta a_j$) increases, but also that the zone that the excess pressure would act on it ($r_c$) is growing, and approaching the radius of the grout spread.

$$\frac{\Delta a(r)}{\Delta a_j} = \left(1 - \frac{P_i}{P_g} \cdot I\right) \frac{I}{r}$$

(40)
The relative pressure and not only just the magnitude of the injection pressure influences the amount of fracture deformation. Rafi and Stille (2014) showed that different relative pressures are applicable to reach a certain deformation in fractures that are situated at different distances from the surface. At shallow depth, a higher relative pressure produces relatively a minor fracture opening, both in the grouted zone and outside. In fractures situated at greater depth, a smaller relative pressure should be applied, i.e. the slope of the graph of the applied pressure versus the overburden is not constant. Thus, the linear relation of applied pressure and depth of fractures that has been proposed by previous workers e.g. Weaver (1991), as shown in section 1 (Fig.1), may not be correct and it overestimate the applicable pressure especially for fractures situated in deeper level (Fig.22). This is coincides with the discussed results in Fig.19.
Fig. 22: Against the empirical charts for distinguishing the design pressure (here is the sample from Weaver (1991), the curve of pressure-depth is not linear. The curves are recommended for three different situations that according to Weaver (1991) are categorized to good, normal and weak rock.

With purpose of optimizing grouting pressure, Rafi and Stille (2014) estimated the applicable relative pressures in the studied cases in THX project by considering the acceptable deformation limit at the intersection point of the borehole and the fracture (fracture aperture was allowed to become twice the initial aperture size). At this pressure, the extent of the deformation at a section corresponding to the radius of the grout spread ($\Delta a(r=I)$) is large, which leads to increase of transmissivity 5 to 8 times. Thus, elastic jacking should be avoided, especially in examined quaternary boreholes, since disturbance of fractures resulting from the grouting of these boreholes may increase the transmissivity permanently.

In attempt for examining GIN method analytically, Rafi and Stille (2014) explained the grout propagation and the interaction of the grout and the fracture along the hyperbola by defining GIN based on the radius of the grout spread. Grout travels up to a large percentage of the maximum penetration at the refusal and after that, grout spreads in a very short distance despite a long grouting time and consequently, maximum penetration ($I_D=1$) is reached after a long time. In grouting of several fractures, relative penetrations ($I_D$) are the same for all fractures, though
grout travels relatively in a shorter distance in relatively smaller fractures. In this case, GIN of the system of the several parallel fractures, is summation of the GINs of each fracture, obtained through Eq.39. As expected, the GIN of the fracture with respectively larger aperture is closer to the summation of the GINs. In order to filling up all of the fractures, grouting should be continued for longer time than grouting of each single fracture along the summation hyperbola, to reach sum of the volume that has been injected in all of the fractures.

Other than estimation of GIN, path of grouting should be known. For this purpose, Rafi and Stille (2014) defined different design approaches. In case of applying lower pressure than in-situ stresses, no deformation may occur, even by injection of large amount of grout and thus, the criterion of maximum volume will become dominant. This procedure may take a long time and applying high pressure may be desired, though over critical pressure fracture will dilate. Therefore, GIN is defined to limit the pressure to the span of beneficial deformations. Grouting is stop in attaining hyperbola in zero flow to avoid probable damages. It means that grouting is completed at the intersection of ZFP and GIN hyperbola. At the completion point, grout has been traveled up to the maximum possible distance ($I_{\text{max}}$). Therefore, by considering the required radius of grout spread equal to maximum penetration length ($I_{\text{req}}=I_{\text{max}}$) and estimating GIN through Eq.32, the grout spread requirement would be fulfilled at completion point. Theoretical jacking limit intersect GIN hyperbola where grout spread to the required distance ($I_{\text{req}}$) in a certain fracture and at a constant pressure (pressure of $P_0$ in figure 23). In case of using a relatively higher grouting pressure, GIN arrives at a flow rate larger than zero, and according to El Tani (2012) grouting should be continued along the hyperbola to reach the refusal. In this case, in injection of an identical grout volume, and in span of permitted deformation, GIN method is conservative and lower pressure is permitted along the hyperbola in compare with the theoretical limit (Fig.23). Applying high pressure can be beneficial since opening of the fracture can increase penetrability and may shorten grouting period however, the un-grouted deformed section may affect sealing efficiency of grouting program negatively.

Considering the merits and disadvantages of elastic jacking, Rafi and Stille (2014) proposed that in attaining the GIN hyperbola, multiplication of the coordinates of the intersection point ($P.V$) not bring the fracture to the ultimate state, and at the stop point, the applied pressure be less than the critical pressure. Thus, to use the permitted deformation capacity of the fractures, a pressure larger than the critical pressure is applied in order to opening the fractures up to the permitted amount (the final size of the fracture becomes less than the critical aperture). Consequently, the large fractures are filled up in a relatively shorter time and there will be a minimum grout take in fractures with small aperture. In this methodology, after attaining the hyperbola, which occurs at intersection with an acceptable theoretical limit curve (defined based on permitted deformation), by lowering down the pressure along the hyperbola to less than the critical pressure, the deformation would be compensated at the completion point (Fig.24). It should be noticed that closure of the fracture might push the grout further, though grout may be flow out from the grout hole. Moreover, in case of dealing with several fractures, dilation of the larger fracture may counteract the opening of the adjacent smaller fractures.
Figure 23 Grouting is completed at intersection of GIN hyperbola and theoretical curve where the injected volume of $V_0$ confirms enough spread of grout and the pressure of $P_0$ limits the fracture deformation to permitted level.

Figure 24 Applying high pressure to attain the GIN hyperbola at permitted deformation and lowering down the pressure along the hyperbola to attain the zero flow at a pressure lower than critical pressure can be the optimal approach. GIN method is more conservative in compare with theoretical approach and allows relatively lower pressure in injection of larger volume.

In establishing the curtain of the dams in split spacing technique, estimation of GIN and grouting pressure are inter-related. According to Lombardi and Deere (1993), since grout travel in short distance in finer fractures, and because the grout pressure diminishes rapidly as it spreads away from the borehole, in grouting of these fractures, the total uplift force, even at high grout pressures, will be much lower than the overburden. Therefore, they suggested
practicing a high pressure in grouting of relatively finer fractures, which is the case in quaternary set of boreholes in grouting the curtain of the dams (Fig. 2). On the other hand, the theoretical approach proposes usage of a certain constant pressure in all sets of boreholes to avoid undesired fracture deformations. In this case, from Eq. 35 and Eq. 36, in grouting fractures that are situated at deeper level ($l \ll h$), weight of the rock mass above the fracture is the main factor in choosing the GIN. Thus in case of assuming one horizontal fracture situated in a deep level with constant aperture that dominates for most of the grout flow, an identical GIN can be used. However, in shallow fractures where penetration ($l$) is of the same order of magnitude as ($h$) or larger, GIN depends on the depth of grout penetration ($l$), and at larger grout spread, hyperbola intersects the theoretical curve in further distance from zero coordinates. This clearly indicates that in using split spacing technique for grouting shallow fractures and in applying a constant pressure, different GIN curves should be considered for grouting different sets of boreholes.

The other studied cases are situated in Norrström service tunnel in the City Line project, which is a 6-kilometer long commuter train tunnel located in Stockholm, Sweden. The dominant rock types are mainly grey granite or reddish grey gneiss and RMR of 70-100 represents very good rock. In this project, grouting duration has been set as the main stop criterion when the required radius of grout spread is achieved, however additional stop criteria in encountering tight holes or distinguishing leakage of grout or fracture jacking have been set as well. Grout material with yield strength of 6 Pa and viscosity of 0.02 Pas has been used. Due to the existence of tectonic stresses that are in result of tectonic activities, the total horizontal stress is much higher than the vertical stress induced by gravity (Palmström & Stille, 2010). Thus, as far as vertical fractures are dominant at this geology, it is reasonable to apply a grouting pressure much higher than the overburden. Many of the boreholes were reported to be tight and in others, no sign of jacking have been observed (Tsuji, et al., 2012) due to large pressure from overburden and/or orientation of fractures.

In this project, the objective of the grouting work was to decrease the conductivity of the rock mass by the order of 10 times. This would oblige filling the initial fractures with grout, without any excess volume being developed. From the grouting records, it seems that jacking of the fractures have been occurred rarely, because of the higher stiffness of the rock mass, and that the grouting of the adjacent boreholes might have filled up any extension of deformations outside the grouted area. As Rafi and Stille (2014) showed it, the high pressure used would have produced a manageable deformation that would have increased the grouting time by less than 5% in achieving 17 meters of grout spread. Thus, it seems that the small elastic jacking that did take place did not influence the grouting performance significantly. Defining a stop criterion based on the required depth of penetration could avoid both excessive spread of grout and the negative consequences of the fracture deformation.
6 Conclusion and future works

Real Time Grouting Control method was found to be a robust tool in evaluation of the performed grouting works and estimation of the grouting design parameters analytically. It makes it possible to approximate the distance that grout spread in the fracture in time steps by simplifying the network of the fractures to a dominant horizontal fracture. Applying data obtained from grouting in sedimentary and hard rock confirmed well performance of this analytical solution, despite the initial assumptions. This theoretical approach later was developed for investigating variation of the fracture aperture i.e. fracture jacking, due to spread of the pressurized grout in the fracture. By examining data from grouting in shallow fractures, the application of the theoretical approach was capable of distinguishing the onset of the jacking in real time.

Examining mechanism of fracture deformation was a clue to find out negative aspects of elastic jacking. It was shown that despite the merit of using high pressure in increase of penetrability, it might disturb the previously grouted section. Quantifying the amount of the increase in transmissivity due extension of the fracture deformation outside the grout zone as well as increase of grouting time provides enough information for optimizing grouting pressure. Furthermore, investigation of effects of grouting pressure on profile of deformed fracture could lead to the conclusion that the fracture deformation not only depends on the grouting pressure but also on the existing stresses in the rock mass i.e. critical pressure. Examining fracture deformation against the ratio of the grouting pressure to the critical pressure, named as relative pressure, showed that higher relative pressure at shallow depth gives minor fracture opening both in the grouted zone and outside, while in fractures situated at larger distance from the surface, a smaller relative pressure is applicable i.e. the slope of the grout pressure versus the overburden is not constant. Therefore, the empirical pressure-depth graph suggests usage of a larger pressure in compare with the theoretical method, especially in grouting fractures of deeper levels.

Using GIN method have been and may can be useful in grouting projects as well, but it was reported not successful in many projects due to lack of understanding and wrong interpretations. In order to examining this popular empirical method closely, GIN and stop criteria are determined analytically based on the distance that grout travel in the fracture. In applying a constant pressure larger than the critical pressure, grouting is completed at the intersection of the GIN hyperbola and the theoretical jacking curve. In this case and especially in shallow fractures, GIN depends on the depth of grout penetration. Thus, in using split spacing technique with a constant pressure for grouting fractures close to the surface, different GINs for different sets of boreholes should be considered. Since attaining the hyperbola at zero flow while applying a constant pressure takes long time, the optimum suggested proposal is applying a high pressure to open the fractures up to a permitted amount followed by decreasing the grouting pressure along the hyperbola after intersecting that, to bring the fracture back to its initial size at the refusal. Analytical investigation of the GIN method shows that in lowering down the
pressure, the GIN hyperbola is conservative in compare with the theoretical jacking curve and suggests applying relatively smaller pressure.

Theoretical approach provides information about the grout propagation and the state of the fracture in each time step. This is essential especially in difficult grouting where a high sealing efficiency is required or, especially in shallow fractures, a precise design to avoid the damages is needed. Furthermore, defining stop criteria based on grouting time can significantly affect economy of the projects. In this research work, in addition to close examination of the fracture deformation and influencing parameters, and in accordance with that, further development of this analytical solution, possible procedures for carrying out off-line and on-line analysis were depicted. Future suggested work could be evaluation of this methodology with data from different geologies as well as implementation of that in field. In examining of shallow fractures, trueness of the assumption that the fracture has been bounded with two half-infinite spaces should be verified, by considering the overburden as a beam. Examining applicable pressure and deformation in vertical fractures, investigating the analyses with unidirectional flow, and considering variation of material properties are among other suggestions in order to justifying the assumptions and bring this theory closer to practice.


Holmberg, M., Tsuji, M., Stille, B., Rafi, J., & Stille, H., 2013. Evaluation of pre-grouting with the RTGC method and results from the City Line project. 7th Nordic Grouting Symposium, Gothenberg, pp.135-145


