From Palmström A.: RMi – a rock mass characterization system for rock engineering purposes. PhD thesis, Oslo University, Norway, 1995, 400 p.

APPENDIX 8

COLLECTED DATA ON GROUND CONDITION AND TBM BORING PERFORMANCE

> *"The geotechnical engineer should apply theory and experimentation but temper them by putting them into the context of the uncertainty of nature. Judgement enters through engineering geology."*
> Karl Terzaghi, 1961

The data applied to correlate the model for TBM boring performance in Chapter 7 with practical experience have been collected from Svartisen hydropower plant and Meråker hydropower plant, both in Norway. The conditions used are described in the following.

1. Boring experience and ground conditions at Svartisen Power plant

58 km of the 79 km water tunnels at Svartisen hydropower plant, Nordland county has been excavated by tunnel boring machines during the years 1988 - 1993. The tunnels have diameter between 3.5 m and 8.5 m.

Data from three of the tunnels have been used in this work to find how the predicted performance developed in Chapter 7 fits with the boring advance obtained. The specifications of the TBM machines are as follows

TBM machine: Robbin high performance	type 251-1	type 252	type 257
Diameter of TBM	5.0 m	4.3 m	3.5 m
Recommended max. thrust per cutter, M_B	314 kN	314 kN	314 kN
Cutter spacing, S_C	100 mm	100 mm	90 mm
Number of cutters	35	29	25
Cutter size	19" (483 mm)	19"	19"
Cutterhead RPM	11.94	11.94	12.6
NTH factor for cutter diameter, k_d	1	1	1
NTH factor for cutter spacing, k_a	0.85	0.85	0.9

1.1 Measured rock properties

The rocks in the three tunnels are of Precambrian - Cambrian age. During metamorphism the sedimentary rocks were changed to mica schist, various gneisses, marble and quartzite. Small sized core drilling, diameter 32 mm, was used to collect samples from three of the tunnels. The results from the laboratory test are shown in Table A8-1. Uniaxial compressive strength could not be measured due to the small sample size.

TABLE A8-1 RESULTS FROM LABORATORY TEST ON WET SAMPLES FROM SVARTISEN

LOCATION		SONIC VELOCITY		POINT LOAD STRENGTH				TYPE OF ROCK	Calculated $\sigma_c = k_{50} \times Is_{50}$	
TBM	chainage	velocity (m/s)	angle	test direc-tion	strength Is_{50} (Mpa)	no. of tests	thickness of sample (mm)		k_{50}	σ_c (Mpa)
252	1200	4680	60°		2.0	10	32	Marble	14	30
	2950	4120	45°	‖ ⊥	1.1 7.9	8 4	32 12 - 16	Mica schist	14 20	15 160
	6480	4435	-	‖ ⊥	6.9 8.5	6 8	32 13 - 25	Gneiss-granite	20 20	140 170
	10180	5260	35°	‖	5.5	6	32	Mica gneiss	16	90
	11755	3160	45°	‖ ⊥	0.6 4.7	5 5	32 12 - 18	Mica schist (laminated)	14 16	10 75
257	1650	5525	0°	‖ ⊥	2.0 6.5	3 6	32 14 - 16	Mica gneiss	14 16	30 100
	3965	3910	35°	‖ ⊥	1.1 3.0	4 3	32 12 - 16	Mica gneiss	14 14	15 40
	4180	3850	40°	‖	1.1	6	32	Mica gneiss (mica layers)	14	15
251-1	6335	5585	5-10°	‖ ⊥	1.5 5.3	2 2	32 14 - 18	Mica schist (laminated)	14 16	20 85
	7460	6110	35°	‖ ⊥	3.6 6.6	5 7	32 16 - 32	Marble (layered)	16 20	50 130
	8445	5150	30°	‖	2.8	4	32	Mica schist	14	40

In addition, laboratory tests carried out by the Robbins company gave the results in Table A8-2.

TABLE A8-2 LABORATORY TEST PERFORMED BY THE ROBBINS COMPANY

LOCATION		COMPRESSIVE STRENGTH		POINT LOAD STRENGTH		TYPE OF ROCK	Calculated $\sigma_c = k_{50}\ Is_{50}$	
TBM	chainage	angle*)	σ_c (Mpa)	test direc-tion	Is_{50} (Mpa)		k_{50}	σ_c (Mpa)
251-1	8142	10°	113	‖ ⊥	1.7 6.1	Mica schist	14 18	20 110
	8400	10°	110	‖ ⊥	1.6 4.7	Mica schist	14 16	20 75
	8456	10°	119	‖ ⊥	2.6 4.8	Mica schist	14 16	35 75
	8494	10°	75	‖ ⊥	1.8 6.1	Mica schist	14 18	25 110

*) Angle between loading and schistosity

The drilling rate index for mica schist and mica gneiss is DRI = 55, for marble DRI = 80.

1.2 Rock mass description in tunnel locations

The detailed registration of the rock mass conditions in the tunnels, Table A8-3, has been worked out from observations made by graduate students at the Technical University of Norway (NTH) in connection with their final dissertation work in tunnel engineering; it is referred to Isaksen and Solberg (1990) and Stang and Aadal (1991). The mica rich rocks encountered in the three tunnels are strongly anisotropic with discontinuities occurring as foliation partings (fissures) spaced 0.1 m - 1 m. Some few random joints occur. Generally, the joints and fissures do not delimit defined blocks.

TABLE A8-3 DESCRIPTION OF THE GROUND CONDITIONS AT VARIOUS LOCATIONS

LOCATION		DESCRIPTION
TBM	chainage	
252	1200	Relatively massive marble with some actinolite. Joint spacing S = 1.6 m, angle with foliation $\alpha = 35^o$. Applied thrust per cutter M_B = 236 kN.
	2950	Mica schist, occasionally containing garnets. The rock is dark often with veins or lenses of quartzpegmatite. Thin layers of mica often occur along foliation, and the rock is partly folded. Spacing of foliation partings (fissures) S = 0.2 m, $\alpha = 10^o$. M_B = 236 kN.
	6480	Granitic gneiss. The rock is light grey and folded. Some few thin layers of mica occur along the foliation. High content of feldspar; hard rock to bore in. Joint spacing S = 0.8 m, $\alpha = 90^o$. M_B = 265 kN.
	10180	Folded mica gneiss, often with quartzpegmatite. Some garnet and thin mica layers along foliation. Many of the joints have mica filling. Foliation partings (fissures) are spaced S = 0.2 m, $\alpha = 44^o$. M_B = 236 kN.
	11755	Folded mica gneiss containing some quartzpegmatite and some few enrichments of mica occurring as veins, thin zones. Dark diorite and granitic gneiss partly occur. Foliation partings are spaced S = 0.3 m, $\alpha = 27^o$, M_B = 228 kN..
257	1650	Partly folded mica schist, frequently containing quartzpegmatite. Some veins or thin layers of mica occur. Spacing of foliation partings (fissures) S = 0.2 m, $\alpha = 0^o$. M_B = 298 kN.
	3965	Mica gneiss with quartzpegmatite and veins of granitic gneiss and layers of mica. Foliation partings are spaced S = 0.4 m, $\alpha = 15^o$. M_B = 289 kN.
	4180	Same as 3965, but the degree of jointing is higher. Foliation partings are spaced S = 0.3 m $\alpha = 15^o$. M_B = 289 kN.
251-1	6335	Mica schist with some quartzpegmatite veins. Foliation partings are spaced S = 0.075 m, $\alpha = 25^o$. M_B = 160 kN.
	7460	Marble with a few veins containing amphibole, sometimes folded. Joint spacing S = 0.8 m, M_B = 240 kN.
	8400	Mica gneiss with quartzpegmatite, sometimes folded, sometimes schistose, sometimes quartzrich. Veins of mica are present. Foliation partings spaced S = 0.4 m, $\alpha = 15^o$. M_B = 272 kN.
	8445	Rock: same as 8400. Foliation partings spaced S = 0.3 m, $\alpha = 15^o$, M_B = 240 kN.
	8456	Rock: same as 8400. Foliation partings are spaced S = 0.3 m, $\alpha = 15^o$, M_B = 280 kN.
	8494	Rock: same as 8400. Foliation partings are spaced S = 0.4 m, $\alpha = 20^o$, M_B = 240 kN.

The marble is almost massive, also the gneissgranite generally contains few joints. In these types of rocks the discontinuities occur mainly as joints. Table 7-2 in Chapter 7 has been applied to find the equivalent block volumes from the spacings. The results of the calculations made to find the TBM jointing factor are shown in Table A8-4.

TABLE A8-4 ROCK MASS FEATURES AND CALCULATED JOINTING FACTORS

TBM and chainage	Rock type	Compr. strength σ_c	Rock factor E	OBSERVATIONS joint spacing	jC	angle	CALCULATIONS*) eq. Vb (m^3)	c_o	JP	k_{eq}
252										
1200	marble	30	1000	massive					1.0	0.74 (0.9)
2950	mica schist	15	750	0.2 m	6	10°	1.5	1	0.54	1.35 (1)
6480	gneissgranite	140	1000	0.8 m	2	90°	50	1.5	0.98	0.66 (0.75)
10180	mica gneiss	90	750	0.2 m	6	40°	1.5	1.5	0.54	1.18 (1.25)
11755	mica gneiss	10	750	0.3 m	6	27°	4	1.25	0.70	1.47 (1.1)
257										
1650	mica schist	30	750	0.2 m	6	0°	1.5	1	0.54	1.10 (1.1)
3965	mica gneiss	15	750	0.4 m	6	15°	10	1.25	0.89	1.0 (0.8)
4180	mica gneiss	15	750	0.3 m	6	15°	4	1.25	0.70	1.30 (1.0)
251-1										
6335	mica schist	20	750	75 mm	6	25°	0.08	1.25	0.25	3.35 (2.27)
7460	marble	50	1000	0.8 m	2	-	50	1	0.98	0.60 (0.42)
8400	mica schist	20	750	0.4 m	6	15°	10	1.25	0.89	0.94 (0.68)
8445	mica schist	40	750	0.3 m	6	15°	4	1.25	0.70	0.97 (1.0)
8456	mica schist	35	750	0.3 m	6	15°	4	1.25	0.70	1.0 (1.0)
8494	mica schist	25	750	0.4 m	6	20°	10	1.25	0.89	0.88 (0.74)

*) The values in brackets have been found using the NHT model, version 5.

TABLE A8-5 MACHINE PARAMETERS AND DRILLING RATE

TBM and chainage	Applied thrust M_B (kN)	TBM jointing factor k_{eq}	CALCULATIONS*) Eq. thrust M_{eq} (kN)	----- TBM penetration ----- per rev. i_o (mm)	boring rate I (m/h)	**Real boring rate** I (m/h)
252						
1200	236	0.74 (0.9)	200	3.0 (3.6)	2.1 (2.6)	2.89
2950	236	1.35 (1)	200	4.8 (4.0)	3.4 (2.9)	4.52
6480	265	0.66 (0.75)	225	3.0 (3.6)	2.1 (2.6)	1.47
10180	236	1.18 (1.25)	200	4.4 (4.6)	3.1 (3.3)	4.8
11755	228	1.47 (1.1)	195	5.0 (4.2)	3.6 (2.9)	4.3
257						
1650	298	1.10 (1.1)	268	6.4 (6.4)	4.8 (4.8)	3.14
3965	289	1.0 (0.8)	260	6.1 (5.4)	4.6 (4.1)	3.86
4180	289	1.30 (1.0)	260	6.8 (6.4)	5.1 (4.8)	4.1
251-1						
6335	160	3.35 (2.27)	135	4.5 (4.0)	3.2 (2.9)	3.85
7460	240	0.60 (0.42)	205	2.7 (1.6)	1.9 (1.2)	3.54
8400	272	0.94 (0.68)	230	4.8 (3.6)	3.4 (2.6)	4.0
8445	272	0.97 (1.0)	230	4.8 (4.8)	3.4 (3.4)	4.5
8456	280	1.0 (1.0)	240	5.3 (5.3)	3.8 (3.8)	5.06
8494	240	0.88 (0.74)	205	3.8 (3.2)	2.7 (2.3)	4.19

*) The values in brackets have been found using the NHT model, version 5.

2. Boring experience and ground conditions at Meråker hydropower plant

9634 metres of the diversion tunnel Dalåa - Torsbjørka at Meråker hydropower plant, Tröndelag county has been excavated using a full face tunnel boring machine. The boring performed 1991 - 1992, started in greywacke and meta-gabbro with unconfined compressive strength 180 - 300 MPa. In fact, the first 400 m of this tunnel was excavated by drill & blast, because the meta-gabbro in this part was assumed too strong for economic TBM boring. Later, a section more than 50 m long was successfully bored in this type of rock. The first of the two locations described in the following, is from the meta-gabbro.

The average net boring advance for the whole tunnel was 6.38 m/h. More than 1000 m/month has been achieved from the beginning, including boring through the strong meta-gabbro mentioned above. The TBM machine specifications are:

Machine: Robbins high performance TBM, type	265
Diameter of TBM	3.5 m
Recommended max. thrust per cutter, M_B	312 kN
Cutter spacing, S_C	90 mm
Number of cutters	26
Cutter size	19" (483 mm)
Cutterhead RPM	13.4
NTH factor for cutter diameter, k_d	1.0
NTH factor for cutter spacing, k_a	0.9

The actual tunnel is located in the Caledonian mountain range. The rocks are mainly of sedimentary or volcanic origin, but have later through metamorphism been changed into phyllite/clayschist and greenstone, respectively. Some eruptive intrusions of gabbro occur occasionally.

The rock mass condition in the tunnel have been mapped in two locations; one in meta-gabbro (chainage 750) and the other in greenstone (chainage 10020). Point load strength tests have been made on wet and dry rock samples as shown in Table A8-6.

TABLE A8-6 RESULTS FROM LABORATORY TEST ON SAMPLES FROM MERÅKER

LOCATION		Condition of sample	Test direction	SOUND VELOCITY	POINT LOAD STRENGTH			TYPE OF ROCK	Calculated $\sigma_c = k_{50} \cdot Is_{50}$	
TBM	chainage			v (m/s)	Is_{50} (Mpa)	no. of tests	thickness of sample (mm)		k_{50}	σ_c (Mpa)
265	750	wet		8000	12.0 [1)]	17	20 - 32	Meta-gabbro	25	300
		dry		4100	13.4	9	28 - 29			
	10020	wet	∥	5160	1.9	6	25 - 26	Greenstone (laminated)	14	30
			⊥	4700	7.1 [2)]	12	18 - 25		20	140
		dry	⊥	3500	14.8	10	15 - 21			

1) Tests carried out by SINTEF, Trondheim gave Is_{50} = 11.0 MPa
2) Tests carried out by SINTEF, Trondheim gave Is_{50} = 7.1 MPa

2.1 Observations at chainage 750

The rock consists of meta-gabbro, slightly chloritized. It contains irregularly distributed white stripes, partly as thin layers up to 2 m long, and lenses 0.1 - 0.2 m thick up to 0.5 m long. The drilling rate index determined at SINTEF, Trondheim is DRI = 24 - 45 (average DRI = 35).

The 1-3 m long joints are unevenly distributed. They are slightly undulating and rough with spacing 0.3 -1 m. Some of the white stripes in the rock represent weakness planes. The block size is mainly Vb = 0.25 - 1 m^3. This could more easily be observed in the drill&blast part of the tunnel excavated before TBM started (chainage 0 - 400).
The applied TBM thrust M_B = 275 kN/cutter resulted in a net advance I = 6 m/h.

2.2 Observations at the brook intake, chainage 10020

The rock consists of a laminated greenstone containing many white and light coloured stripes. It splits along thin foliation partings with chlorite/mica which are spaced 0.03 m - 0.2 m. The drilling rate index has been measured as DRI = 43.
The strike of the foliation is 20 - 30^o related to the orientation of the tunnel with dip 30^o towards the intake.

The joints consist mainly of the 0.1 - 2 m long foliation partings which have slightly undulating, smooth joint surfaces. Occasionally more massive (approx. 1 m thick) 'layers' occur. Where locally some few 3 - 4 m long random joints occur the expereince was that the same boring advance could be achieved with less cutter thrust.

The applied TBM thrust is M_B = 265 kN/cutter which resulted in a net advance
I = 7.7 m/h.

TABLE A8-6 ROCK MASS FEATURES AND CALCULATED JOINTING FACTORS

Chainage	Rock type	Compr. strength σ_c	Rock factor E	OBSERVATIONS Vb (m^3)	OBSERVATIONS jC	OBSERVATIONS angle	CALCULATIONS c_o	CALCULATIONS JP	CALCULATIONS k_{eq}
750	meta-gabbro	300	1000	0.5	2	0 - 5^o	1	0.22	1.55
10020	greenstone	30	750	0.2	2	12^o	1	0.17	3.5

TABLE A8-7 MACHINE PARAMETERS AND DRILLING RATE

Chainage	Applied thrust M_B (kN)	TBM jointing factor k_{eq}	CALCULATIONS Eq.thrust M_{eq} (kN)	CALCULATIONS ---- TBM penetration ---- per rev. i_o (mm)	CALCULATIONS TBM penetration boring rate I (m/h)	**Real boring rate** I (m/h)
750	275	1.55	250	6.8	5.5	6.0 [1)]
10200	265	3.5	240	8.3	6.7	7.7 [2)]

[1)] Calculations carried out by NTH: average net advance I = 4.05 m/h with 275 kN/cutter and DRI = 40.
[2)] NTH calculation: average net advance I = 5.19 m/h with thrust M_B = 265 kN/cutter and DRI = 42.