KARAKTÄRISERING AV BERGMASSOR – SYSTEMATISKA FEL OCH MÖJLIGA ÅTGÄRDER

Rock mass characterization – Systematic errors and how they can be avoided

Robert Swindell, Trafikverket
Fredrik Johansson, KTH
Ingrid Kjellström, ÅF Consult/KTH
Mehdi Benhalima, KTH

Abstract

Rock mass quality assessment is performed in a variety of situations by engineers and geologists during design and excavation of rock engineering projects. The results form the basis for rock engineering design and are an important part of the tender documents and contract for rock engineering works. Trafikverket sponsored two Masters Theses to analyze the occurrence and possible causes of systematic "errors" introduced during rock mass characterization. This paper provides a summary of the results of these theses and shows that there are clear indications that systematic "errors" are introduced due to the methods used for rock mass characterization. The paper also provides suggestions for how these errors can be mitigated in future projects. Possible remedial measures include the introduction of guidelines for drill core logging, incorporation of geotechnical baseline reports, better coupling of rock mass characterization and rock engineering design, implementation of guidelines for excavation mapping and continued statistical analysis of rock mass characterization data.

Sammanfattning

Ingenjörer och geologer genomför karaktärisering av bergmassor i många olika situationer inom ett bergprojekt under både design och utförandeskedet. Resultatet används som underlag för projektering och är en viktig del i förfrågningsunderlag och byggkontrakt. Trafikverket har sponsrat två examensarbeten med syfte att utvärdera eventuella systematiska ”fel” som introduceras i samband med karaktärisering av bergmassor i de olika skedena. Denna artikel utgör en sammanfattning av examensarbetena och visar att det finns tydliga indikationer på att systematiska ”fel” förekommer på grund av de olika metoder som tillämpas vid karaktäriseringen. Artikeln lämnar även förslag för hur sådana ”fel” kan undvikas framöver. Dessa förslag består av att ta fram riktlinjer för kartering av borrkärnor inom branschen, utvärdering av ”Geotechnical Baseline Reports”, tydligare kopplingar mellan karaktärisering och bergmekanisk projektering, implementering av riktlinjer för kartering i byggskedet samt fortsatt statistisk analys av data från karaktärisering av bergmassor.

1 Introduction

Rock mass quality assessment is performed in a variety of situations by engineers and geologists during design and excavation of rock engineering projects. A variety of systems developed within the international rock engineering community are currently used for the purpose of rock mass characterization. The results form the basis for rock engineering design and are a key parameter for determining permanent support measures during excavation. Furthermore, the forecast rock mass conditions are an important part of the tender documents for procurement of rock engineering works and form the baseline for resolution of claims associated with differing ground conditions.

Cost increases due to rock engineering projects encountering less favourable ground conditions during construction are a common occurrence both internationally and within Sweden. Lundman (2011) studied data from tunnel excavations for the Botnia Line (Botniabanan) in order to analyze the causes of cost increases in tunneling projects. Lundman concluded that large cost increases are generated from optimistic prognoses and cautious rock mass assessment during excavation field mapping. The Swedish Transport Administration (Trafikverket) commissioned two projects (Trafikverket publication 2010:037 and 2012:213) to further study these effects based on data from the Ådal Line (Ådalsbanan) and from the City Line (Citybanan). The results from these projects further supported Lundmans view that engineering geological forecasts tend to describe more favourable rock mass quality compared with the results of excavation mapping. Conslusions from Trafikverket's latest study (2012:213) suggest that the most likely causes of this effect are the quantity and quality of pre-investigation data and the method and manner in which the rock mass quality assessment is performed throughout the different phases of the project.

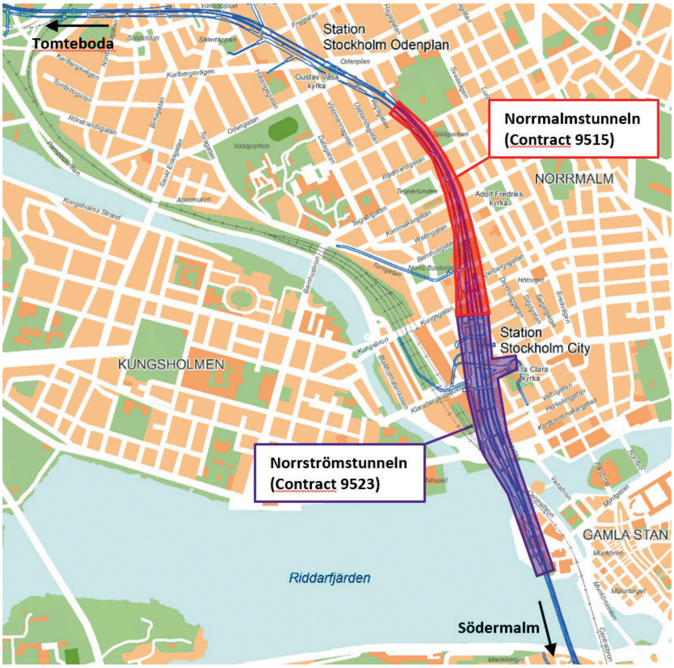
Trafikverket sponsored a Masters Thesis (Kjellström, 2015) to analyze the occurrence and possible causes of systematic "errors" introduced during rock mass characterization within the City Line (Citybanan) project. This was subsequently followed by a second Masters Thesis (Benhalima, 2016) applying the same analysis methods but using data from the Northern Link (Norra Länken) project. A summary of the results of these thesis will be presented in this paper together with suggestions for how systematic errors can be minimized in future rock engineering projects.

2 Rock mass characterization - City Line & Northern Link

2.1 City Line

2.1.1 Project description

The City Line tunnel project is located in central Stockholm, Sweden and comprises a 6 km long double track commuter train tunnel, including two new underground stations and will be completed in summer 2017. The tunnels were excavated in crystalline granite and gneiss using conventional drill and blast methods, together with systematic pre-injection grouting. Two of the larger rock engineering contracts, Norrmalmstunneln and Norrströmstunneln formed the basis for Kjellströms work and their location is shown on the map in Figure 1.



Norrmalmstunneln • 400 000 m^3 rock excavations • Designer: WSP • Contractor: Strabag	**Norrströmstunneln** • 510 000 m^3 rock excavations • Designer: WSP • Contractor: NCC

Figure 1. Map showing the northern part of the City Line and tunneling contract 9515 and 9523.

2.1.2 Methodology for rock mass characterization

Both the RMR system (Bieniawski, 1989) and the Q-system (Barton, 2002) were used for characterizing the rock mass in the City Line project. The RMR system was selected as the primary system for rock mass characterization meaning that the design criteria and reinforcement classes were linked to RMR (in special situations even additional parameters and criteria were also used). A series of reports were produced during the conceptual design phase that specified guidelines for how these two systems should be applied when conducting drill core mapping, production of engineering geological forecasts (EGF) and for tunnel mapping. The methodology used for rock mass characterization is summarized in Tables 1 and 2. For further details regarding the methodology see Swindell and Rosengren (2007) and Kjellström (2015).

Table 1. Method for RMR parameter assessment applied for the City Line project.

Parameter	Drill Core	Engineering Geological Forecast (EGF)	Tunnel Mapping
1. Intact strength	Estimated based on lab testing per meter drill core	*Not assessed in tunnel scale.*	Estimate of characteristic value based on lab and field testing for a representative area in the tunnel (typically 3-10 m of excavated tunnel)
2. RQD	Calculated per meter drill core		Estimated (or occasionally measured) based on fracture frequency. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
3. Discontinuity spacing	Average spacing of all natural discontinuities per meter drill core		Estimate of characteristic value based on observation in the tunnel. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
4. Discontinuity condition	Characteristic value estimated per meter drill core		Estimate of characteristic value based on observation in the tunnel. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
5. Groundwater	*Not assessed in drill core*	Estimated in tunnel scale based on hydraulic testing and geological forecast	Estimate of characteristic value based on observed inflow in the tunnel. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
6. Discontinuity orientation	*Not assessed in drill core*	Estimated in tunnel scale based on structural geological analysis	Estimate of characteristic value based on structural geological conditions in the tunnel. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
RMR_{Bas}[i)]	Calculated value per m drill core	Forecast in tunnel scale based on geological interpretation (drill core and other data)	Calculated value for a representative area
RMR	*Not assessed in drill core*	Calculated in tunnel scale based on forecast RMR_{Bas} and parameter 5+6	Calculated value for a representative area

i) RMR_{Bas} = Basic RMR value calculated by the sum of parameter 1 to 4 and with parameter 5 (groundwater) set to completely dry (15 points).

Table 2. Method for Q parameter assessment applied for the City Line project.

Parameter	Drill Core	Engineering Geological Forecast (EGF)	Tunnel Mapping
RQD	Calculated per meter drill core	*Not assessed in tunnel scale*	Estimated (or occasionally measured) based on fracture frequency. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
Jn[i)]	Estimated per meter drill core		Estimated (or occasionally measured) based on structural geological conditions. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
Jn correction[i)]	*Not assessed in drill core*	Correction for tunnel intersections and portals applied for standard area	Correction for tunnel intersections and portals applied for standard area (same method as forecast)
Jr	Assigned based on discontinuity with lowest estimated shear strength per meter drill core	*Not assessed in tunnel scale*	Estimate of value based on observation of least favourable discontinuities according to Q-system guidelines. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
Ja	Assigned based on discontinuity with lowest estimated shear strength per meter drill core		Estimate of value based on observation of least favourable discontinuities according to Q-system guidelines. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
Jw	*Not assessed in drill core*	Estimated in tunnel scale based on hydraulic testing and geological forecast	Estimate of characteristic value based on observed inflow in the tunnel. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
SRF		Estimated in tunnel scale based on rock cover, stress regime and rock mass quality	Estimate of value based on encountered/forecast rock cover, geological forecast and rock conditions. The estimate applied over a representative area (typically 3-10 m of excavated tunnel)
Q_{Bas}[ii)]	Calculated value per meter drill core	Forecast in tunnel scale based on geological interpretation (drill core and other data)	Calculated value for a representative area (typically 3-10 m of excavated tunnel)
Q	*Not assessed in drill core*	Calculated in tunnel scale based on forecast Q_{Bas}, Jn correction, Jw and SRF	Calculated value for a representative area (typically 3-10 m of excavated tunnel)

i) Jn = Basic Jn parameter taking no account of geometrical corrections; Jn correction = Jn after application of geometrical corrections for tunnel intersections and portals.

ii) Q_{Bas} = Basic Q value calculated by setting Jw and SRF = 1 and taking no account of geometrical corrections for Jn.

2.1.3 Data analysis and results

Preparation of the data began by taking the pre-existing data sets for drill core mapping, engineering geological forecasts (EGF) and tunnel mapping and normalising these to 1 m sections. This process was not generally required for the drill core as the rock mass characterization was conducted in 1 m sections during drill core mapping, however it was a necessary process for the engineering geological forecasts and the tunnel mapping. This meant that for example a 15 m stretch of mapped (or forecast) tunnel with the same rock mass characteristics formed 15 samples in the database. The data sets that formed the basis for the analysis after normalization to 1 m sections are summarized in Table 3. Values for RMR_{Bas} and RMR data were sorted into histogram bins with an interval of 5 points and the results are presented in Figure 2.

Table 3. Data sets for rock mass characterization for the City Line project.

Tunneling contract	Drill core (m)	EGF (m)	Tunnel mapping (m)
Norrströmstunneln (9523)	2131	3996	4596
Norrmalmstunneln (9515)	682	2735	2557

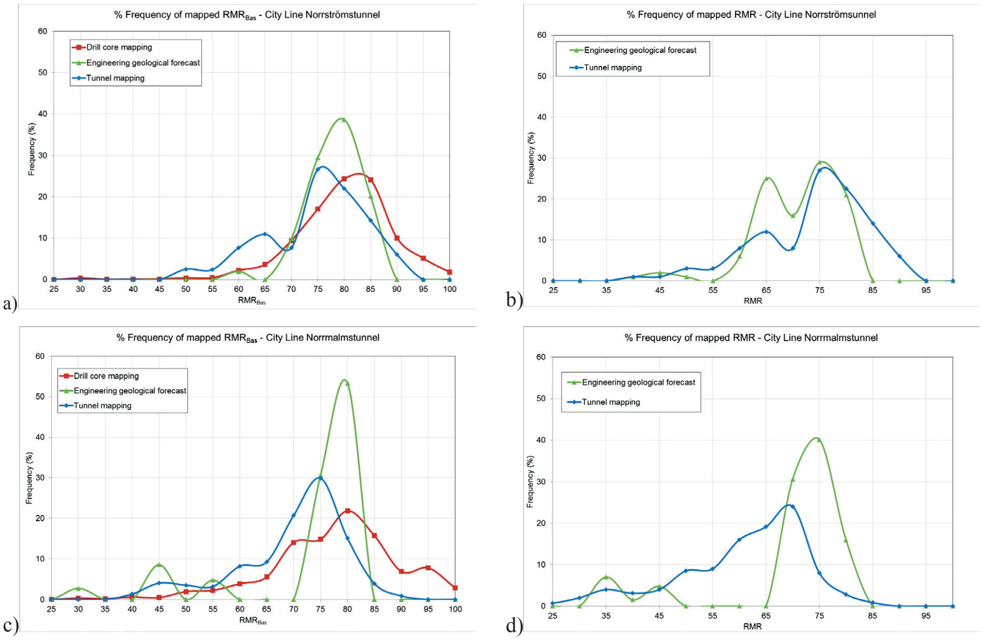


Figure 2. Frequency distributions for rock mass quality assessments performed during different phases in the City Line project.

The charts in Figure 2 for RMR_{Bas} (chart a and c) for both tunnel contracts show that extremely high values from drill core mapping have not been included in the engineering geological forecast (EGF) and that instead the majority of the rock mass has been forecast to be of good quality rock (RMR_{Bas} 70-85). Portions of fair rock (RMR_{Bas} 60-70) encountered in the drill core do not appear to have been forecast to occur in significant quantities in the EGF for both RMR_{Bas} and the full RMR value. The tunnel mapping data has a wider distribution with a significantly larger proportion of fair rock compared with drill core and particularly the EGF. This effect of a shift from good rock to fair rock between the EGF and the tunnel mapping is most obvious in tunnel contract Norrmalmstunnel. Such a shift has a direct consequence on the prescribed reinforcement classes (more reinforcement) and therefore results in a probable cost increase. In order to analyze the possible causes of these shifts in the distributions, the same analysis procedure was applied to the individual parameters in the RMR system, see Table 3.

Table 3. Changes in the average value for the input parameters in the RMR system during the different phases of rock mass assessment. Increases and decreases of more than 1 point in the RMR system are marked in green and red respectively.

RMR Parameter	Norrmalmstunneln Tunnel Mapping – Drill Core	Norrströmstunneln Tunnel Mapping – Drill Core	Norrmalmstunneln Tunnel Mapping - EGF	Norrströmstunneln Tunnel Mapping - EGF
1. Intact strength	+0.23	+0.21		
2. RQD	-3.85	-2.38		
3. Discontinuity spacing	+3.01	-0.31		
4. Discontinuity condition	-6.78	-2.56		
5. Groundwater	---	---	-2.62	+0.65
6. Discontinuity orientation	---	---	-0.99	+0.08
RMR_{Bas}	-7.53	-5.03	-3.04	-5.09
RMR	---	---	-7.95	-4.5

As can be seen in Table 3, the primary cause for the lower assessed RMR_{Bas} and RMR values during tunnel mapping come from the RQD and discontinuity condition parameters (tunnel mapping compared with drill core data). Even the assessment of the groundwater parameter was generally lower when performing tunnel mapping compared with the EGF for Norrmalmstunneln.

2.2 Northern Link

2.2.1 Project description

The Northern Link is a 5 km stretch of motorway located on the northern edge of Central Stockholm, for which approximately 4 km is located in rock tunnels, see Figure 3. A small portion of the tunnel excavations were started in 1991, however, the project was put on hold and the majority of the tunnels were excavated between 2006 and 2010. Benhalima's work focused on the rock tunneling contracts NL22, NL33, NL34 and NL35.

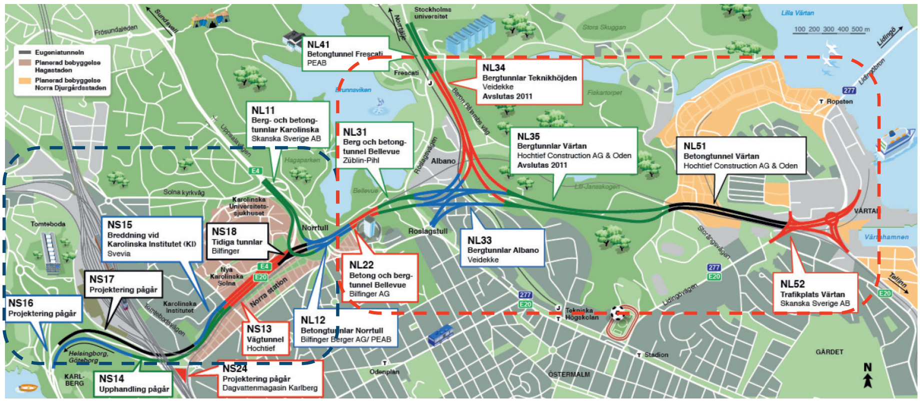


Figure 3. Map showing the Northern Link project in Stockholm and the various construction contracts. The blue dashed line shows the K1 design area and the red dashed line shows the K3 design area.

2.2.2 Methodology for rock mass characterization

The Q-system (Barton, 2002) was used as the primary means of characterizing the rock mass in the Northern Link project. Drill cores for the Western area (K1 in Figure 3) were mapped with no standard section lengths, which meant that the core logger determined the section length, whilst rock mass characterization of drill cores in the Eastern area (K3 in Figure 3) was done in 1 m sections. The core logging for these two areas was also done by geologists from two different companies. It is unclear exactly how the core mapping was conducted, however, the core logs suggest that all the six parameters in the Q-system were assessed and a final Q value calculated in the core logs. It is also unclear how the geological interpretation and production of the EGF was performed in the Northern Link project as the methods used were not documented. Rock mass characterization performed during tunnel mapping in the construction phase was performed on a systematic basis. The work was performed by geologists and engineers from Sweco who represented the client. The methods that are thought to have been used for rock mass characterization using the Q-system in the Northern Link project are summarized in Table 4.

Table 4. Presumed method for Q parameter assessment applied for the Northern Link project.

Parameter	Drill Core	Engineering Geological Forecast (EGF)	Tunnel Mapping
RQD	Calculated for the section (usually 1 m)	*Uncertain if these parameters were assessed in the engineering geological forecast*	Estimated (or occasionally measured) based on fracture frequency. The estimate applied over a representative area (typically 5 m sections of excavated tunnel)
Jn[i]	Estimated for the section (usually 1 m)		Estimated (or occasionally measured) based on structural geological conditions. The estimate applied over a representative area (typically 5 m sections of excavated tunnel)
Jn correction[i]	*Uncertain if this was corrected*		Correction for tunnel intersections and portals applied for standard area
Jr	Assigned based on discontinuity with lowest estimated shear strength for the section (usually 1 m)		Estimate of characteristic value. The estimate applied over a representative area (typically 5 m sections of excavated tunnel)
Ja	Assigned based on discontinuity with lowest estimated shear strength for the section (usually 1 m)		Estimate of characteristic value. The estimate applied over a representative area (typically 5 m sections of excavated tunnel)
Jw	Assigned based on packer testing results		Estimate of characteristic value based on observed inflow in the tunnel. The estimate applied over a representative area (typically 5 m sections of excavated tunnel)
SRF	Western holes =1, Eastern core holes assigned according to likely stress conditions (mostly 2,5)		Estimate of value based on encountered/forecast rock cover, geological forecast and rock conditions. The estimate applied over a representative area (typically 5 m sections of excavated tunnel)
Q	*Calculated value*	Assigned value based on geological interpretation	Calculated value for a representative area (typically 5 m of excavated tunnel)

i) Jn = Basic Jn parameter taking no account of geometrical corrections; Jn correction = Jn after application of geometrical corrections for tunnel intersections and portals.

2.2.3 Data analysis and results

Preparation of the data began by taking the pre-existing data sets for drill core mapping, engineering geological forecasts and tunnel mapping and normalizing these to 1 m sections in the same way as was done for the City Line (see section 2.1.3). The data sets that formed the basis for the analysis after normalization to 1 m sections are summarized in Table 5.

Q values were sorted into histogram bins for the corresponding rock class using the standard intervals applied in the Q-system and the results are presented in Figure 4.

Table 5. Data sets for rock mass characterization for the Northern Link project.

Tunneling contract	Drill core (m)	EGF (m)	Tunnel mapping (m)
K1 (design contract)	356	---	---
NL22	---	---	81
NL31	---	---	89
NL33	110	2292	2292
NL34	97	897	897
NL35	653	1932	1932
TOTAL	**1216**	**5121**	**5291**

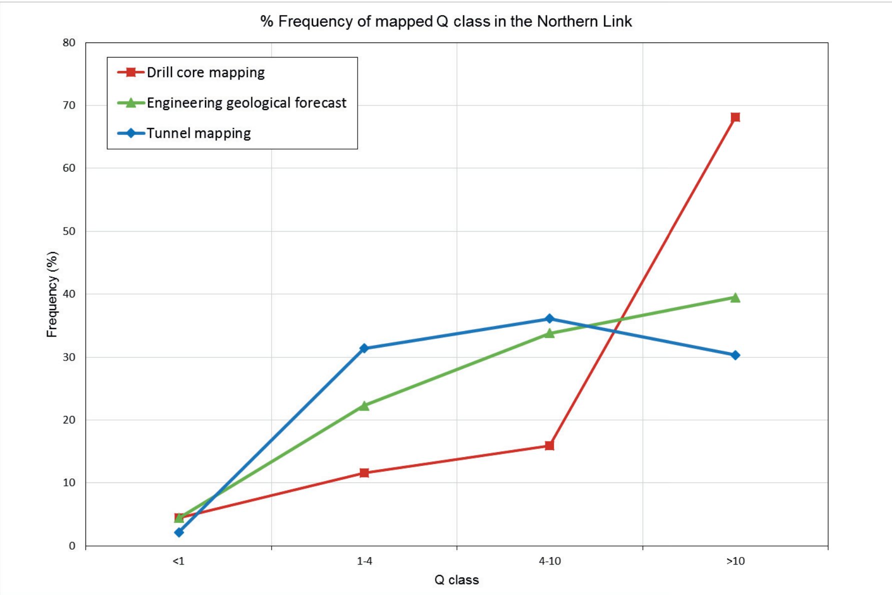


Figure 4. Frequency distribution for rock mass quality assessment (Q-values) performed during different phases in the Northern Link project.

The chart in Figure 4 shows that the majority (approximately 69%) of Q assessments in drill core resulted in a Q value >10. The corresponding proportion of the rock mass forecast to have a value of >10 in the EGF was however approximately 30% less than the drill core statistics. As the process for the assessment of drill core mapping and forecasting of the rock conditions has not been documented there remains a degree of uncertainty as to the exact reasons behind this difference. It is however likely to be connected to a combination of the use of additional geological data in the EGF together with a conservative mindset of the geologist responsible for the interpretation.

The distribution of the Q value assessments from tunnel mapping are in good general agreement with the EGF which suggests that the possible conservative geological interpretation compared to the drill cores was well motivated. In order to analyze the possible causes of these distributions, the same analysis procedure was applied to the individual parameters in the Q system, see Table 6.

Table 6. Changes in the mean value (mode is shown in brackets) for the input parameters in the Q system during the different phases of rock mass assessment. Changes resulting in a significant decrease or increase in the final Q value are marked in red and green respectively.

Parameter	NL33			NL34			NL35			Norra Länken (All Contracts)		
	Mean tunnel mapping	**Mean drill core**	**Diff mean [%]**	**Mean tunnel mapping**	**Mean drill core**	**Diff mean [%]**	**Mean tunnel mapping**	**Mean drill core**	**Diff mean [%]**	**Mean tunnel mapping**	**Mean drill core**	**Diff mean [%]**
RQD	87 [95]	81 [100]	7,6	90 [95]	60 [80]	49,9	88 [90]	74 [100]	19,5	88,1	73,1	20,4
Jn	11,9 [9]	4,19 [3]	182,6	7,9 [6]	4,9 [6]	61,1	9,9 [9]	4,3 [3]	132,1	10,5	4,3	142,8
Jr	1,5 [1,5]	2,46 [2]	-39,2	1,5 [1,5]	2,4 [3]	-39,0	1,5 [1,5]	2,3 [2]	-35,9	1,5	2,3	-36,1
Ja	2,2 [2]	2,36 [2]	-6,4	1,9 [1]	2,8 [2]	-30,5	2,5 [2]	2,6 [2]	-4,5	2,3	2,6	-13,4
Jw	1 [1]	1 [1]	0,0	1 [1]	1 [1]	0,0	1 [1]	1 [1]	0,0	1,0	1,0	0,0
SRF	1,2 [1]	2,5 [2,5]	-53,1	1,1 [1]	2,5 [2,5]	-57,0	1 [1]	2,5 [2,5]	-60,0	1,1	2,5	-55,5
RQD/Jn	10,1	44,75	-77,3	13,18	17,86	-26,2	9,85	36,64	-73,1	10,5	35,6	-70,5
Jr/Ja	0,9	1,43	-39,3	1,11	1,03	7,8	0,7	1,13	-38,0	0,9	1,2	-26,5
Jw/SRF	0,9	0,39	132,7	0,96	0,39	142,5	1	0,4	150,0	1,0	0,4	138,7
Q	**8,2**	**25,7**		**14,2**	**7,4**		**6,9**	**16,6**		**9**	**17**	
Length	2292 m	110 m		897 m	97 m		1932 m	653 m		5121 m	864 m	

Estimation of the RQD values when performing tunnel mapping is in relatively good agreement with the measured values in the drill core, with the exception of NL34. However, the drill core dataset for NL34 is only based on a limited amount of drill core (97 m). The Jn value is clearly assessed significantly higher compared with the drill core mapping in all tunnel contracts. This can most likely be attributed to an underestimation of the number of joint sets in the drill core, however, it may also be a factor of Jn corrections for intersections and portals that may not have been applied during drill core mapping. Jr values estimated during tunnel mapping are on average approximately 35-40% lower than the values mapped in the drill cores. This can possibly be attributed to the presence of a few planar fractures in the tunnels that are deemed to be unfavourable for the tunnels stability dictating the Jr selection during Q parameter assessment. Such fractures have a significantly lower contribution to the drill core statistics where the “worst fracture” is assessed per meter core whilst such fractures in the tunnel can affect several meters of tunnel. This scale effect is not however seen in the average value for Ja which is generally in good agreement between tunnel mapping and drill core mapping. Similarly Jw shows little difference in the average value for tunnel mapping and drill core mapping for all the tunnel contracts. Interestingly the SRF value was generally set to 1 for the tunnel mapping in all contracts (average value 1 to 1,2) whilst the average in the drill core was 2,5 in all contracts which suggests that the methods for assessment of SRF differed between the two phases. It should also be noted that the sections of drill cores logged in the K1 area all had SRF values of 1. The average final Q value was generally 2-3 times greater for the drill core mapping compared with the tunnel mapping for all contracts, with the exception of NL34.

2.3 Comparative analysis

Kjellstöm (2015) also studied the distribution of Q parameters for the City Line contracts. These results, together with the results from the Northern Link presented in section 2.2 are summarized in Figure 5.

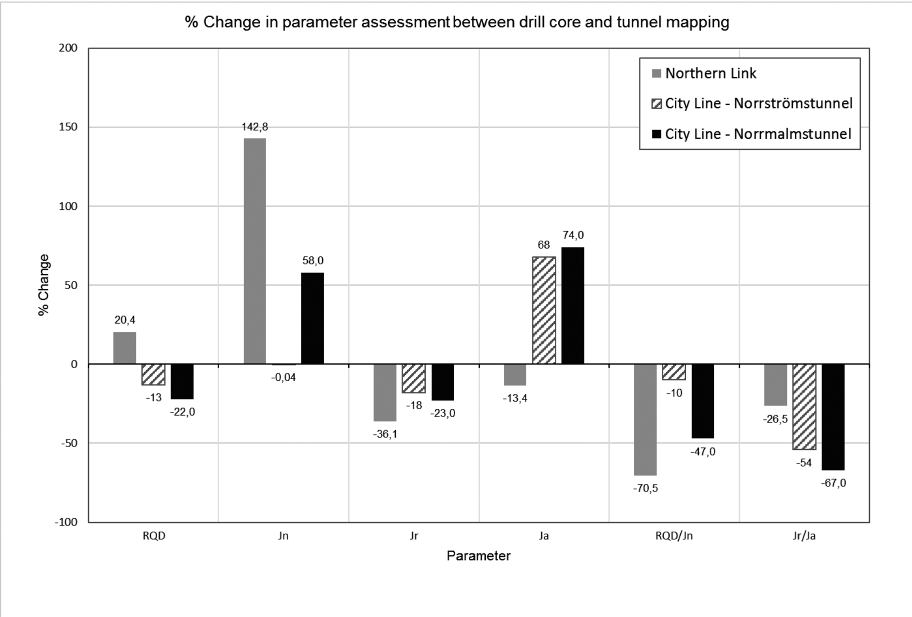


Figure 5. Diagram showing the mean change in Q parameter assessments from the drill core mapping to the tunnel mapping. Note that an increase in the denominators in the Q system (Jn and Ja in the diagram) results in a lowering of the final Q value.

2.3.1 Block size (RQD, Jn och discontinuity spacing)

RQD values measured during drill core mapping and estimated during tunnel mapping do not appear to be particularly sensitive to the methods used. This may be due to the fact that RQD is a parameter that is directly measured during drill core mapping and is therefore less open to subjective assessment. The decreases in the estimated RQD mapping values from the tunnel mapping in the City Line contracts is most likely due to the fact that RQD was calculated in 1 m sections in the drill core whereas, a characteristic value for RQD was applied to an area of tunnel during tunnel mapping. This process generally leads to slightly cautious estimates of RQD by the mapping geologist/engineer. Even possible blast induced fractures may contribute to a lower RQD assigned during tunnel mapping. The Northern Link data shows an increase of 20% in RQD for tunnel mapping compared with drill core mapping and does not agree with the City Line data. This may however, be due to the fact that a large number of the drill cores targeted weakness zones in the rock mass meaning that the data set is not necessarily representative of the general rock mass conditions. What can however, be concluded is that the method of evaluation of the RQD value in core logging and tunnel mapping appears to be reasonably consistent.

The average Jn value assessed during tunnel mapping (10.5) is significantly higher compared with core logging for the Northern Link (4.3). Whilst there is a degree of uncertainty regarding how geometry corrections for Jn were applied in the core logs, it is doubtful that the difference can solely be attributed to this. A similar although less dramatic trend with an increasing Jn value during tunnel mapping compared with drill core logging can be seen in the data for Norrmalmstunneln. The average Jn value from core logging and tunnel mapping is in good agreement for Norrströmstunneln.

The first quote in the Q system (RQD/Jn), which roughly equates to an approximation of block size, is estimated to be slightly lower for Norrströmstunneln and significantly lower for Norrmalmstunnel and the Northern Link when comparing average values for tunnel mapping compared with drill core logging. The equivalent block size estimates using the RMR system (RQD and discontinuity spacing) for the City Line contracts does not show such large discrepancies. This may partly be due to the fact that the Q-system works on a logarithmic scale. A further contributing factor may be the fact that both RQD and discontinuity spacing are measureable parameters, whereas Jn in the Q system requires a more subjective assessment of the number of joint sets. Jn is often difficult to evaluate in drill core and during tunnel mapping in excavated in rock masses with complex structural geology such as those that are commonly encountered in the Stockholm Region.

2.3.2 Discontinuity properties (Jr, Ja and discontinuity condition)

The average Jr value is roughly 10-30% lower in the tunnel mapping compared with drill core characterization in all the tunneling contracts. This effect clearly indicates that the methods used for determining representative Jr values introduce a systematic “error”. Jr is a parameter that is based on both large and small scale roughness features of discontinuities and the large scale “waveiness” portion is notoriously difficult to estimate in drill core. Furthermore the choice of parameter for Jr should be based on the discontinuity that is least favourable for stability both from the point of view of orientation and shear resistance. This means that there is an inherent difference in the method when selecting the least favourable discontinuity in 1 m sections of drill core compared with when this is done on a tunnel scale for representative areas. This “scale” effect is also likely to be present when assessing Ja values in rock cores and tunnels and is likely to be a contributing factor for the large decrease in average Ja value for the two City Line contracts in Figure 5. Interestingly however this effect does not seem to be apparent on the Northern Link project to the same degree.

Even RMR parameter 4 “discontinuity condition” shows a decrease in the average value from core logging to tunnel mapping. In the case of Norrströmstunneln the decrease is 2.56 points and in the case of Norrmalmstunneln it is 6.78 points. The previously mentioned “scale effect” is more than likely a contributing factor to these decreases.

2.3.3 Water conditions (Jw, groundwater)

The drill core assessment of Jw and assessment performed during tunnel mapping are for the Northern Link in excellent agreement and have an average value of 1 (dry conditions). This suggests that the good rock mass conditions, low groundwater pressures and systematic pre-grouting resulted in dry conditions in the tunnel. No significant discrepancy between core logging and tunnel mapping was seen in the assessment of parameter 5 in the RMR system, “Groundwater” for the Norrströmstunneln contract. This is likely to be due to the same reasons as for the Northern Link project. An average decrease of 2.62 points from core logging to tunnel mapping was observed on the Norrmalmstunneln contract and can most likely be attributed to the presence of waterbearing zones enountered in this contract that were difficult to seal during grouting. Large, systematic errors do however, not appear to have occurred when assessing water conditions in the various systems and contracts.

2.4 Limitations

One of the main limitations of this analysis is the assumption that the drill core provides a statistical representation of the rock mass for each tunneling contract. This assumption becomes progressively weaker as the amount of drill core data is reduced compared with the amount of tunnel excavated. The ratio of mapped drill core (m) to mapped tunnel (m) is 0.22 for the Northern Link project, 0.27 for Norrmalmstunneln and 0.46 for Norrströmstunneln.

A further limitation is the fact that in some of the contracts drill cores were specifically targeted to investigate weakness zones and poor rock conditions. This would, however, result in a bias towards less favourable parameter assessments during the drill core mapping, which is not an obvious trend in the data analyzed.

3 Discussion

Whilst there are clearly a number of limitations in the methodology used for these analyzes, there would appear to be clear trends in the data that suggest that systematic “errors” are introduced when performing rock mass characterization during the different phases of the project. These “errors” appear to result in lower RMR and Q values being assigned to an equivalent rock mass when performing tunnel mapping compared with when performing drill core logging. The process of performing geological interpretation and producing the EGF reduced this “gap” significantly in the Northern Link project, and to a certain extent for the Norrströmstunneln contract of the City Line but had limited impact on the “gap” for the Norrmalmstunneln contract.

The results also show that there is a significant variation in the way the parameters are assessed by different geologists and engineers in the different phases of the projects and tunneling contracts. This suggests that despite the fact that attempts were made to standardize the way in which the rock mass assessments were carried out, there remained a large degree of freedom for different interpretations. It should also be considered that the methods that were applied, particularly the use of standard 1 m sections for drill core assessment compared with representative areas in tunnel scale are likely to have contributed to the introduction of systematic “errors”.

One of the major questions a geologist or engineer faces when performing rock mass assessments during tunnel mapping is to consider what is representative for the tunnel section. There is always some degree of natural variation in the geological conditions and the selection of representative parameters becomes increasingly difficult with increasing heterogeneity of the rock mass. This problem is also shared by the tunnel designer and is illustrated in Figure 6.

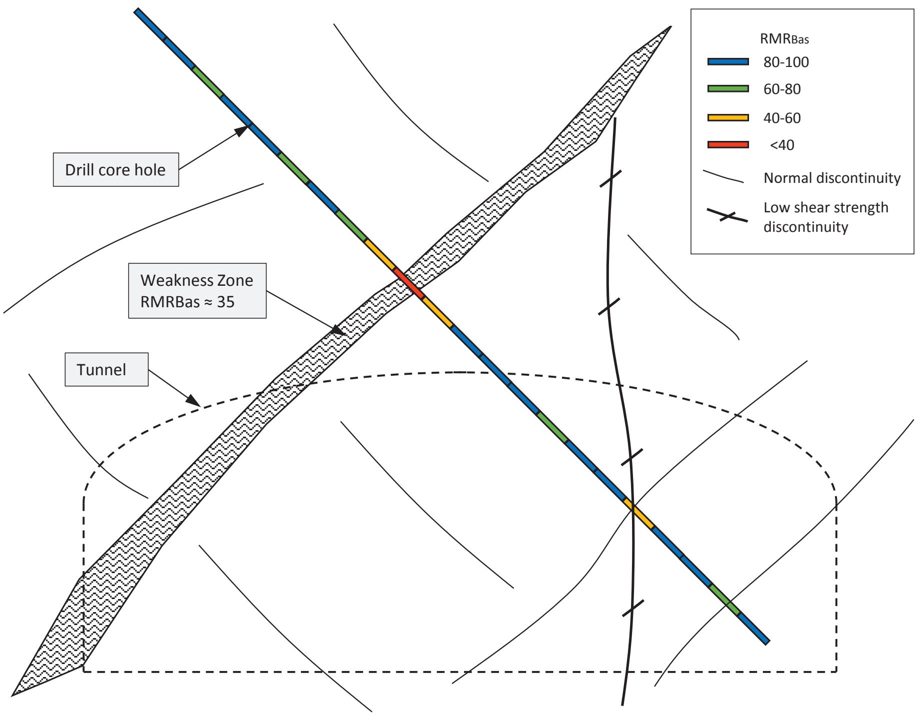


Figure 6. Example tunnel cross section showing rock mass quality in a drill core logged in 1 m sections together with the geological conditions encountered in the tunnel.

The example illustrated in Figure 6 is relatively typical of rock mass conditions in crystalline bedrock such as those encountered in the Northern Link and City Line projects. In this case the rock mass assessment of the drill core gives a general picture of a good quality rock mass with a small weakness zone (0,3-1 m thick). The orientation and location of the weakness zone, together with the presence of a low shear strength discontinuity would, however, likely result in a conservative assessment of the rock mass quality during tunnel mapping. Clearly this case could be forecast and designed for if sufficient geological information is available. However, such detailed information regarding the rock mass conditions is seldom available for the majority of the tunnel system and the design in such cases is generally done using typical support classes coupled with rock mass classes (usually Q or RMR). It is also difficult in such circumstances to forecast the presence of such features due to a lack of geological information at tunnel level. These issues can, if not properly accommodated for, result in the introduction of discrepancies between the forecast and the mapped rock mass quality. In order to assess the risk for introducing such systematic errors and resulting problems due to differing ground conditions, the following questions need to be addressed:

1. Does the rock mass assessment in the surrounding drill cores give a fair assessment of the geological conditions? Is the sampling size likely to introduce systematic “errors”?
2. Have the small but potentially critical portions of poor rock been adequately accounted for in the engineering geological forecast? This question is particularly relevant in areas where only limited pre-investigation data is available.
3. What is the basis for the rock engineering design? Is it based on an average rock mass quality, a “characteristic” rock mass quality or a minimum rock mass quality?

4. Are the methods used for characterizing the rock mass relevant to the chosen design methods and failure mechanisms?
5. Is it clear how the rock mass assessment during tunnel mapping should be performed in relation to the rock engineering design? For example should the assessment be done for the average rock mass quality, the "characteristic" rock mass quality or for the poorest rock mass quality?
6. Are the chosen methods for describing ground conditions in the design, tendering and construction phases relevant for the construction methods to be used?

In order to minimize the risk of introducing systematic errors during rock mass characterization the questions in point 1-5 above must be addressed together during the early stages of design work and prior to tendering. Point 6 relates more specifically to the way in which geological conditions are described for contractual purposes and should be given due consideration during the design phase from both technical and contractual aspects.

4 Recommendations

4.1 Guidelines for drill core logging

At present there is a lack of clear guidance for how drill cores should be logged and characterized. Current practice is based on the ISRM suggested methods (Brown, 1981). However, these offer little advice on how the various systems for rock mass classification/characterization should be applied on drill cores. The Swedish Transport Administration's rock engineering design handbook (Trafikverket publication 2014:144) gives some guidance for drill core logging but there is a lack of a modern standard/guideline that clearly states what parameters should be assessed and how the important rock mass characterization parameters are to be assessed. One possibility for this would be to develop a standard within the Swedish rock engineering community that defines a number of types/levels of core logging based on the detail and information required from the drill core. Such a standard could be included in tender documents and design contracts. This would also facilitate easier transfer of standardized digital data that subsequently can be submitted to the Swedish Geological Survey (SGU).

4.2 Geotechnical Baseline Reports

The North American geotechnical community have in recent years developed a concept for describing geotechnical conditions in a single interpretative report called a ***Geotechnical Baseline Report (GBR)*** which is included in the contract documents. The primary purpose of the GBR is to establish a single source document where contractual statement(s) are referred to as baselines and geotechnical risks can clearly be apportioned between the Owner and the Contractor. Interpretative documents and drawings for geological/geotechnical conditions are in most cases included in rock engineering contracts in Sweden. They are, however, frequently written in ambiguous terms. The GBR attempts to provide a clear and measurable baseline statements that also include information on the anticipated behavior of the ground with regard to the applicable methods of excavation and ground support. Guidelines for using GBR have been published by The American Society of Civil Engineers (Essex et al, 2007). It is recommended that the concept of GBR should be further investigated in order to assess if, and how, they can be applied in Swedish rock engineering contracts

4.3 Rock mass characterization for design purposes

The present method of designing rock engineering structures in many cases struggles to fully incorporate the complex geological conditions that are encountered in the tunnel. This is primarily due to a lack of available data regarding geological conditions, limitations in design methods and difficulties coupling the rock mass characteristics used in the design with characteristics that can be observed/measured during excavation. Advances have been made to this end by introducing specific engineering geological design criteria (see for example Swindell et al 2013), however, there is a need for further progress in this regard. The problem becomes accentuated when dealing with typical reinforcement design as it is generally used over large portions of a project with limited geological information.

There is in the authors' opinions a need for an objective review of the existing systems for rock mass characterization. What are the strengths and weaknesses of each system? How suitable are they for the local geological conditions and the type of rock excavations that are to be conducted? Can they be improved or modified to better describe the rock mass conditions and the likely failure mechanisms and selected design methods? How should the various systems be applied when applying them in the various phases of the project? These are all questions that need to be addressed when selecting methods for characterization of rock masses and a strategy for rock engineering design.

4.4 Guidelines for excavation mapping

Trafikverkets rock engineering design handbook (Trafikverket publication 2014:144) includes guidelines for engineering geological mapping of tunnels and rock slopes. The guidelines provide recommendations for the basic collection and presentation of engineering geological data during excavation mapping. They do not however include guidelines for the use/application of the various systems that are commonly used for rock mass characterization (RMR, Q, GSI etc.). The primary reason for their exclusion is that this process is directly association with the methods and assumptions applied during rock engineering design.

It is therefore recommended that guidelines for rock mass characterization conducted during excavation mapping are produced specifically for each project. Such guidelines should take into consideration design assumptions and methodologies and the methods used for producing the engineering geological forecast to ensure consistency in the methods applied during rock mass characterization during the various phases of a project.

4.5 Statistical analysis

The methods presented here should form the foundation for further statistical analysis of rock mass characterization methods on forthcoming rock engineering projects. The results should be used to form an empirical database to enable the rock engineering community to learn more about the engineering geological conditions commonly encountered in each respective geological region and to improve rock engineering design processes.

5 Acknowledgments

The authors would like to thank WSP and Sweco for providing rock mass characterization data and details of how the work was conducted for both the City Line and Northern Link contracts. Fredrik Bengtsson and Lars Martinsson also made significant contributions and provided useful advice for the work conducted on both Masters theses.

References

Barton, N. (2002) “Some New Q-value Correlations to Assist in Site Characterization and Tunnel Design”. *Int. J. of Rock Mech. & Min. Sci.* **39**. pp. 185-216.

Benhalima M. 2016. “Evaluation of the differences in characterization and classification of the rock mass quality: A comparision between pre-investigations, engineering geological forecast and tunnel mapping in the Northern Link project and the City Line project”. MSc thesis, KTH Royal Insitute of Tehcnology, Stockholm.

Brown, E. T. 1981. “Rock Characterization Testing and Monitoring”. ISRM Suggested Methods (Ed. E. T. Brown). Oxford: Pergamon Press.

Bieniawski, Z.T. (1989) *Engineering Rock Mass Classifications*. New York: Wiley & sons. ISBN 0-471-60172-1.

Essex, R.J. ed. (2007) *Geotechnical Baseline Reports for Construction: Suggested Guidelines*, American Society of Civil Engineers. ISBN: 9780784409305.

Kjellström, I. 2015. “Utvärdering av skillnader vid karaktärisering och klassificering av bergkvalitet: En jämförelse mellan förundersökning, prognos och byggskede i projekt Citybanan”. MSc thesis, KTH Royal Insitute of Tehcnology, Stockholm.

Lundman, P., 2011. “Cost Management for Underground Infrastructure Projects: A Case Study on Cost Increase and its Causes.” PhD thesis, Luleå Tekniska Högskola.

Swindell, R. and Rosengren, L., 2007 “Ingenjörsgeologiska Prognoser Inom Projekt Citybanan” (English Title: *The prediction of ground conditions for the City Line Project*). Proceedings Bergmekanikdagen 2007.

Swindell, R., Holmberg, M., Rosengren, L. and von Matérn, M., 2013 “Citybanan - tillämpning av aktiv design i entreprenad Norrströmstunneln” English Title: *Application of the active design concept for City Line contract Norrströmstunneln*). Proceedings Bergmekanikdagen 2013.

Trafikverket publication 2010:037 ” Förundersökningar vid undermarksprojekt - osäkerheter och deras hantering.”

Trafikverket publication 2012:213 “Osäkerheter i bergprognoser vid utförande av infrastrukturtunnlar – analys av två järnvägsprojekt”

Trafikverket publication 2014:144 ”Projektering av bergkonstruktioner”.