A NOMOGRAM FOR THE DESIGN OF CEMENT GROUTING

Ett nomogram för dimensionering av cement injektering

Mashuqur Rahman, ÅF Infrastructure

Ulf Håkansson, Skanska AB

SUMMARY

In recent decades, significant theoretical development has been achieved concerning the estimation of the propagation of grout inside one dimensional and two dimensional geometries, the implementation of which will increase the predictability of the work and reduce unnecessary spread of grout. The yield stress of grout is required to estimate the spread of grout and due to its thixotropic nature; the yield stress depends on the shear history and shear rate, generated during propagation of grout. Therefore, in the design of grouting, the estimation of grout spread should be designed considering the prevailing shear rate at the grout front for the required spread. Moreover, when the yield stress and viscosity of grout are measured at the laboratory, using the Bingham model fitting, different range of shear rates will lead to different values of the estimated rheological properties. Although analytical solutions for velocity and shear rate are available for one-dimensional geometries, a different approach must be used for two-dimensional radial Bingham fluid flow. This is due to the non-linear pressure and velocity distribution leading to a change of the plug thickness along the radial distance. In this work, a nomogram is developed based on a 'semi-analytical' approach to estimate the shear rate at the grout front. The relevant design parameters can be obtained from the nomogram for the corresponding relative spread of the grout, and it can therefore be used as a simple design tool for cement grouting.

SAMMANFATTNING

Under de senaste decennierna, har viktig teoretisk utveckling uppnåtts om spridningen av injekteringsbruk i endimensionella och två dimensionella geometrier, som kan öka kvaliteten i utförandet och minskar onödig spridning av bruket. Flytspänningen av bruket är en förutsättning för att uppskatta spridning. På grund av sin tixotrop natur, är flytspänning beroende av skjuvningshistorien och skjuvhastigheten, som är alstrat under spridning av bruket. Vid dimensionering av injektering tiden, bör därför uppskattningen av spridningen utförmas med avseende på en bestämd skjuvhastighet av bruket för att önskad spridning. Dessutom, när flytspänning och viskositeten mäts på laboratoriet, med en Bingham anpassning och olika intervall av skjuvhastigheter leder detta till olika värden av de reologiska egenskaperna. Även om analytisk lösningar för hastighet och skjuvhastighet är tillgängliga för en dimensionell geometri, måste en annan metod användas för tvådimensionell radiell Bingham flöde. I detta arbete en icke dimensions nomogram har utvecklats baserat på en "semi-analytiska" metod för att uppskatta skjuvhastigheten av bruket fram. Relaterad dimensionering parameter kan erhållas från nomogrammet för motsvarande relativa spridningen av injekteringsbruk, och det kan användas som ett enkelt dimensionering verktyg för injektering.

INTRODUCTION

Grouting is a significant part of tunnelling and underground constructions in rock. It is performed in order to decrease the lowering down of the ground water level. In urban areas, the environmental regulation is rather strict in Scandinavia and the typical allowable limit for water in flow is 0.5 - 30 l/min/ 100 m tunnel (Grov and Woldmo). This implies that water sealing is required and results in a significant cost.

Cementitious materials are most commonly used grouting material due to its relatively lower cost. Grout is injected inside the bore holes and a typical water to cement ratio 0.6-1.0 is used. The current grouting design, used in Sweden, is based on the estimation of the spread of grout under a constant pressure. To obtain a proper water sealing, a certain spread of grout must be achieved. The grouting time is designed based on the estimated spread of grout.

The rheological properties, yield stress and viscosity of grout are the major governing factors to design the spread of grout. Yield stress influences the relationship between pressure and flow. When grout advances inside rock fractures, the shear stress decreases and when the wall shear stress reaches the yield stress; the flow stops. Viscosity is the relationship between the shear stress, emerged due to the applied pressure and prevailing shear rate of the material. The viscosity can be changed due to the change of temperature (Banfill 2006).

The rheology of cement grout is considered complex due to the thixotropic nature and hydration of grout. Thixotropy implies that the rheological properties depend on the shear history of the material. When the material is under shear or applied pressure, structural break down is taken place. This is a process of breaking certain linkages between cement particles. On the other hand, when the material is at rest, structural build up is taken place (Møller et al. 2006). Therefore, the yield stress and viscosity of grout would be a subject to thixotropic behaviour and result in different values depending on whether it is at the 'broken-down' or 'build-up' state. The thixotropic behaviour and effect of hydration of cement grout is shown in Figure 1. Here the down curve resembles the 'broken-down' state. In contrast, the up curve was measured after the grout was at rest for a certain period and therefore, resembles the 'build-up' state.

The yield stress and viscosity of grouts are typically measured in a laboratory using rheometers. A range of shear stress is applied on a sample grout and the corresponding torque is measured. The prevailing shear rate can be calculated from the associated torque. The shear stress vs. shear rate curve is generally fitted to and described using different rheological models, as shown in Figure 2. The Herschel-Bulkley model can reproduce the non-Newtonian shear thinning behaviour and includes a yield stress. The Bingham model comprises a linear relationship between the shear stress and shear rate. The gradient of the linear fit is the viscosity and the interception at the y axis is determined as the yield stress. Since the geometry of the rock fractures are not fully known, the Bingham model is widely used to determine the rheology of cement grout, due to its simplicity. As shown in Figure 2, the linear fit of the Bingham model is highly dependent on the range of the shear rate and different ranges will result in variable values of yield stress and viscosity (Håkansson 1993). However, as of today, no guideline is available on what shear rate range to be used for cement grout when the Bingham model is used (Rahman et al. 2015).

The current grouting practice in Sweden is based on the estimation of grout spread inside rock fractures at constant pressure. The yield stress and viscosity are used as an input to estimate the grouting time. State of the art grouting theories allows the real time estimation of the grout spread, provided that the rheological properties are measured in real time. However, the current practice is based on the measurement of the rheological properties of a trial mix, using a rheometer before grouting. The shear stress vs. shear rate curve is fitted using a Bingham model and the determined yield stress and viscosity is used to estimate the grouting time. As shown in recent literatures (Rahman et al. 2017), the yield stress of cement grout depends on the prevailing shear rate and increases due to thixotropy when the shear rate is very low. This implies that, if the grouting time is designed for a higher relative spread of grout, the static yield stress value should be used. Even though this is not the typical case, the designer should be concerned regarding the prevailing shear rate at the grout front for the required spread of grout. Therefore, there is a strong need to define the shear rate range that is to be used while fitting the rheological models to rheology data. In addition, the shear rate should be estimated during the design process of the grouting time to ensure a 'broken-down' state of the cement grout.

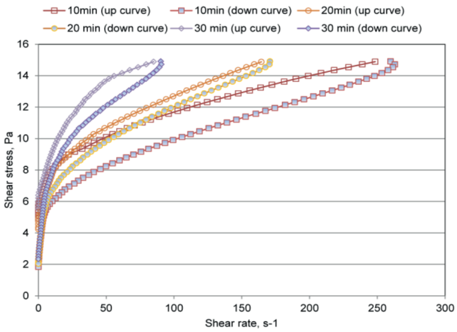

Figure 1 Thixotropic behaviour of cement grout and the effect of hydration

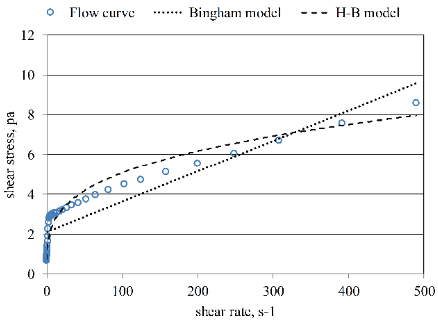

Figure 2 Use of different rheological models to estimate the yield stress and visocity of grout

The purpose of this work is to present a nomogram which can be used to estimate the grouting time, velocity and shear rate of the grout front at the required relative spread of grout. The advantage of using the nomogram is that it is independent of the geometry and rheological properties, and the above mentioned parameters can be estimated from known input. The author's anticipate than it can be used as a simple design tool.

Design of cement grouting

In Sweden, grouting design is based on the so called 'Real Time Grouting Control (RTGC)' concept. The theory assumes the flow of grout as a Bingham flow, consisting of a yield stress and viscosity. The assumption of Bingham flow implies that when the cement grout flows, a stiff region is formed at the center of the velocity profile which flows as a stiff plug/core.

Analytical solutions for estimating grout spread under constant pressure were presented by Gustafson et al. (2013). The grout spread is calculated with respect to two non-dimensional parameters, the relative grout spread (I_D) and the relative grouting time (t_D). The advantage of using non-dimensional parameters is that the relative spread of grout becomes independent of the applied pressure and the rheological properties and can thus be used for wider applications. The relative grouting time, t_D, is defined as

$$t_D = \frac{t}{t_0} \tag{1}$$

Where t is the actual time span and t_0 is the characteristic grouting time defined by

$$t_0 = \frac{6\mu_g \Delta P}{(\tau_0)^2} \tag{2}$$

Where τ_0 is the yield stress and μ_g is the plastic viscosity of grout. It should be noted that the closed-form solutions for relative time as a function of relative spread, $t_D = f(I_D)$, are available only for 1D flow and the analytical solution is not solved explicitly for 2D. In order to address this, approximate solutions were introduced by Gustafson and Stille (2005) for channel and radial flow, given as

$$I_D \approx \sqrt{\frac{t_D^2}{4(\delta + t_D)^2} + \frac{2t_D}{\delta + t_D}} - \frac{t_D}{2(\delta + t_D)} \tag{3}$$

where $\delta = 0.6$ for a 1D channel and $\delta = 3$ for a 2D radial flow.

The wall shear rate can be calculated from the Bingham model definition and after further re-arrangement can be shown as

$$\dot{\gamma}_W = \frac{\tau_0}{\mu_b}\left(\frac{1}{\xi} - 1\right) \tag{4}$$

Where, ξ is the relative plug thickness inside the stiff plug of the velocity profile. As can be seen in equation (4), for a certain relative plug thickness, the shear rate will remain same for a 1 D or 2D flow, however, they will take place at different times. For 1D pipe or channel flow, the plug thickness changes linearly with the change of pressure. However, for a 2D radial flow, a numerical approach must be used. This is due to the fact that for a 2 D radial flow, the plug thickness is a function of the radius, r, which changes non-linearly with pressure.

Bingham Number (B_N), non-dimensional velocity ($\frac{dI_D}{dt_D}$) and plug thickness

The yield stress can be determined using the force balance assumption, i.e., $\tau_0 = {}^{b\Delta P}\!/_{2I}$ where τ_0 is the yield stress, b fracture aperture, ΔP is the differential pressure over the spread of grout, I.

To simplify the determination of the velocity and plug thickness of the grout front for two dimensional flows, a dimensionless parameter, the Bingham Number, B_N was used and can be shown as

$$B_N = \frac{b\tau_0}{\mu_B \overline{v_z}} \tag{5}$$

where, b is the thickness of the radial disk and $\overline{v_z}$ is the mean velocity of the grout front. As shown in equation 5, the Bingham Number is the governing factor for determining the mean velocity $\overline{v_z}$. For a two dimensional flow, $\overline{v_z}$ is a function of the radial distance; therefore, Bingham Number will change accordingly.

To determine the Bingham number and the velocity for two dimensional flow, the analytical expression for the derivative $\frac{dI_D}{dt_D}$ is required. Since I_D is the relative penetration of grout in a relative time, t_D ; $\frac{dI_D}{dt_D}$ can be defined as the dimensionless velocity. $\frac{dI_D}{dt_D}$ is a function of relative time, t_D and can be shown as

$$\frac{dI_D}{dt_D} = \frac{t_D}{2(\delta + t_D)^2} - \frac{1}{2(\delta + t_D)} - \frac{\dfrac{3t_D}{2(\delta + t_D)^2} - \dfrac{2}{(\delta + t_D)} + \dfrac{t_D^2}{2(\delta + t_D)^3}}{2\sqrt{\dfrac{2t_D}{(\delta + t_D)} + \dfrac{t_D^2}{4(\delta + t_D)^2}}} \quad (6)$$

To estimate the velocity, the corresponding $\frac{dI_D}{dt_D}$ has to be used and the Bingham number at the grout front can be given by

$$B_N = \frac{12}{dI_D/dt_D} \quad (7)$$

Since the non-dimensional velocity can be calculated using equation (6), the expression for the true mean velocity for two-dimensional flow can be shown as

$$v = \frac{\tau_0 b}{12\mu_B} \frac{dI_D}{dt_D} \quad (8)$$

The relative plug thickness of a 2D radial flow can be shown as

$$\xi_{radial} = 2\sqrt{\frac{1}{B_N} + \frac{1}{4}} \cos\left(\frac{\pi}{3} + \frac{1}{3} \arccos\left(\frac{1}{\left(\frac{1}{B_N} + \frac{1}{4} \right)^{1.5}} \right) \right) \quad (9)$$

Proposed design procedure following the RTGC theory

General

Based on the theory described earlier, the following steps are suggested in the design process to determine the Bingham number, plug thickness, velocity and shear rate. The procedure is based on a horizontal fracture with 2D radial flow.

Input

1. The yield stress, τ_0, and viscosity, μ_B, of the grout are known 'a-priori' from a linear Bingham model curve-fit to rheometric data.

2. The fracture aperture, b, is determined from e.g. water pressure tests.
3. The required grout spread, I , is specified based on the distance between the boreholes, e.g. at least half of the distance between the holes.
4. The constant pumping pressure, ΔP , is specified beforehand.

Calculations following the RTGC theory

5. The characteristic grouting time, is calculated using equation (2).
6. The maximum spread of grout, $I_{\max}$, is calculated by $\mathrm{I}_{\max} = \dfrac{b\Delta P}{2\tau_0}$ and relative grout spread is given by $I_D = \dfrac{I}{I_{\max}}$.
7. The relative grout spread is determined from equation (3).
8. The designed grouting time, t , is determined from the relative grouting time, where $t = t_D * t_0$.

Estimation of Bingham number and plug thickness

9. The Bingham number is determined from equation (6) and (7).
10. The relative plug thickness is determined from equations (9) using the corresponding Bingham number for radial flow.

Output

11. The mean velocity, v, is determined using equation (8).
12. The wall shear rate is determined using equation (4).

Graphical method for the estimation of shear rate

A nomogram to estimate the velocity, plug thickness and shear rate at grout front is shown in Figure 4. The advantage of using the proposed nomogram is that it is based on non-dimensional parameters and is therefore independent of the rheological properties, fracture aperture and applied constant pressure. The nomogram can be used to estimate the shear rate at the grout front during the preliminary design of the grouting time. Therefore, the grouting time can be designed such a way that the grout front at the desired spread would be sufficiently sheared to remain at a broken down state.

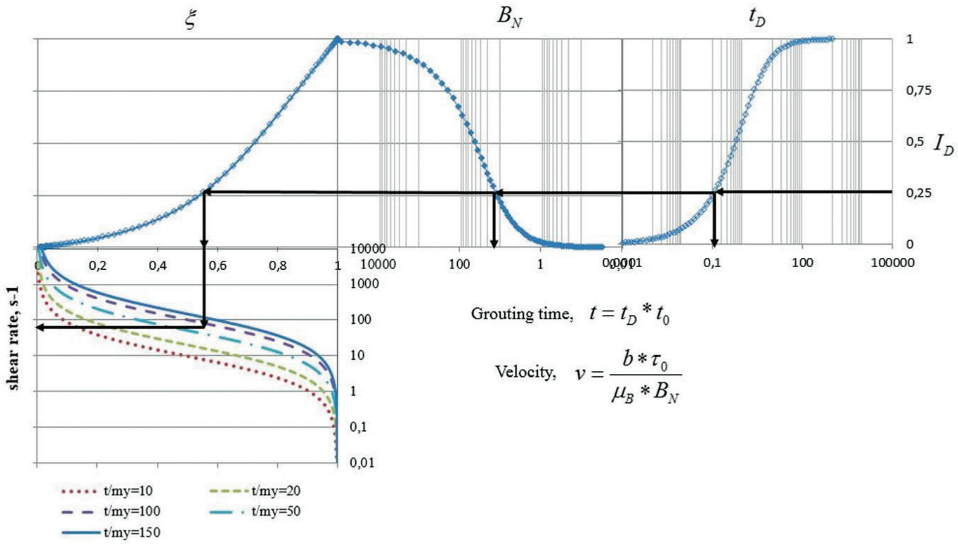

Figure 4 Nomogram for the estimation of velocity, plug thickness and shear rate

The principle procedure for determining the plug thickness, velocity and shear rate using the nomogram is divided into the following steps:

1. The relative spread is determined for the required grout spread, grout properties, aperture and constant pressure, which will lead to the time required to achieve the desired spread of grout by using the characteristic time.
2. The Bingham number is obtained using the relative spread vs Bingham number curve, for the relative grout spread values from step 1. The real mean velocity is determined using equation (8).
3. The relative plug thickness is determined from Figure 4 for the relative grout spread value from step 1.
4. The wall shear rate is determined from the relative plug thickness and for the corresponding τ_0/μ ratio.

CONCLUSION

In this work, a nomogram is presented which can be used as a simple tool to estimate the velocity, plug thickness and shear rate at the grout front. This shear rate should be used while applying a Bingham fit to rheometer data to determine the yield stress and viscosity of the grout. In addition, it should be checked that the estimated shear rate is sufficient to keep the grout in a 'broken-down ' state and confirm the 'dynamic' state of yield stress.

The future goal would be to implement the nomogram and RTGC calculation steps in an in-line industrial rheometer, which will enable the real time estimation of spread of grout and shear rate, based on the real time estimation of the rheological properties of grout. As a result, unnecessary spread of grout can be avoided and rheological properties, according to the design specification, can be ensured.

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