CALCULATION TOOL FOR HYDRAULIC CHARACTERIZATION DURING GROUTING DESIGN

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SUMMARY

An understanding of the fracture aperture distribution facilitates design of grouting measures in crystalline rock masses, this since both the penetrability (ability of grout to enter the fractures) and penetration length is linked to the aperture. This is considered in a design process for rock grouting that has been developed at Chalmers University of Technology [1]. The process suggests that fracture aperture distribution can be estimated based on transmissivity data from hydraulic tests combined with fracture data from boreholes. However, hydraulic tests seldom contain information that can be linked to individual fractures and measurement data need to be further processed using probability distributions. To resemble a rock mass where few fractures dominate the flow Fransson [2] suggested the use of a Pareto distribution and combinatorics to estimate transmissivity of individual fractures.

A freely available computational tool for the statistical analyses based on this concept with Pareto distributed fractures was developed in [3]. The purpose of the tool is to process field data and create probability distributions that can be used as input to grouting design and approximate tunnel leakage estimates. The methodology has been developed with tunnel data, which sofar has been the main application. For dam and open cut grouting (see e.g. [4]), with higher proportions of surficial rock the validity of the connectivity assumptions may need to be investigated. This paper briefly present the design process and calculation tool in its context using real datasets from a Swedish tunneling project, to provide advice on usage and to give examples of pitfalls in data collection.

INTRODUCTION

Strict inflow demands in rock construction projects often lead to a need to seal rock fractures with small apertures. This, in turn, requires a good understanding of the type of grout that can penetrate the fractures, the proportion of fractures that can be sealed with the chosen grouting methodology, and what inflow reduction it may lead to. These issues are considered in a design process for rock grouting that was developed at Chalmers University of Technology [1]. The process is based on the assumption that there are inflow demands that shall be fulfilled and that the groundwater flow can be characterized by flow in individual fractures of the rock mass. The work stages included in the process are presented in Figure 1.

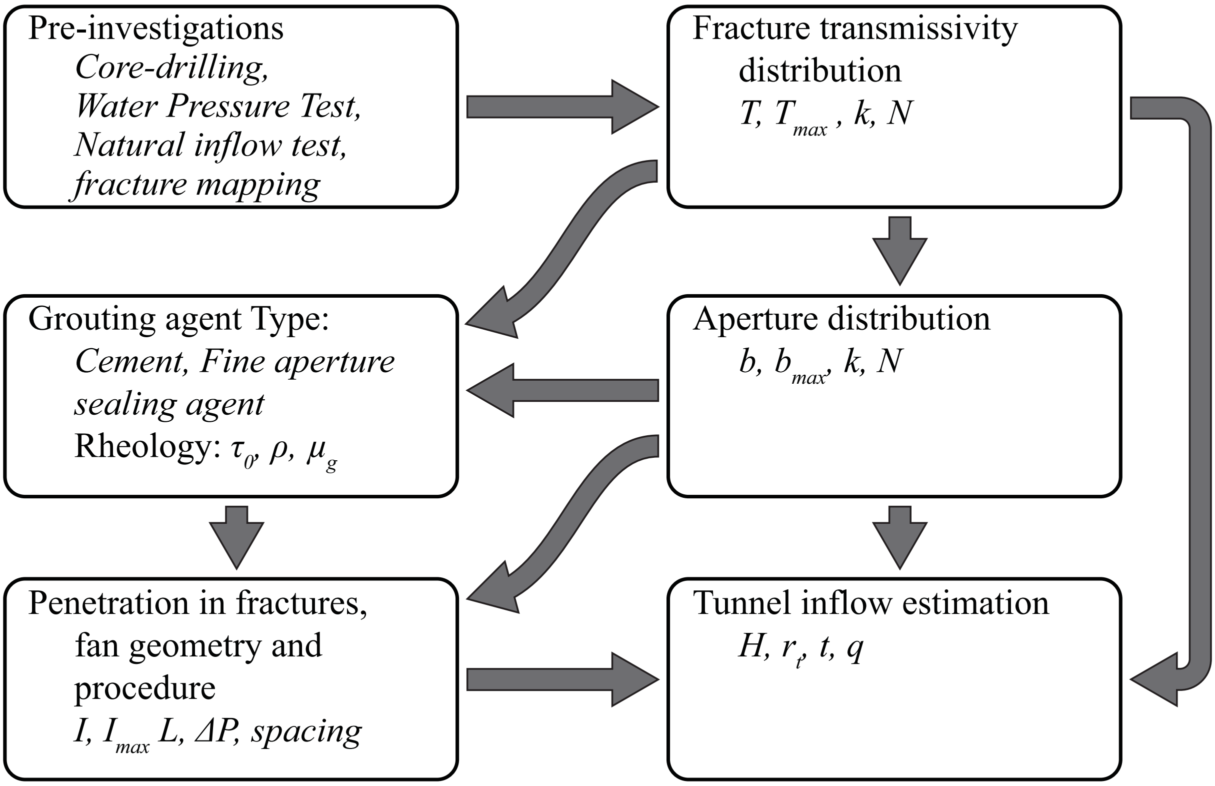


Figure 1: Design process for grouting. Modified from [5].

The first stage is the collection of appropriate input data for the characterization of fractures. The subsequent two stages are concerned with creating fracture transmissivity distributions and fracture aperture distributions, respectively. These distributions are based on data from hydraulic section tests and fracture data from boreholes. However, as a result of interval lengths and measurement limits, these hydraulic tests seldom contain information that can be linked to individual fractures. Measurement data must therefore be processed with statistical distributions and the design methodology proposes the use of the Pareto distribution. A computational tool presented in [3] facilitates the statistical analyses included in these two stages. The output from the computational tool can be used in the subsequent stages of the design process; assessing tunnel inflow, choosing appropriate grouting agent, grout properties, and designing grouting fan geometry and grouting procedure.

The aim of this paper is to present the calculation tool in the design process context using a real dataset from a Swedish tunneling project, to provide advice on usage and to give examples of pitfalls in data collection.

THEORETICAL BACKGROUND

Input data

The parameter hydraulic aperture and the distribution of hydraulic apertures in the rock mass is of central importance in the design process for grouting (Figure 1). In order to estimate the aperture distribution of a specific rock volume two main input datasets are needed:

1. The number of fractures along intervals of an investigation borehole, and
2. Interval transmissivities evaluated from hydraulic tests along the same borehole.

These datasets are collected mainly through water pressure tests in 3 or 5 m long sections in cored boreholes with mapped cores.

Ideally, core mapping protocols, outlining the position of each fracture along the core, is linked directly to the boundaries of each hydraulic test section. Fracture mapping listing the number of fractures for each meter of the core can also be used and summed to the appropriate section length. However, care must be taken to ensure that hydraulic test sections and the fracture number sections align.

The design process uses the transmissivity, T [m^2/s], which is proportional to the hydraulic conductivity, to express the amount of water that can be transported through a fracture. The transmissivity of a borehole interval is calculated using flow and pressure data of a predetermined length in a borehole with known dimensions, for example using the Moye equation (Eq. 1) e.g. [5] or the specific capacity (Eq. 2) [6]:

$$T = \frac{Q\rho_w g}{2\pi \cdot dp}\left[1 + \ln\left(\frac{L}{2r_w}\right)\right] \qquad \textit{Eq. 1}$$

$$T \approx \frac{Q}{\Delta h} \qquad \textit{Eq. 2}$$

Where Q [m^3/s] is the flow in the end of the test period, dp [Pa] is the constant injection pressure, ρ_w [kg/m^3] is the density of water, g [m/s^2] is the gravitational constant, r_w [m] is the borehole radius, L [m] is the section length and Δh is [m] the change in the hydraulic head during the test.

The hydraulic test data used for these evaluations includes assumptions of the rock being possible to describe as a homogenous continuum and that the test reaches stationary conditions, i.e. that flow and pressure conditions are constant.

The hydraulic aperture b_{hyd} [m] of a fracture can be linked to its transmissivity, T, using the cubic law [7] (Eq. 3) μ_w [Pa s] is the viscosity of water.

$$b_{hyd} = \sqrt[3]{T \cdot \frac{12\mu_w}{\rho_w g}} \qquad \textit{Eq. 3}$$

The probability distribution

Input data from hydraulic tests can seldom be translated directly into a reliable fracture aperture distribution. This since hydraulic data often are aggregated due to data being collected in sections and censored due to the equipment having measurement and detection limits. However, the use of probability distributions can provide a probabilistic description of all individual fractures from the input data. The probability distribution suggested in the design process and used in the computational tool is the Pareto distribution. The distribution function for the Pareto distribution in the context of transmissivity data (Eq. 4) is based on a maximum fracture transmissivity value T_{max}, estimated for the most conductive fracture in the tested intervals [8].

$$p(T < T_n) = 1 - \frac{(T_{\max}/T_n)^k}{N+1} \qquad \textit{Eq. 4}$$

Here $P(T<T_n)$ is the probability that the transmissivity of an arbitrary fracture is less than the transmissivity of a fracture T_n in a sample of N fractures sorted according to transmissivity magnitude. The k parameter given in Eq. 4 is the Pareto distribution parameter. In the computational tool the k-value is evaluated as the slope of a straight line in a plot of log(1 – $P(T<T_n)$ versus log(T_n).

The value of the k parameter describes the relation between the most conductive fracture and the total transmissivity of the borehole. A $k < ½$ describes that the most conductive fracture is in the same magnitude as the interval transmissivity, whereas larger k-values describes less spread in fracture transmissivity between fractures, although the most conductive fracture is still dominating the total interval transmissivity [5].

The input data for the determining the Pareto distribution of a data set is typically evaluated based on fixed-interval transmissivity. This is modified with additional assumptions of statistical nature to estimate the individual contribution of each fracture to the interval transmissivity. The method used is based on combinatorics, e.g. described by [2]. The fracture transmissivity distribution is then translated into a distribution of hydraulic apertures by using the cubic law (Eq. 3) (both represented by a few large values and several small).

Model assumptions

The calculations referred to in the previous section include some simplifications and model assumptions that a user of the calculation tool need to be aware of.

The use of the cubic law implies that individual fractures are simplified as 2D conductors between smooth parallel plates, see Figure 2. In reality fractures have variable aperture and contact areas. The simplification of smooth parallel plates render the smallest errors for large aperture fractures (see eg. [9-11]) and the notion that the largest fracture dominate the flow supports the use of the cubic law.

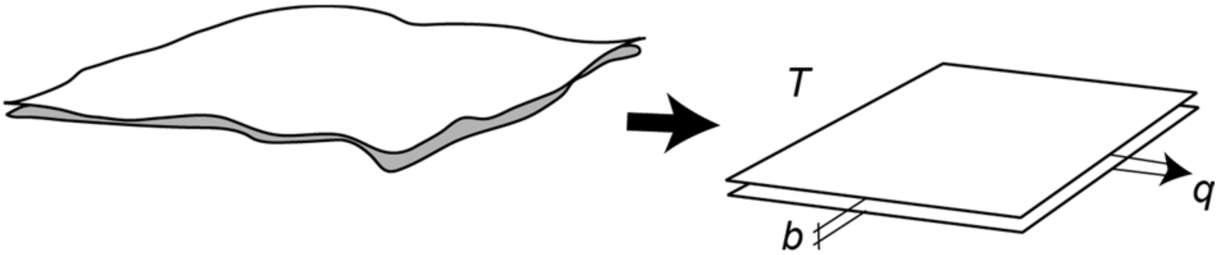


Figure 2. A fracture simplified as a 2D-conductor of groundwater, where the flow q is proportional to a transmissivity T and a hydraulic aperture b. Modified from [4].

In the construction of a fracture aperture distribution the largest fracture of each section is given a flowrate in the same order of magnitude as the total flow in the section [2]. The smaller fractures of a section share the remaining flow in the section. Moreover, the analysis assumes that the hydraulic properties of fractures are statistically independent and not affected by nearby fractures [2]. This approach means that regardless if transmissivity is measured across each fracture, across sections or the entire borehole, the total transmissivity is assumed to be the same. For fracture zones the flow in individual fractures can hardly be regarded as independent, therefore setting the number of fractures to 1 in such sections can be advisable. This simplification is also advised as subject for testing in a sensitivity analysis.

Addressing fracture connectivity is of importance when conducting tunnel inflow estimations. A study in [12] found the design process to overestimate inflows in a tunnel with a poorly connected fracture network and underestimate inflows in a well-connected fracture network. Also, dividing the rock mass into hydraulic domains (e.g. separating deformation zones and surrounding rock mass) and evaluate the domains separately in the design process might be advisable.

Finally, the evaluated interval transmissivity from hydraulic tests at stationary conditions represents a local transmissivity in close vicinity of the borehole [13]. As the borehole may have intersected a part of the fracture that has a locally smaller aperture than the effective hydraulic aperture of the fracture, it is possible that the effective fracture aperture is larger than the evaluated value (which could be of importance during inflow predictions, which represents groundwater flow in a larger scale).

Subsequent steps in the design process

The generated aperture distribution is used in the subsequent stages in the design process for grouting [1], Figure 1. These include estimating leakage to a tunnel, selecting grouting agent and estimating grout penetration in the simulated fracture apertures. A basic method for estimating inflow to a tunnel, suggested by e.g. [5] is given in Eq. 5. It is based on the model assumption that flow in fractures are independent and total inflow can therefore be calculated from the aperture of each fracture in the simulated population. The sum of all fracture transmissivities corresponds to the total transmissivity T_{tot} in Eq. 5. Further, q = tunnel inflow, L = length of tunnel section, H = hydraulic head, t = thickness of grouted zone around tunnel ξ = skin factor.

$$q = \frac{2\pi \cdot T_{tot}/L \cdot H}{\ln\left(\frac{2H}{r_t}\right) + \left(\frac{T_{tot}}{T_{inj}} - 1\right) \cdot \ln\left(1 + \frac{t}{r_t}\right) + \xi} \qquad \textit{Eq. 5}$$

The transmissivity of the grouted zone, T_{inj}, is the result from removing the largest transmissivities from the sum T_{tot}, down to apertures of say 100 µm (3*d_{95} of common grouting cements, which can be used as a rule of thumb for penetrability, [5, 14, 15]). This corresponds to removing the flow from the largest fractures that is reasonable to seal fully using common cement grout. The inflow q can then be compared to inflow requirements to see whether the requirements can be met using standard procedure, or if a fine sealing agent is needed. Working the other way around, calculating what aperture that corresponds to the inflow requirements, b_{crit}, and designing a grouting procedure that meets this could of course also be done.

When the smallest fracture that needs to be sealed is estimated, the rate of penetration in this fracture can be calculated for different grout recipes and grout pressure and time. This can be used as input in selecting the number of boreholes in a grout fan. See further in e.g. [5, 16].

ADVICE ON DATA COLLECTION

It is, as always, recommended that the designer is involved in both the design of the test program and on site during the execution in order to get a better understanding of the different uncertainties that is introduced for each test method and to inform the contractor what the scope of the tests are.

To collect fracture and hydraulic data with a high level of detail in resolution regarding measurement limits it is suggested that core drilling combined with water pressure test in maximum three meter sections is used.

Core drilling is preferred since it produces a smooth borehole wall in comparison to a hammer drilled hole. A smooth borehole wall will significantly reduce the risk of leakage between the packers and the wall during water pressure tests. A smooth borehole wall is also recommended if the borehole should be filmed or photographed with a borehole camera which can improve the interpretation from core log.

Water pressure tests should be performed with digital piezometers in the test section that measure the pressure change in real-time. It is also recommended that digital piezometers is used above and below the packers in order to identify if there is a leakage passed the packers. The water flow should be logged digitally in real-time and the measurement limits should be designed according to the smallest fracture that needs to be grouted. A section length of 3 m is suitable for practical reasons. No exact minimum number of sections can be given, but a core drilling program aiming at studying a couple of critical sections at tunnel depth will suffice.

CALCULATION TOOL

The calculation tool is implemented in Microsoft Excel, for availability and enabling the user to update and modify the code without extensive programming experience. The tool is released under the MIT license, which allows for any type of usage under the condition that the original authors are attributed, i.e. citing ref [3]. This is free of charge, and no warranties are provided. The tool and its manual are written in Swedish, and it is strongly advised that a user reads the manual.

The tool has a run-sheet (Figure 3) with a number of options. *Konditionera data* (Data conditioning) directs to a sheet where input data is typed or pasted. The data is then saved as a text file in a standardized format. A set of radio-buttons tells the program if the data contains transmissivities or conductivities, or if these are to be calculated according to Moye (Eq. 1), or as specific capacity (Eq. 2). *Utför Beräkning* (Conduct Calculation) prompts for that text file and fits a Pareto distribution to the dataset, and simulates fracture apertures from that distribution. Results are presented a summary report (Figure 4) that can be saved as a pdf-file (*Spara rapport*-button).

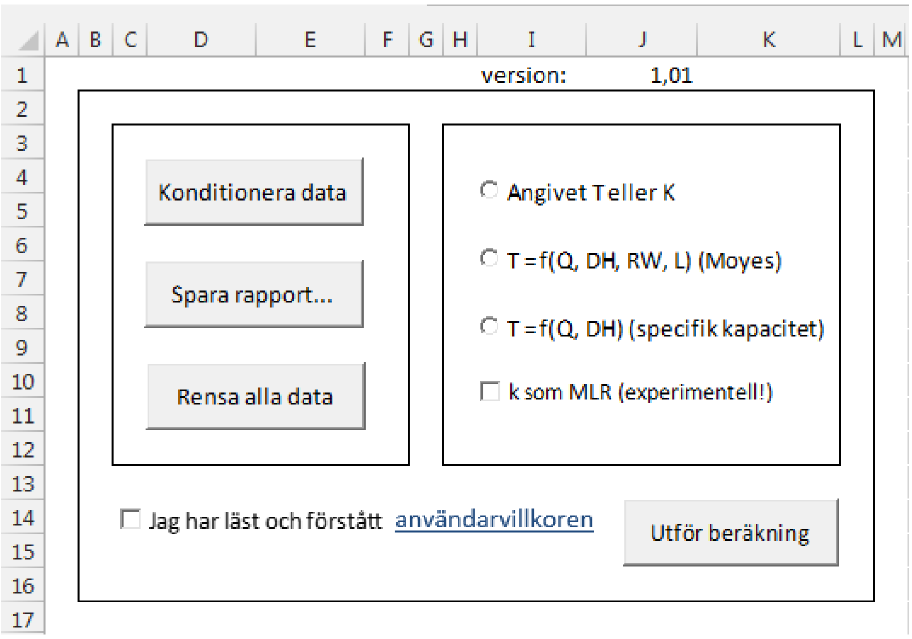


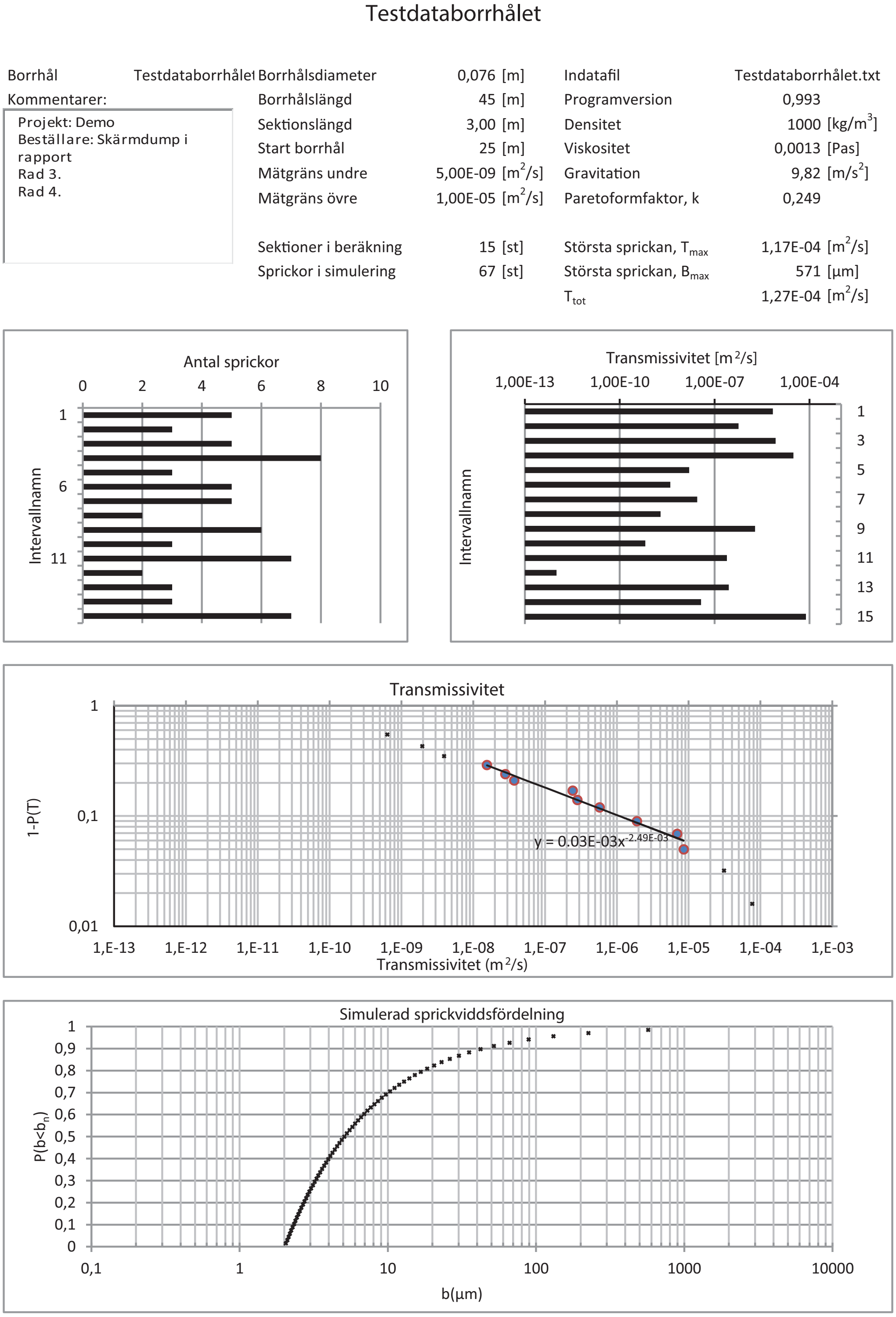
Figure 3: The run-sheet interface

Data conditioning

Recalculating the input data into common units is referred to as data conditioning. A sheet in the excel tool lets the user input data of hydraulic permeability either in terms of flow and overpressure, as conductivity or as transmissivity. The borehole length can be included as a fixed interval length, intervals of individual lengths or as upper and lower section of all intervals. Supplemented by the number of fractures this is typed or pasted (as numbers) into the main body of the sheet, each column is labeled with type of content and unit using drop-down menus. Some additional data like gravity, density and borehole diameter is given before the data is converted and saved as a text file that the program reads for running the simulation.

Results report

A click on the *Utför Beräkning* (Conduct Calculation) button prompts for the conditioned text file and runs the calculation. After the calculation has finished a results report is presented to the user, see Figure 4. This together with the conditioned input text-file accounts for traceability between different runs. The data presented can also be accessed in the sheets for further treatment, such as inflow estimations and determining the minimum aperture that needs to be sealed in order to meet a certain inflow limit.



Testdataborrhålet

Borrhål	Testdataborrhålet	Borrhålsdiameter	0,076	[m]	Indatafil	Testdataborrhålet.txt	
Kommentarer:		Borrhålslängd	45	[m]	Programversion	0,993	
Projekt: Demo Beställare: Skärmdump i rapport Rad 3. Rad 4.		Sektionslängd	3,00	[m]	Densitet	1000	[kg/m^3]
		Start borrhål	25	[m]	Viskositet	0,0013	[Pas]
		Mätgräns undre	5,00E-09	[m^2/s]	Gravitation	9,82	[m/s^2]
		Mätgräns övre	1,00E-05	[m^2/s]	Paretoformfaktor, k	0,249	
		Sektioner i beräkning	15	[st]	Största sprickan, T_{max}	1,17E-04	[m^2/s]
		Sprickor i simulering	67	[st]	Största sprickan, B_{max}	571	[µm]
					T_{tot}	1,27E-04	[m^2/s]

Figure 4: Output data report generated by the tool. From the top: Description of the borehole with the number of fractures and interval transmissivities. Cumulative distribution function diagram with interval transmissivities and evaluated Pareto distribution. Simulated hydraulic aperture distribution.

CASE STUDY – THE VÄSTLÄNKEN PROJECT

Västlänken, i.e. *the west link*, is a planned railway tunnel under Gothenburg which includes three commuter train stations. The planned tunnel length is six km where four km of tunnels are to be constructed in crystalline rock. The construction is planned to start in 2017-2018. The rock in the area mainly consists of gneiss, often heavily foliated. Fractures mainly occur in three sets, N-S with dip 35-45° (parallel to foliation) E-W steeply dipping, and a S-N set with roughly the same dip as the N-S set. The rock is sparsely fractured (cf. Figure 5) with low amounts of water.

Figure 5: Photo of a quite typical core box from the boreholes included in the analysis.

A number of hydraulic tests have been carried out during different planning stages of the tunnel project. This has enabled a comparison between different datasets in terms of suitability for usage in the design process for rock grouting. Here we present an early dataset collected during initial works aiming at describing general hydraulic properties of the rock mass, and a more recent one collected as input to detailed grouting design aiming at a lower measurement limit. The datasets were collected from the same boreholes. In this paper both datasets are run in the calculation tool and compared to highlight how data can be used when collected properly for grouting design and help in distinguishing a dataset that does not meet standards in these terms.

The initial dataset is represented by input data from water pressure tests carried out in three cored boreholes using a pump, flow meter and pressure meter at ground level outside the borehole. The revisited dataset is from an additional set of water pressures tests using equipment with higher flow resolution in the same boreholes. Both test rounds were conducted in three meter long sections. The initial test round used three overpressure steps (0.3 MPa – 0.5 MPa – 0.3 MPa) with the flow being measured for five minutes per step. The revisited tests used one overpressure step (0.3 MPa) and the flow was measured until stationary conditions were reached, defined as when the change of flowrate was less than 5% per minute, but at least 10 minutes.

The revised procedure sought to mitigate problems that arose when attempting grouting design using data collected in the initial testing round. Such problems were: not stationary flow conditions in some cases, and in some cases backflow when lowering the pressure from 0.5 MPa to 0.3 MPa. Also pressure measurement was installed in the test section rather than on the ground surface, which also improves the results. The most important difference between the two test rounds were the measurement limits of the flow logger. The lower measurement limit for the initial test was unknown, but a detection limit was set to 0.1 L/min and the upper limit was 36

L/min. The lower measurement limit for the revisited test was set to 0.005 L/min and the upper 100 L/min (NB: the setup had more than one flow meter).

Figure 6 presents section transmissivities for both datasets, and which sections that are within measurement limits. The slope of the trend lines present in the figure corresponds to the Pareto distribution parameter, *k*. The total flow measured in the boreholes is fully comparable in both datasets, $T_{tot} = 4 \cdot 10^{-6}$ and $5 \cdot 10^{-6}$ m^2/s. This difference originates from the initial dataset having a couple more tested sections in the surficial rock. The simulation presented in Figure 7 represents the total flow of the borehole distributed among the total number of fractures using the Pareto fit identified in Figure 6.

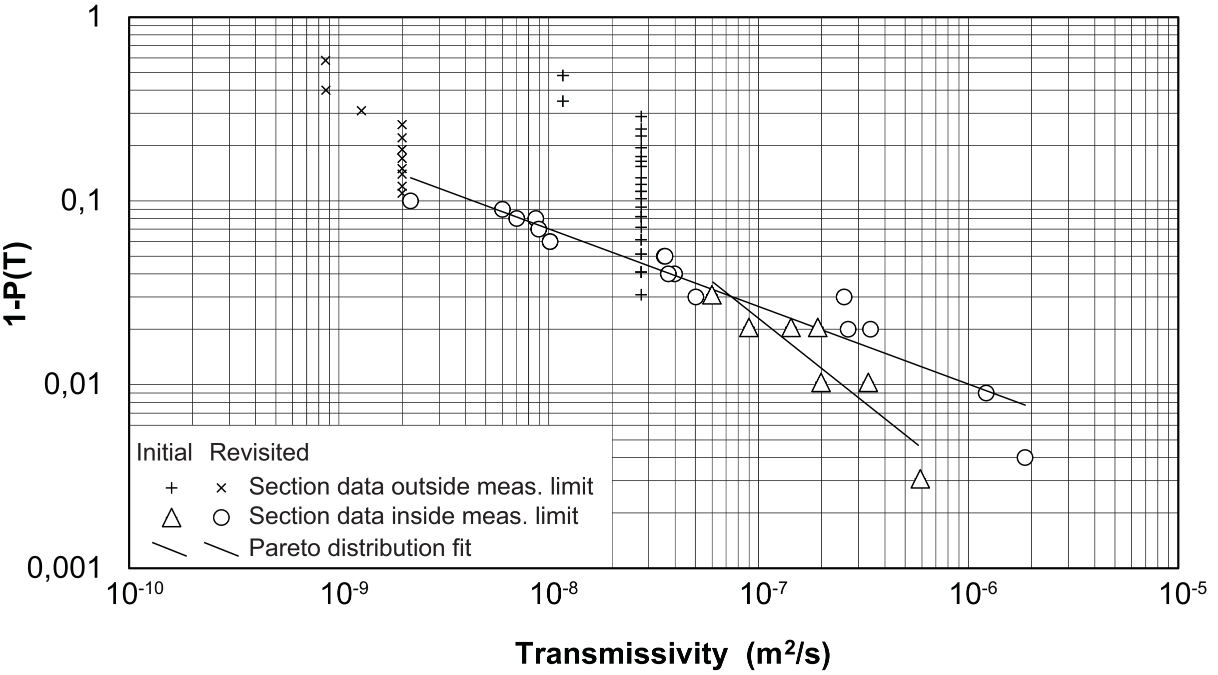


Figure 6: Pareto distributions fitted to the both datasets. The Pareto form factor, k, corresponds to the slope of the straight trend lines. These trend lines are only drawn for data within the measurement limits.

A comparison between the two datasets show differences of importance for the subsequent use of the data in grouting design. The main difference is reflected in the evaluated Pareto coefficient, *k*. The initial dataset gives a *k*-value of 1.1, whereas the revisited set gives a *k*-value of 0.42. When k-values exceed 0.5 it is according to [5] a sign of a highly fractured rock mass (such as in deformation zones) where aperture differences between fractures are less distinct and many fractures contribute to the total flow. The aperture distribution of the initial test thus indicate fairly evenly sized fractures where most fractures have apertures between 20 - 40 μm (>60% of the simulated fractures are in this interval). These hydraulic apertures represents a flow that was smaller than the measurement limit of the equipment (equivalent to 50 μm) and is therefore an estimation based on fewer data points only reflecting the few, large fractures. The revisited test had measurement limits that enabled a measurements of flows coming from fractures with apertures down to around 15 μm. The aperture distribution derived from the new test is a distribution that is typically found in sparsely fractured, crystalline rock, where the spread between fracture apertures is large and a few large fractures dominate the flow (a handful, around 2% of the fractures have hydraulic apertures larger than 50 μm in the distribution simulated from the revisited dataset).

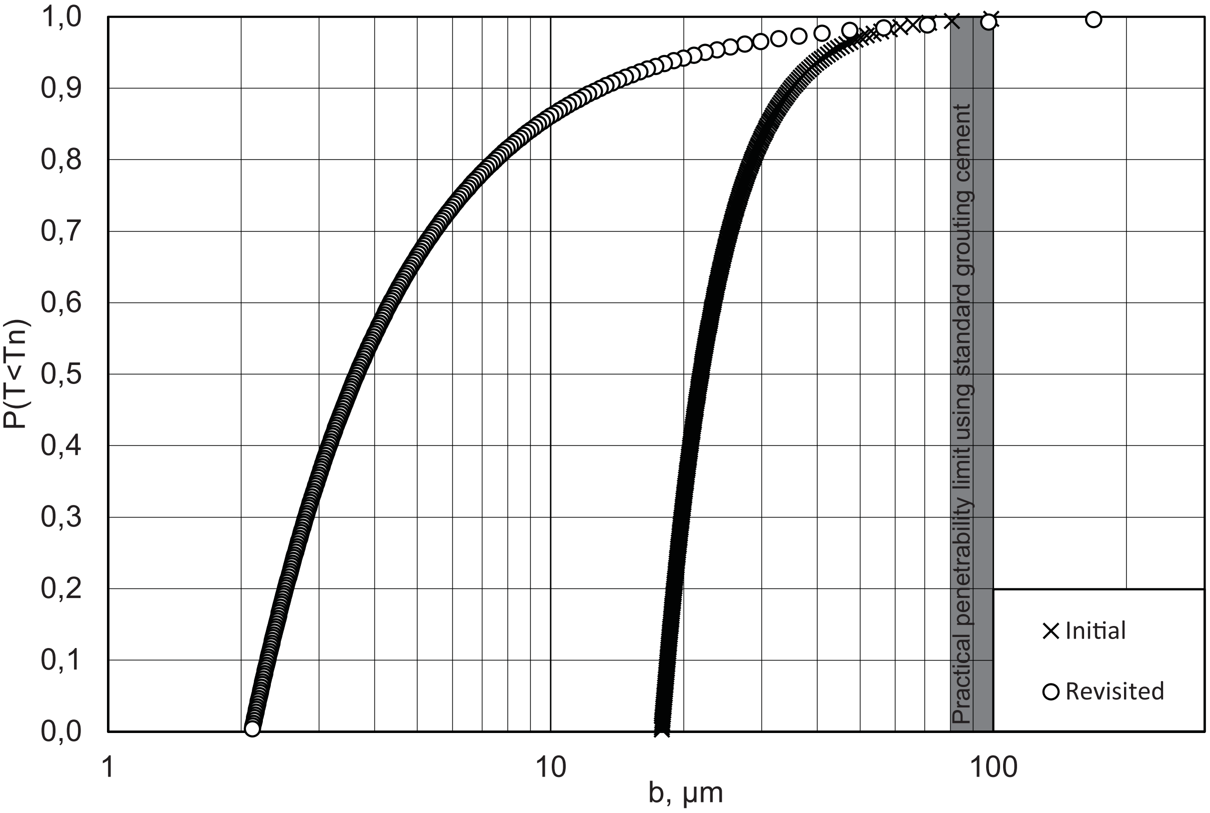


*Figure 7: Simulated fracture apertures from the two Västlänken datasets. The shaded area corresponds to the practical penetration limit using standard grouting cement and the rule of thumb of penetration down to 3*d_{95} of the cement. The sum of flow from fractures below this area corresponds to the inflow after grouting. This residual flow is much higher for the initial dataset.*

A tunnel inflow estimation using the two datasets and Eq. 5 was made (with $H = 30$ m, $r_t = 5$ m, $t = 5$ m). Significant differences can be seen between the datasets using a hypothetical inflow requirement of e.g. 3 L/min*100 m. Inflow to an ungrouted tunnel ($T_{tot}/T_{inj} = 1$ in Eq. 5) is almost the same, 8 L/min*100 m, since the total borehole inflow is the same, differing only in the topmost interval not being tested in the revisited tests. Assuming grouting with standard grouting cement, sealing down to 100 µm reduces the inflow in the revisited dataset to 5 L/min*100 m, while the inflow using the initial dataset only reduces 1%. Thus, the revisited dataset agree with the empiricism that it is possible to achieve a sealing effect in this type of rock mass with standard grouting cement.

Such a conclusion cannot be drawn using the initial dataset. Further, to meet a total inflow of 3 L/min*100 m the revisited dataset indicates that fractures down to 50 µm needs to be sealed, for the initial dataset the corresponding number is less than 20 µm (and 22 µm to meet 5L/min*100 m). Again, the prognosis based on the revisited dataset seems reasonable, and possible to reach using micro- or ultrafine cement grout. It should be noted that the tunnel is not yet constructed and grouted. So there is no correct answers available yet although the revisited dataset corresponds well to the impression of rock quality from the core mapping and required minimum apertures to seal. It should be pointed out again that the rock is the same for both datasets, only the measurements vary. The revisited dataset, as exemplified above, allow for inflow prognoses that are in line with empiricism on which apertures that can be penetrated, and results that can be achieved. The initial dataset does not.

CONCLUSIONS

The computational tool solves a calculation step in a design process for grouting and the output from the tool can be used in subsequent steps of the design process. This includes inflow estimates, needed grout penetrability, grout selection and fan design parameters. However, the design process relies on the use of appropriate input data and care must be taken during the data collection process to ensure that the hydraulic data are suitable for grouting purposes. The comparison of two datasets from the Västlänken project shows that highly censored hydraulic data, having a high detection limit for flow is unsuitable for hydraulic characterization for grouting using the design process.

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