THE USE OF PROXY PARAMETERS IN PRE-INVESTIGATION, DESIGN AND CONSTRUCTION OF TUNNELS WITH APPLICATION TO GROUTING

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SUMMARY

The information on what lies ahead of the tunnel front is never complete and adjustments on reinforcements and grouting to rock conditions have to be made regularly. This approach is formalized in the Observational method. The evaluation of the behavior of a tunnel can in reality not be done during construction. The solution will be to use parameters that predict the behavior of system as a proxy for the real behavior. In this paper a formal framework for the use of proxy parameters is derived and tested successfully on data from a major grouting experiment performed in Sweden.

INTRODUCTION

At present several tunneling projects are carried through in the major cities in Sweden. A common and notorious problem is that the projects are delayed and budgets are exceeded. This has lead to costly law suits and a general suspicion between consultants, contractors and clients like the road and railway authorities (Vägverket and Banverket). In this the geological information and background data almost always play a dubious role. A translation of geological information to straightforward engineering information is not trivial. Rock classification systems like the *RMR* [1] and *Q* [2] systems are attempts to condense geological information and present it in a way that engineers can digest. Efforts have been made to tie the classifications to data-bases from case studies to give direct construction guidelines. The results are however not encouraging and in reality the classification systems as they are used seem to be a part of the problem rather than the solution [3]. However, in tunnel construction the information on what lies ahead of the tunnel front is never complete and adjustments on reinforcements and grouting to rock conditions have to be made regularly. This approach is formalized in the Observational method according to Eurocode 7 [4] where the rules for how the design is reviewed are based on observation during construction to arrive at an acceptable behavior of the system. The problem is that stability can not be assessed until the final rock supports are made, leakage to a tunnel can not be measured until the tunnel is built and weirs are installed etc. Added to this remediation of inadequacies later on are very costly and in some cases not feasible.

PERFORMANCE ASSESSMENT OF TUNNEL CONSTRUCTION IN THE CONTEXT OF THE OBSERVATIONAL METHOD

In Eurocode [4] the portal paragraphs regarding the Observational method state that:

1. *When prediction of geotechnical behaviour is difficult it can be appropriate lo apply the approach known as "the observational method", in which the design is reviewed during construction.*
2. *The following requirements shall be met before construction is started:*
   - *Acceptable limits of behaviour shall be established.*
   - *The range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits.*
   - *A plan.....*

As stated the system behaviour should be monitored but the problem is that parameters describing system behaviour can in general not be measured directly. The solution will be to use parameters that predict the behavior of system as a proxy for the real behavior. In this context we define these as **proxy parameters**.

DEFINITION OF PROXY PARAMETERS

The proxy parameter, *Z*, or short proxy, should be coupled by some deterministic algorithm (equation) to the system behaviour so it could be predicted provided that the effective parameters of the algorithm are fully known. In accordance with the statements of Eurocode 7 we can define behaviour, *B*, of the system, *S,* as:

$$B(S) = f_S(Z) \tag{1}$$

The behaviour, $B(S)$, is thus a function of the proxy, *Z*. The monitoring plan states a set of measurements, $\breve{Z} = \{Z_1, Z_2, ...Z_N\}$, to be observed to asses the system behaviour and to evaluate if there is an acceptable probability, p_A, that the actual behaviour will be within the acceptable limits, *A*. Thus we find a criterion for acceptable behaviour *B*(*A*) as:

$$p\left(B(S) \in B(A) \middle| \breve{Z}\right) > p_A \tag{2}$$

I.e. the probability that the behaviour of the system stays within the acceptable limits given the set of measured values of the proxy is greater than the acceptable probability p_A.

PROXIES FOR DIFFERENT CLASSES OF SYSTEM BEHAVIOURS

In tunnelling normally three basic aspects have to be considered:

1. The stability or integrity of the tunnel – here typically convergence measurement are made and followed up behind the tunnel front, rock classification based on mapping of the fresh rock or simply block bolting based on manual inspection.

2. The inflow of groundwater to the tunnel – during tunnelling inflow to probe-holes and water pressure tests in grouting and control boreholes are made. However, the final ingress to the tunnel will only be known when weirs eventually are installed.

3. The influence of the tunnel on the environment – also here tunnel inflow is important but compliance levels are often tied to piezometric measurements in boreholes.

Parts of this type of approach have previously been tested on grouting data from a railway tunnel in North Sweden [5] and on deformation measurements in an Austrian tunnel [6]. Specifically we will here evaluate how the future inflow of groundwater to the tunnel can be assessed by inflow or water pressure tests in probe and grouting boreholes, and how many data, i.e. control boreholes, are required for a given level of confidence.

A PROXY FOR WATER INGRESS

A common problem is to decide whether grouting should be made or a grouting operation approved based on Water Pressure Tests (WPT) in probe boreholes. The system behaviour is thus the inflow, q, to a limited reach of a tunnel, L_t, typically corresponding to the length of a grouting fan, L. Acceptable behaviour is that this will be smaller than a critical design value q_A. A possible parameter to observe is the inflow or water loss to probe or control boreholes.

The ingress of water to a tunnel, whether it is grouted or not can be estimated with [8]:

$$q = \frac{2\pi T \cdot H / L_t}{\ln(2H / r_t) + (T / T_{inj} - 1) \cdot \ln(1 + t / r_t) + \xi} \tag{3}$$

In this equation H is the resting groundwater head, assumed to be approximately the distance to the ground surface, r_t is the tunnel radius and t is the thickness of the grouted zone. T / T_{inj} is the ratio of the transmissivity of the ungrouted rock close to the tunnel section and the transmissivity of boreholes measured in the grouted zone for the same part of the tunnel. X is the skinfaktor that lumps other effects that restrict inflow to the tunnel, here conservatively set to $\xi = 0$.

An often used approximation for the bulk conductivity of the rock is the Matheron conjecture [8] which says that the effective transmissivity can be estimated by the geometric mean of a sample of independent transmissivity measurements in a flow field. For an approximately lognormal transmissivity distribution it can be assessed by the median, $T \cong T_m$. For the ungrouted tunnel the second term of the denominator in Equation 3 vanishes. Thus:

$$q = \frac{2\pi T_m \cdot H / L_t}{\ln(2H / r_t)} \tag{4}$$

From which in accordance with Equation 2 follows an acceptable behaviour:

$$B(A) = q < q_A \rightarrow T_m < T_A \quad \text{or} \quad p\left(T_m < T_A \middle| \breve{T}\right) > p_A \tag{5}$$

Where $\breve{T} = \{T_1, T_2, ...T_N\}$ is the set of transmissivities evaluated from the tested boreholes.

PROBE HOLE TRANSMISSIVITIES

Water pressure tests (WPT) give a local (borehole) value of the transmissivity [9]:

$$T \approx Q / dh = \frac{Q \cdot \rho_w g}{\Delta p_w} \tag{6}$$

Where Q is the injection rate and $dh = \Delta p_w / \rho_w g$ is the applied overpressure measured in m water column. The Flow Test (FT) is a similar test where the borehole is allowed to flow freely and the inflow, Q, and the rest level, H, are measured. The transmissivity is estimated to be:

$$T \approx Q / H \tag{7}$$

CONFIDENCE INTERVAL FOR THE MEDIAN TRANSMISSIVITY

If we can assess the probability, p, that the median of the transmissivity distribution is smaller than a critical design value, $T_m \leq T_A$, we will have a good support for the decision if a tunnel section should be grouted or not. Thus, using the acceptable value for the ingress, q_A, and Equation 4 give:

$$T_A = \frac{\ln(2H / r_t)}{2\pi} \cdot \frac{L_t}{H} \cdot q_A \tag{8}$$

If we assume that the transmissivities found follow a continuous distribution (which they do) and are independent (which is not totally true) the probability that an arbitrary test T will be greater than T_m is ½. The same goes for T being smaller than T_m. Thus: $p(T < T_m) = 0{,}5$ and $p(T > T_m) = 0{,}5$. If we pick two values, T_1 and T_2 we find that $p(T_1$ and $T_2 < T_m) = 0{,}25$, $p(T_1$ or $T_2 < T_m) = 0{,}5$ and $p(T_1$ and $T_2 > T_m) = 0{,}25$.

This can easily be generalised to a higher number of observations. Let us call the number of values that are smaller than T_m for n^- and the number that are greater for n^+. The total number is then: $N = n^- + n^+$. Thus the probability that a certain number of observations, n^+, out of N is smaller than the median is binomially distributed so that:

$$p = 1 - Binomial(n^+, N, ½, cumulative) \tag{9}$$

In our case we want to determine the confidence level that the median is smaller than a critical value T_A. One way to do that is to assume that the critical value is the median and then calculate the probability for that. In our case we thus make N boreholes, test them and by comparing T_A to the evaluated transmissivities we find the number of values, $n^+ \in [0, N]$ larger than this. Using Equation 9 we can make a table of these probabilities.

Table 1. Confidence levels for the median, T_m, to be smaller than a critical value, T_A, for a single grouting fan.

N↓ n+→	0	1	2	3	4	5
1	0,50	-	-	-	-	-
2	0,75	0,25	-	-	-	-
3	**0,88**	0,50	0,13	-	-	-
4	**0,94**	0,69	0,31	0,06	-	-
5	**0,97**	0,81	0,50	0,19	0,03	-
6	**0,98**	**0,89**	0,66	0,34	0,11	0,02

Here the required confidence level has to be discussed. For the single grouting fan the number of WPTs in probe-holes is small (2-5). However if one fan fails it is normally not a serious problem if the other fans in a series fulfil the requirements. Thus we see that if we want $p \approx 0,9$ we can not accept any value higher than T_A out of 3 boreholes or one out of 6. If we accept $p \approx 0,7$ we can not accept any $T > T_A$ out of 2 boreholes, one $T > T_A$ out of 4 or two out of 6.

For a longer part of the tunnel, say 100 m, which normally corresponds to about 5 fans there are about 5 times as many probe-holes. The same table for that case is shown in Table 2.

Table 2. Confidence levels for the median to be smaller than a critical value for about 5 grouting fans.

N↓ n+→	0	1	2	3	4	5	6	7	8	9	10
10	**1,00**	**0,99**	**0,95**	0,83	0,62	0,38	0,17	0,05	0,01	0,00	0,00
15	**1,00**	**1,00**	**1,00**	**0,98**	**0,94**	0,85	0,70	0,50	0,30	0,15	0,06
20	**1,00**	**1,00**	**1,00**	**1,00**	**0,99**	**0,98**	**0,94**	0,87	0,75	0,59	0,41
25	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	**0,99**	**0,98**	**0,95**	0,89	0,79
30	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	**0,99**	**0,98**	**0,95**

If we compare the tables we see that if we do not get $T > T_A$ for any of the single fans, $n^+ = 0$, we will be quite confident that the median is smaller than the critical value, $p \approx 1,00$. Here simply the total number of probe-holes is the number for each fan multiplied by the number of fans (5). Table 2 is basically the same table as Table 1 but for higher numbers of probe-holes. We find thus, that a higher number of observations increases the confidence level for the same number of $T > T_A$. Since we want to assess the ingress not just for a single fan but for a longer portion of the tunnel it is actually this table that should be the basis for a decision. The problem is that we get the information fan by fan. However, using Table 2 we find that $n^+ \leq 5$ gives a confidence level of at least 85 % if we use 3 probe-holes, $N = 15$, per fan. If we accept $p \approx 0,85$ we can have at least one $T > T_A$ failure per fan.

INGRESS TO THE GROUTED TUNNEL

The ingress to a grouted tunnel may be estimated by Equation 3. The parameters of the equation are in most cases unknown when a decision on an approval of a grouting fan has to be made. However, with some simplification a rule-of-thumb criterion can be set up.

In order to evaluate the ratio T/T_{inj} the flow field around the grouted tunnel has to be discussed a bit. Data have shown that both T and T_{inj} are approximately lognormal and reasonably independent which means that the ratio also is lognormal. We do not know too much of the details of the flow-field in the hydraulically heterogeneous area close to the tunnel. We may however assume that the flow field is approximately radial. Thus the ratio can then be reduced to:

$$T/T_{inj} \approx T_m/T_{m,inj} \qquad (10)$$

A successful grouting operation requires that the ratio $T_m/T_{inj} \rightarrow 50-200$. We also normally assume that the thickness of the grouted zone is about the same as the tunnel diameter. This means that Equation 4 can be approximated as:

$$q \leq \frac{2\pi H}{L_t} \cdot T_{m,inj} \quad \text{or} \quad T_{A,inj} = \frac{L_t}{2\pi H} \cdot q_A \qquad (11)$$

Here $T_{m,inj}$ is the median of the probe-hole transmissivities after grouting. This means that the same approach as for the ungrouted case can be used but a critical borehole transmissivity after grouting, $T_{A,inj}$, will be the target value to compare with.

APPLICATION IN THE S-TUNNEL, ÄSPÖ HARD ROCK LABORATORY

The Äspö HRL (Hard Rock Laboratory) is an underground research laboratory situated close to the nuclear power plants in Oskarshamn along the Baltic in SE Sweden. Here the Swedish Nuclear Fuel and Waste Management Company (SKB) compile and refine knowledge of all the processes that occur in a final nuclear waste repository. During 2008-2010 a major grouting experiment was carried through in connection with the excavation of the S tunnel [10] at 450 m depth under groundwater head of $H = 330$ m, see Figure 1. The tunnel is approximately 80 m long and was excavated by the drill and blast method in stages defined by the pre-excavation grouting fans. The tunnel cross sectional area is 18 m^2 giving a tunnel radius of $r_t \approx 2{,}5$ m. Totally 6 fans were executed. Three fans were made with a conventional design. Fans 4 – 6 were drilled with grouting boreholes within the contour of the tunnel, leaving no boreholes outside when the tunnel was excavated. This could be an important feature in a nuclear waste repository.

Measuring weirs were arranged at the onsets of Fans 2, 4, 5 and close to the face at the tunnel end. The design comprised 3 – 4 probe boreholes, grouting in two stages, in general with colloidal silica, followed a set of control boreholes. In all boreholes a short inflow test (IFT) was made. It should be pointed out that Fan 4, which was the first attempt to grout with a fan within the tunnel contour, was made with an erroneous design giving too small an overlap of grout between the boreholes and a too thin grouted zone outside the tunnel. This fan was later used for a blasting damage experiment and a test with post excavation grouting. See Figure 1.

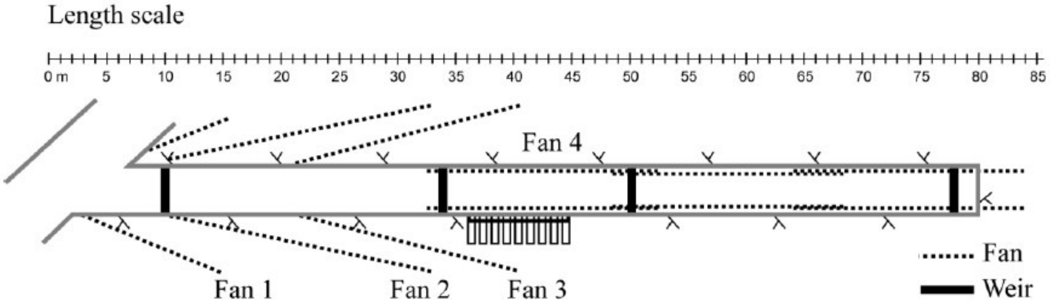

Figure 1. The lay out of the S-Tunnel [10].

The results of the IFTs for each fan can be summarized with empirical cumulative distribution plots (CDF). An example is given in Figure 2.

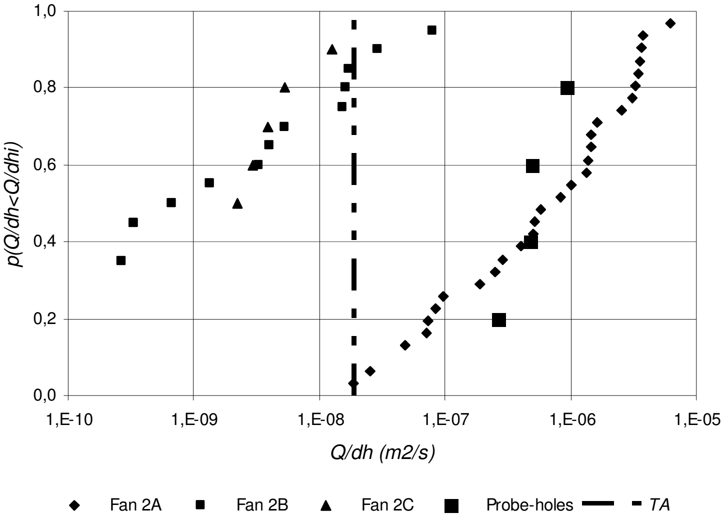

Figure 2, CDF of measured specific capacities, Q/dh, for water inflow tests (IFT) performed in Fan 2.

In Fan 2 four probe-holes, two full grouting fans (2A and 2B) and six control boreholes (2C) were tested. In Fan 2A the boreholes with high yields were grouted with low-pH cement and the rest with silica sol [11]. Fan 2B and the control boreholes were grouted with silica sol. The sealing effect can be directly read out in a diagram such as Figure 2 as the distance between the curves. The median is thus reduced with more than two orders of magnitude. From Figure 2 it is obvious that the grouting of Fan 2 was successful. The question is if this is good enough. With an acceptable inflow of 1 l/min per 60 m tunnel = $2{,}8 \cdot 10^{7}$ $m^3/s \cdot m$ and the given geometry of the tunnel the acceptable transmissivity for the 25 m long Fan 2 we find that

$T_A = \frac{\ln(2H/r_t)}{2\pi}\cdot\frac{L_t}{H}\cdot q_A = \frac{\ln(2\cdot 330/2{,}5)}{2\pi}\cdot\frac{25}{330}\cdot 2{,}8\cdot 10^{-7} = 1{,}9\cdot 10^{-8}$ m^2/s (Equation 4) for an ungrouted tunnel and $T_{A,inj} = \frac{L_t}{2\pi H}\cdot q_A = \frac{25}{2\pi\cdot 330}\cdot 2{,}8\cdot 10^{-7} = 3{,}4\cdot 10^{-9}$ m^2/s (Equation 11) for the grouted tunnel.

The same type of plot of the results from all probe-holes, PH 2 – 7, and control boreholes, 2C – 6C, is shown in Figure 3.

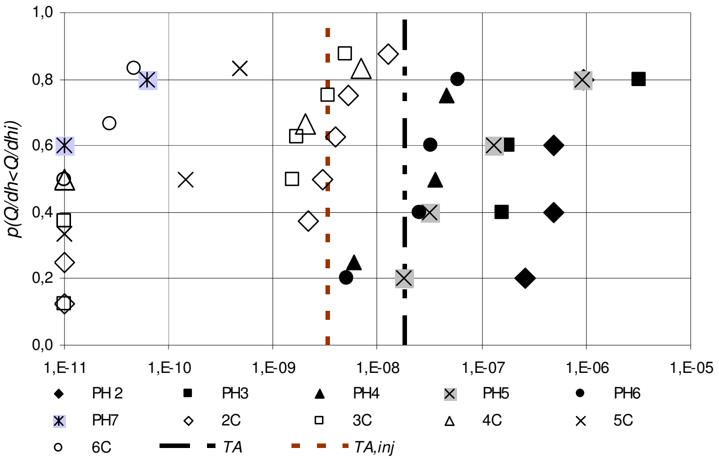

Figure 3. Specific capacities measured in probe holes (filled markers) and control boreholes (unfilled markers). The acceptable values are marked with different dashed lines.

The reduction in transmissivity is in general two orders of magnitude or more. In order to evaluate if this means that the ingress will be acceptably small the level of confidence for a successful grouting was evaluated. Table 3 shows the results for the probe-holes. As shown only the probe-holes for Fan 7 indicate that pre-grouting is not required. This Fan was never excavated and the leakage from the probe-holes continued to be very low. All other fans have a negligible probability for success as shown in Table 3.

Table 3. Number of transmissivities, n^+, for probe holes which are greater than the acceptable value out of total number, N, and the corresponding confidence level for an acceptable ingress to the ungrouted tunnel.

Before grouting	*N*	*n+*	$p(T_m<T_A)$
Fan 2 - Probe,	4	4	0,00
Fan 3 - Probe.	4	3	0,06
Fan 4 - Probe,	3	2	0,13
Fan 5 - Probe.	4	3	0,06
Fan 6 - Probe.	4	3	0,06
Fan 7 - Probe.	4	0	0,94

Next the same table is shown for the control boreholes after final grouting, see Table 4 In this case all fans except Fan 2 show very high confidence levels that grouting was successful.

Table 4. Number of transmissivities, n^+, greater than the acceptable value for the control boreholes out of total number, N, and the corresponding confidence level for an acceptable ingress to the grouted tunnel.

After grouting	*N*	*n+*	$p(T_{m,inj}<T_A)$
Fan 2	7	3	0,50
Fan 3	7	1	0,94
Fan 4	5	0	0,98
Fan 5	5	0	0,98
Fan 6	6	0	0,98

Finally these results should be compared to the inflows measured by the weirs. The evaluation is made for all probe and control boreholes positioned between two weirs. The results are summarized in Table 5.

Table 5. Confidence levels for an acceptable ingress, Q_A, of the weir section and measured ingress, Q.

Weir	*N*	*n+*	$p(T_m<T_A)$	Q_A (l/min)	Q (l/min)	
Fans 2+3	14	4	0,91	0,40	0,38	after grouting
Fan 4*	5	0	0,97	0,27	0,74	bef, postgrouting
Fans 5+6	10	0	1,00	0,51	0,37	after grouting
Fan 7	4	0	0,98	(-)	0,01	no grouting
*Fan 4 made with incorrect design						

CONCLUSIONS

Except for Fan 4 which basically for ignorance was made by an erroneous design the confidence level of an acceptable behaviour for all fans are higher than 91%. This is also confirmed by the measured inflows. Thus the analysis of data from the S-tunnel confirms that the approach with the transmissivity of probe and control boreholes is feasible.

The remaining question to address is the reasonable level of confidence for successful grouting. As Table 5 shows, the assumption that the number of $T > T_A$ evaluated for both fans between the weirs give a high level of confidence that the ingress would be acceptably low. This was also confirmed by the measured inflow. Thus it seems reasonable to accept a somewhat lower level of confidence for each fan and rely on that this will give a sufficiently high confidence for an acceptable behaviour for the tunnel. We suggest that at least four probe and control boreholes should be drilled for each fan, of which not more than one may have an unacceptably high transmissivity. This gives a level of confidence of an acceptable behaviour of at least 69 % for each fan. For 5 Fans in a row this will give a confidence level for an acceptably small ingress of more than 99 %.

Finally we stress that the design and performance of grouting operations is a necessity for a successful and economic grouting operation. Fan 4 is a good example of that. It was the first attempt to make pre-grouting with boreholes inside the tunnel contour. When we found that the ingress was higher than expected a back calculation showed that the same design as for the conventional fans gave a penetration of grout too small to give a sufficient grout overlap in the fractures outside the tunnel. When this was changed for the following fans the targets were reached.

ACKNOWLEDGEMENT

We thank the Swedish Nuclear Fuel and Waste Management Co (SKB) for support and making data from the S-tunnel available.

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