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Forsmark site investigation

Rock mechanics characterisation of borehole KFM04A

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October 2005

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

Abstract

The report illustrates the characterisation of borehole KFM04A by means of the two independent empirical systems Q (version 2002) and RMR (version 1989). The systems are applied to the geomechanical data provided in digital format by SICADA according to SKB's Methodology for the "characterisation" of the rock mass.

The quality of the rock along the borehole is generally "good" to "very good", and improves for the lower 500 m of the borehole. On average RMR is 89 for the competent rock and 82 for the deformation zones/fractured rock, respectively. On average, Q is 266 for the competent rock and 45 for the deformation zones, respectively. By means of empirical relations, the mechanical properties of the rock mass could also be estimated.

The deformation modulus varies between 53 and 65 GPa if determined by means of RMR, while it varies between 34 and 69 GPa when determined by means of Q. The Poisson's ratio could be estimated to about 0.23 for the competent rock and 0.20 for the deformation zones. By means of the relations between RMR, GSI and the Hoek and Brown's Strength Criterion, the uniaxial compressive strength, cohesion and friction angle of the rock mass were calculated. The uniaxial strength varies between 95 and 60 MPa, the cohesion between 27 and 22 MPa and the friction angle between 49° and 48° for stresses from 10 to 30 MPa, where the highest value applies to the competent rock and the lowest to the deformation zones, respectively. The analyses also show that the empirical methods give different results depending on the length of core on which they are applied: RMR does not vary much, while Q diminishes when longer core sections are considered. This is mainly due to the number of fracture sets that increase by increasing the length of the borehole section producing a lower Q-value. The results listed for each rock unit in this report are also delivered to SICADA (for 5 m core length).

The P-wave velocity was measured on the core at different depth. Here, its correlation with the rock foliation and its variation with depth are investigated. A rather abrupt decrease of the P-wave velocity can be observed below 500 m. However, the minimum P-wave velocity is almost constantly larger than 5,000 m/s.

Sammanfattning

I denna rapport beskrivs den empiriska karakteriseringen av borrhål KFM04 med hjälp av de två oberoende empiriska systemen RMR och Q. Systemen tillämpas på geomekanisk data i digitalformat enligt SKB:s metodologi för ”karakterisering” av bergmassan.

Generellt varierar bergmassans kvalité mellan ”bra” och ”mycket bra” berg och är bättre under 500 m. I genomsnitt är RMR-värdet 89 för kompetent berg och 82 för deformationszoner. Q är i genomsnitt 266 för kompetent berg och 45 för deformationszonerna. Med hjälp av empiriska samband kan bergmassans mekaniska egenskaper beräknas.

Deformationsmodulen varierar mellan 53 och 65 GPa när den uppskattas med RMR, medan den varierar mellan 34 och 69 GPa vid uppskattning med Q. Poisson-talet kan uppskattas till 0,23 för kompetent berg respektive 0,20 för deformationszoner. De empiriska sambanden mellan RMR, GSI och Hoek and Brown’s Criterion ger bergmassans enaxiella tryckhållfasthet, kohesion och friktionsvinkel beräknas. Enaxiella tryckhållfastheten varierar mellan 95 and 60 MPa, kohesionen varierar mellan 27 och 22 MPa medan friktionsvinkeln varierar mellan 49° and 48° för bergspänningar mellan 10 och 30 MPa, där de högsta värden gäller kompetent berg och de lägsta deformationszoner. Analysen påvisar att de empiriska metoderna ger olika resultat beroende på vilken borrkärnlängd de tillämpades på. RMR varierar inte så mycket, däremot minskar Q när längre borrkärnebitar karakteriseras. Detta beror på antalet spricksystem som ökar när längre kärnbitar karakteriseras och leder till att Q-värdet minskar. Resultaten redovisas för varje bergenhet 5 m borrkärnelängd och därefter levereras till SICADA.

P-vågshastigheten analyserades med djupet och korrelerades med foliationen i berget. En skarp gräns går vid 500 m där P-vågshastigheten börjar minska långsamt. Den lägsta P-vågshastigheten är oftast högre än 5 000 m/s.

Contents

1 Introduction

1.1 Background

Borehole KFM04A is a peripheral placed telescopic core borehole drilled towards the Forsmark Candidate Area. The borehole has a length of about 1,001 m and is drilled with a bearing angle of 45° and inclination of 60°. The core diameter for the depths between 100 and 1,001 m is 51 mm. The complete core was recovered and pictures of the borehole walls were continuously recorded by BIPS /Petersson et al. 2004/.

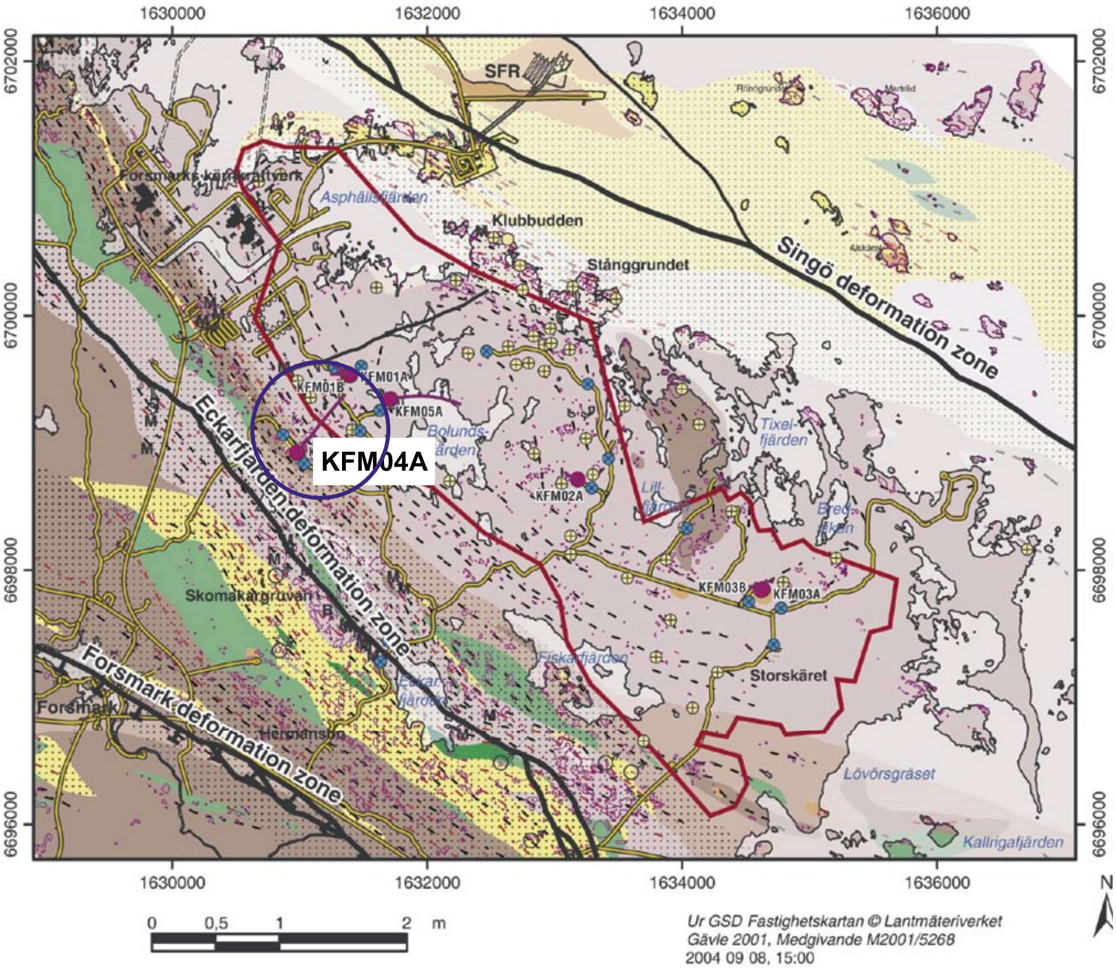

Figure 1-1. *Overview of the Forsmark Site with indication of the Candidate Area and borehole KFM04A.*

1.2 Objectives

The objectives of this study are as follows:

- Evaluate the rock mass quality along borehole KFM04A by means of the empirical systems RMR and Q.
- Quantitatively characterise the rock mass by determining its deformation modulus, Poisson's ratio, uniaxial compressive strength, cohesion and friction angle.
- Give summarising properties for the pseudo-homogeneous rock units identified in the geological single-hole-interpretation /Carlsten et al. 2004/.
- Discuss the results of the characterisation and list the main conclusion of the work.

1.3 Scope

The characterization of the rock mass along the borehole is performed mainly based on data that come directly from the borehole (single-hole interpretation). This enables for a rock quality determination that apply locally. When comparing the results for different depths, the spatial variation along borehole KFM04A can be highlighted. This Rock Mechanics Report is structured as follows:

- Summary of the BOREMAP data on rock types and fractures. The fracture sets occurring along the borehole are illustrated together with their frequency and spacing.
- Summary of the mechanical properties of the common rock types at the site and of the rock fractures (see also Appendix A).
- Application of the RMR and Q empirical systems for determination of the rock quality along borehole KFM04A (see also Appendix B). The determination of the input parameters is illustrated as well as some spatial variation, scale effect and uncertainty.
- Determination of the continuum equivalent mechanical properties of the rock mass based on empirical relations with RMR and Q. The deformation modulus, Poisson's ratio, uniaxial compressive strength, cohesion and friction angle of the rock mass are determined and shown as a function of depth. The uncertainties of the deformation modulus determination are also treated (see also Appendix C).
- Discussion of the results.
- Storage of the results in SICADA.
- Appendices.

2 Boremap data

Borehole KFM04A was mapped by examining the core and the BIPS pictures taken on its wall /Petersson et al. 2004/. The geological parameters obtained and stored in SKB's geological database SICADA were:

- Frequency of the fractures.
- RQD evaluated on core lengths of 1 m.
- Rock types, rock alteration and structural features.

Each fracture observed along the borehole was classified among "open" and "closed" ("sealed" or "unbroken"). The rock mechanics characterisation in this report is based on the properties of the "open" and "partly open" fractures. The following geological features of the fractures were observed:

- Depth of occurrence.
- Mineralization or infilling.
- Roughness and surface features.
- Alteration conditions.
- Orientation (strike and dip).
- Width and aperture.

A direct estimation of the Q-parameter Joint Alteration Number (J_a) was performed by the geologists. The information listed above is contained in the geological and rock mechanics digital database SICADA by SKB.

For the rock mechanics evaluation of the geological information, some more parameters were determined:

- Bias correction of the orientation and spacing by Terzaghi's weighting.
- Assignation of each fracture to a fracture or to a group of random fractures.

The recognition of the main fracture sets occurring in the rock mass along the borehole was based, not only on the BOREMAP information directly available, but also on the indications of earlier studies for the construction of the Unit 3 of the Nuclear Power Plant and for the SFR Repository for low and intermediate active nuclear waste. Figure 2-1 shows the summary pole plot of the fracture set orientation. Some of the open fractures were not assigned to any fracture set and constitute the group of "random fractures".

Once the fracture sets were identified within each rock unit along the borehole, the mean orientation and Fisher's constant were determined (Table 2-1 and Table 2-2). Based on the orientation pole concentrations shown in Figure 2-1, the fractures were assigned to the fracture sets for every 5 and 30 m core length. In this way, not only the number of fractures for each occurring set could be calculated, but also the frequency and spacing of each fracture set were determined. For the fracture spacing the Terzaghi's correction was applied considering the linear sampling of the fractures applied by the drilling.

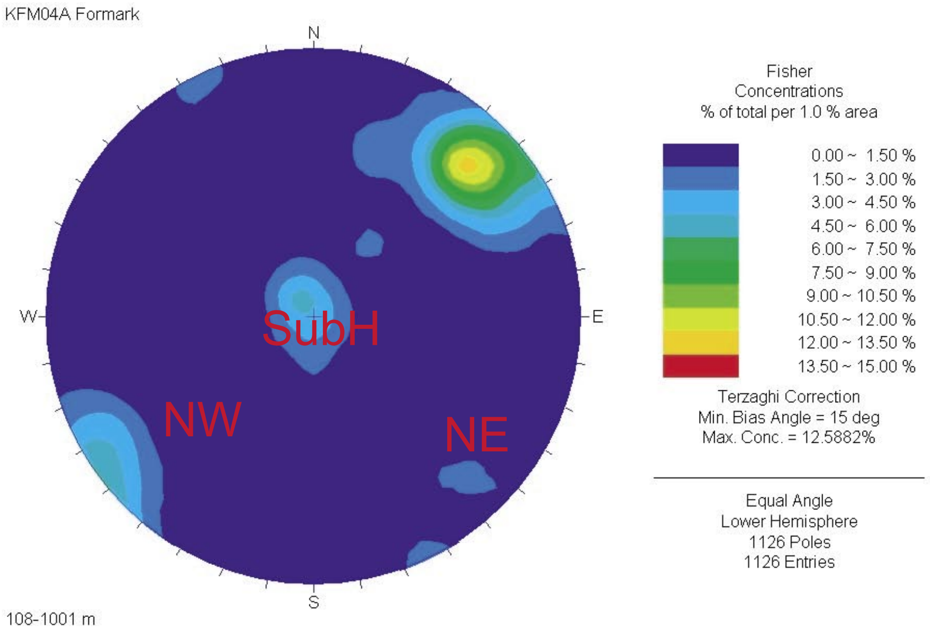

Figure 2-1. *Equiangle pole plot of the fractures logged along borehole KFM04A and indication of the main fracture sets. The borehole orientation is 045/60.*

Table 2-1. Set identification from the fracture orientation mapped for borehole KFM04A (SICADA, 04-05-25). The orientations are given as strike/dip (right-hand rule).

Depth [m]	No. of fractures	EW	NW	NE	SubH
107–177	193		139/80	228/87	308/04
177–275	242		136/74		359/03
275–342	142		135/84	230/82	
342–443	244		134/84		100/12
443–500	77		146/75		079/16
500–724	86	071/86	144/75		099/13
724–743	20		142/73		072/17
743–938	100		148/85		067/06
938–1,000	22		143/87		

Table 2-2. Fisher's constant of the fracture sets identified for borehole KFM04A (SICADA, 04-05-25).

Depth [m]	No. of fractures	EW	NW	NE	SubH
107–177	193		61.1	91.8	27.7
177–275	242		68.1		24.3
275–342	142		29.1	46.7	
342–443	244		21.7		7.3
443–500	77		79.3		17.5
500–724	86	184.9	39.3		22.1
724–743	20		27.4		25.7
743–938	100		29.9		30.0
938–1,000	22		32.9		

The total frequency of the fractures gives an idea of the degree of fracturing of the core. In Figure 2-2, where the frequency is averaged for each 5 m core length, some zones of higher fracture frequency are observed at the depth between 165 and 250 m and between 350 and 380 m (more than 5 fractures per metre). The peaks of frequency of the sub-horizontal fracture set also occur at those depths. The peak at about 350–380 m does not involve sub-horizontal fractures.

The Rock Quality Designation, RQD, that give the sum of the length of core pieces longer than 100 mm for every metre of borehole core, is also given in SICADA and plotted in Figure 2-2. Here, average values for every 5 m core length are presented. RQD shows values down to 65 at about 235 m depth. RQD is otherwise relatively high (larger than 80).

By counting the number of fracture sets occurring in each 5 m section of core, the plot of the number of fracture sets contemporarily occurring in Figure 2-2 can be obtained. For borehole KFM04A, the number of fracture sets occurring at the same time is generally one or two. Only at the depth of 145 m three fracture sets are occurring at the same time.

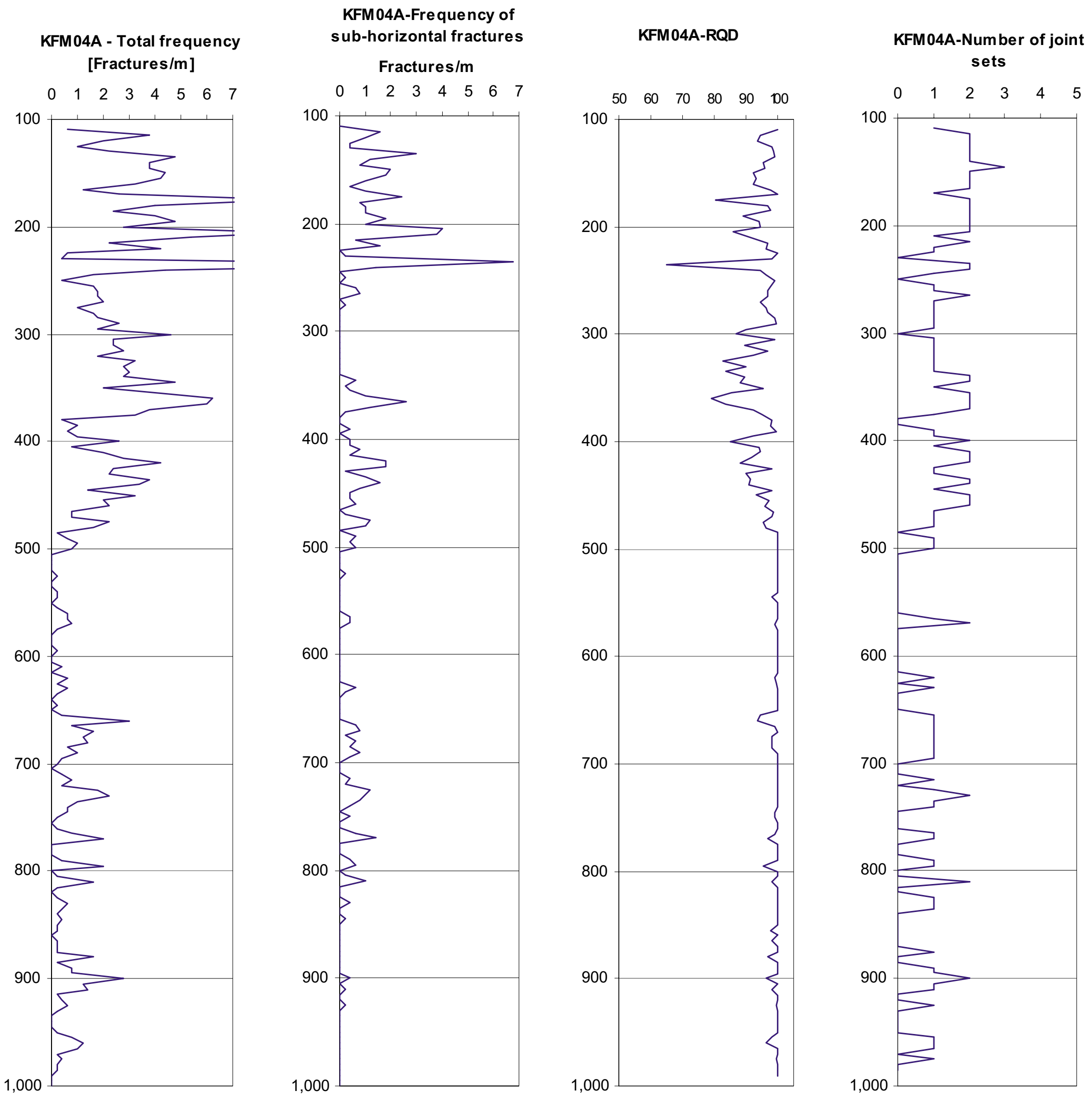

Figure 2-2. Variation of the total fracture frequency, frequency of the sub-horizontal fractures, RQD and number of fracture sets with depth for borehole KFM04A. The values are averaged for each 5 m length of borehole.

The spacing of each of the fracture sets occurring in Borehole KFM04A is shown in Figure 2-3. The sub horizontal fracture set SubH, occurs above 830 m with rather varying spacing down to a fraction of metre. The set NW appears along continuous core sections of length of about 40 to 200 m. The sets EW and NE can be observed in very short sections of the boreholes. The set NS is completely absent in KFM04A. Low fracture spacing is experienced below 500 m and RQD is almost constantly 100.

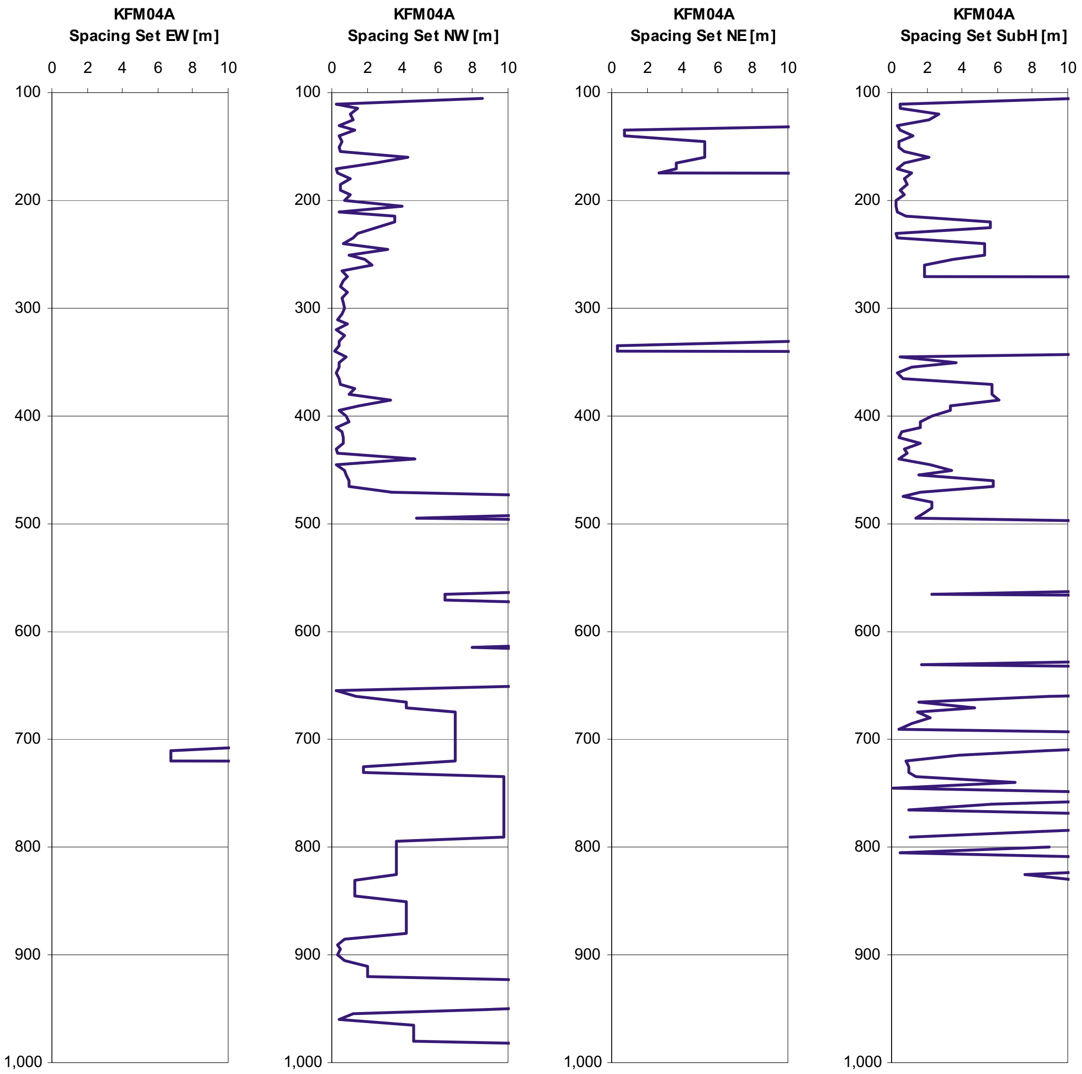

Figure 2-3. *Fracture spacing with depth for the five facture sets in borehole KFM04A. The values are averaged for each 5 m length of borehole.*

3 Mechanical tests

A campaign of laboratory tests was carried out on core samples from Borehole KFM01A, KFM02A, KFM03A and KFM04A. The results were delivered to SKB's database SICADA on July 30th, 2004. (The characterisation of borehole KFM04 was carried out right after this date.) The data contain:

- Uniaxial (68) and triaxial (59) compressive tests on intact rock.
- Indirect tensile strength tests on intact rock (143 Brazilian Tests).
- Shear tests (96) on fracture samples (9).
- Tilt tests (142) on fracture samples.

Two representative rock types were sampled in Forsmark: granite (medium-grained metagranite, rock code 101057) and tonalite (medium-grained metatonalite, rock code 101051).

3.1 Intact rock density

The intact rock density for the rock types in Forsmark varies around 2.75 g/cm^3.

3.2 Intact rock strength

Uniaxial compressive tests were performed on the samples of granite. Table 3-1 shows the range of variation and the mean value of the laboratory results.

Table 3-1. Summary of the results of Uniaxial Compressive Strength tests (UCS) on granite to granodiorite samples performed on intact rock samples from boreholes KFM01A–KFM04A.

Rock type	Number of samples	Minimum UCS [MPa]	Mean UCS [MPa]	Frequent UCS [MPa]	Maximum UCS [MPa]	UCS's Standard deviation [MPa]
Granite to granodiorite, metamorphic, medium-grained	52	166	225	223	289	22

A set of representative mechanical properties of the intact rock based on the laboratory data has been used for determining the empirical ratings for the RMR and Q systems. These values consider the broader variability due to the presence of: i) occurrences of different rock types within a pseudo-homogeneous rock unit; ii) possible sampling bias on preferably very good rock; ii) presence of sealed fractures that have not been taken into account otherwise in the empirical characterisation; iii) accounting for alteration within the sections with higher fracture frequency and within the deformation zones. The rock mechanics properties used in this report are:

- Uniaxial compressive strength of the intact rock.
- The Hoek and Brown's parameters of the intact rock obtained from triaxial tests.
- The Young's modulus and Poisson's ratio of the intact rock.

The values of these parameters for granite to granodiorite and for tonalite to granodiorite (estimated) are listed in Table 3-2.

Table 3-2. Mechanical properties of the intact rock used for the empirical characterisation and of the rock mass. The same set of properties is used to determine the mechanical properties of the rock mass.

Rock type	Material property	Minimum	Mean	Frequent	Maximum
Granite to granodiorite	UCS [MPa]	100	200	210	300
	Young's modulus E [GPa]	40	75	75	90
	Poisson's ratio ν [–]	0.17	0.24	0.24	0.31
	Hoek and Brown's m [–]	25	30	30	35
Tonalite to granodiorite (estimated by July 30th, 2004)	UCS [MPa]	100	150	150	200
	Young's modulus E [GPa]	40	75	75	90
	Poisson's ratio ν [–]	0.20	0.27	0.27	0.34
	Hoek and Brown's m [–]	7	9.5	9.5	12

3.3 Rock fracture properties

Tilt tests and direct shear tests were performed on samples from borehole KFM04A. In Table 3-3, a summary of the frictional properties of the tilt test on samples from borehole KFM04 are summarised. Table 3-4 shows the cohesion and friction angle determined based on all direct shear test results available in Forsmark by July 30th, 2004.

Table 3-3. Summary of the results of tilt tests performed on rock joints from borehole KFM04A (SICADA, 2004-07-30).

Fracture set	Number of samples	Basic friction angle**	JRC(100)**	JCS(100)**	Residual friction angle**
Set NW	2	32	4–7	60–63	26–27
Set SubH	8	30–33	5–7	48–139	25–34
Random	2	29–32	6	65–102	28–29
All fractures	22*	31(1)	6 (1)	80(23)	28 (2)

* This number includes the testing results of twelve sealed fractures.
** The ranges of variation of the parameters are reported. For all fractures, instead, the average value and the standard deviation (between brackets) of the parameters are listed.

Table 3-4. Mean on friction angle and cohesion for the Coulomb's Criterion of all direct shear tests on samples from boreholes KFM01A–KFM04A (SICADA, 2004-07-30).

	Average Friction angle [°]	Cohesion [MPa]
Peak envelope	34.6	0.67
Residual envelope	30.8	0.49

4 Characterisation of the rock mass along the borehole

According to the methodology for rock mass characterisation in /Andersson et al. 2002/ and /Röshoff et al. 2002/, two empirical classification systems should be used for the purpose of determination of the mechanical property of the rock mass: the Rock Mass Rating, RMR, and the Rock Quality Index, Q. These classification systems are applied here for the "characterisation" of the rock mass, in contraposition to their general use for "design" of underground excavations. This implies that constrains due to the shape, orientation, function and safety of a potential excavation are not considered.

4.1 Equations for RMR and Q

The very well known relations for RMR and Q are reported here for convenience of the reader. The basic equation for the RMR /Bieniawski, 1989/ is:

$$RMR = RMR_{strength} + RMR_{RQD} + RMR_{spacing} + RMR_{conditions} + \\ + RMR_{water} + RMR_{orientation} \quad (1)$$

where the subscripts strength, RQD, spacing, conditions, water, orientation refer to the strength of the intact rock, to the Rock Quality Designation, to the conditions and spacing of the fractures, to the groundwater conditions and the orientation of the fracture sets with respect to the hypothetical tunnel orientation, respectively. In the source, each rating is provided with a description and a table.

The basic equation for Q /Barton, 2002/ is:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \quad (2)$$

where, besides RQD, Jn depends on the number of fracture sets, Jr and Ja on the roughness and alteration of the fractures, Jw on the groundwater conditions and the Stress Reduction Factor, SRF, takes into account the stresses in the rock mass. Also these parameters are described and tabulated in the source.

Table 4-1. Rock mass classification based on RMR and Q.

RMR rating	100–81	80–61	60–41	40–21	20–0
Rock class	I	II	III	IV	V
Classification	Very good	Good	Fair	Poor	Very poor
Q number	> 40	10–40	4–10	1–4	0.1–1
Classification	Very good	Good	Fair	Poor	Very poor

4.2 Partitioning the borehole into rock units

The geological single-hole interpretation provides a partitioning of borehole KFM04A into pseudo-homogeneous sections that apply also for the rock mechanics analysis. 13 "rock units" in four different rock type groups are recognised together with 5 deformation zones /Carlsten et al. 2004/.

The rock type groups in Forsmark can be shortly described as:

- Medium-grained metagranite to granodiorite (A).
- Medium-grained metatonalite to metagranodiorite (B).
- Fine to medium-grained metatonalite (C).
- Pegmatitic granite (D).
- Amphibolite (E).

For Rock Mechanics purposes, the partitioning according to rock type groups was kept to investigate possible differences in the rock quality. In Table 4-2, the rock units, rock type groups and the decision process for the choice of the fractured zones for Rock Mechanics are reported.

Table 4-2. Partitioning of borehole KFM04A: rock units, rock types and deformation zones.

Rock units/ Depth [m]	Rock unit ID	Rock type	Depth [m]	Deformation/ Fractured zones
107–177	RU2	B	169–176	Deformation Zone 1
177–275	RU3	A	202–213	Deformation Zone 2
			232–242	Deformation Zone 3
275–342	RU4	A		
342–443	RU5	A+B	412–462	Deformation Zone 4
443–500	RU3	A		
500–724	RU6	A	654–661	Deformation Zone 5
724–743	RU7	E		
743–938	RU6	A		
938–967	RU8	A		
967–990	RU6	A		
990–1,000	RU7	E		

4.3 Characterisation with RMR

For each 5 and 30 m sections of borehole, the geomechanical parameters from borehole logging were scrutinized (see also Appendix B). The minimum, average, most frequent and maximum ratings for RMR were determined for each borehole section, sometimes through averaging processes. The plots in Figure 4-1 and Figure 4-2 are obtained for the RQD, fracture conditions, spacing rating that result into the RMR values shown on the right for 5 and 30 m core sections, respectively.

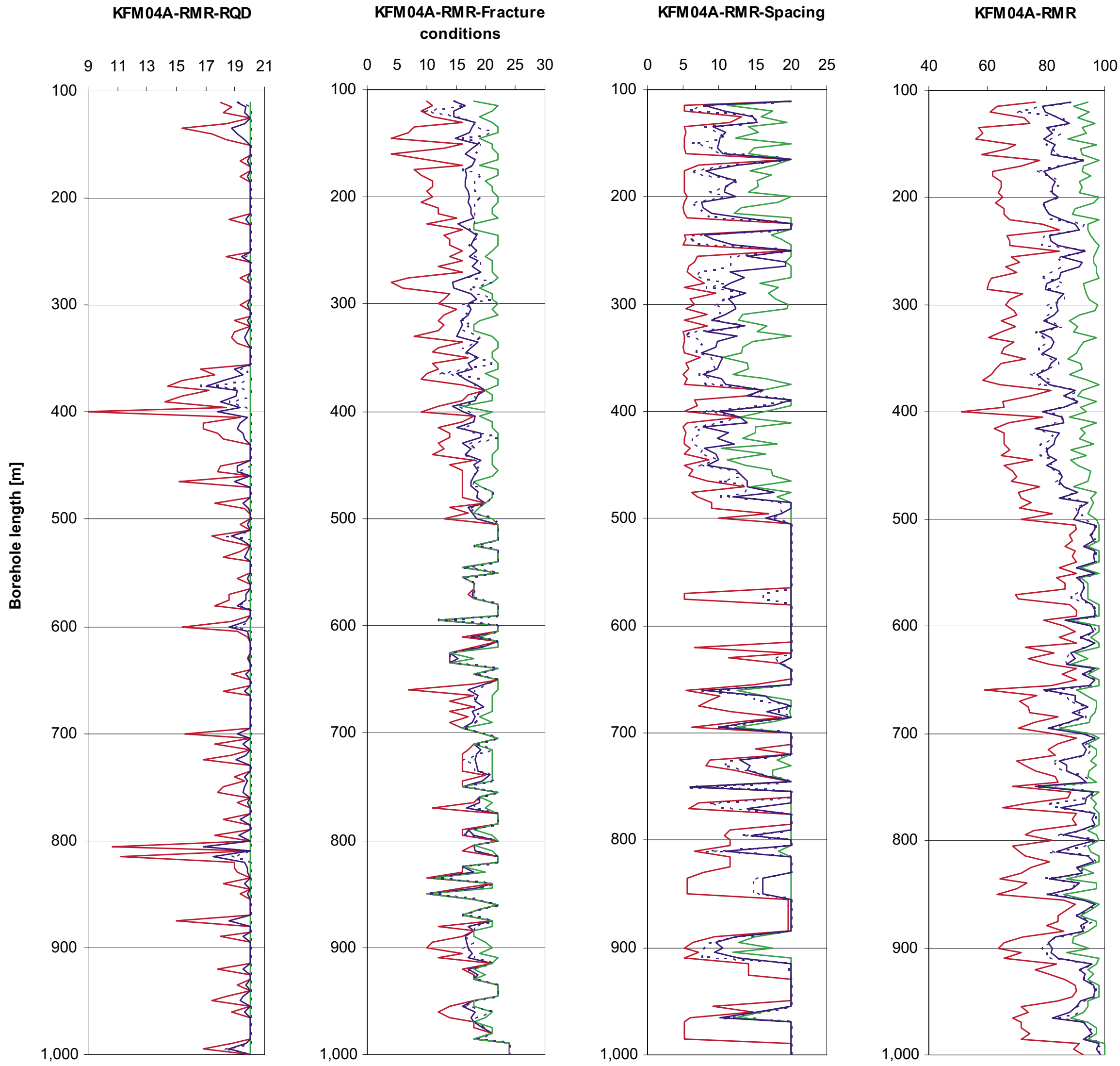

Figure 4-1. *Ratings for RMR characterisation and resulting RMR values for borehole KFM04A. The ratings for RQD, fracture conditions, fracture spacing are plotted with depth together with RMR. The lines in red, blue, dashed blue and green represent the possible minimum, average, most frequent and possible maximum values observed every core section 5 m long, respectively.*

The ratings for tunnel orientation and water pressure were assumed for "fair conditions" and for a "completely dry" borehole, as prescribed for rock mass characterisation (RMR orientation = 0, RMR water = 15).

The RMR values were also summarised for each rock type group, for competent rock, deformation/fractures zones and for the whole borehole as shown in Table 4-3. When referring to the rock quality classes in Table 4-1, the rock mass along borehole KFM04A can be described as "very good" along most of its length (lower range of this class). A distinct property change can be seen at depth 500 m where there is a change in rock type. The rock groups A and E that dominate below 500 m whereas above 500 m rock groups A and B dominate. The rock above this depth generally classifies as "very good" rock although in the lower range of this class (RMR about 83), while below 500 m the quality

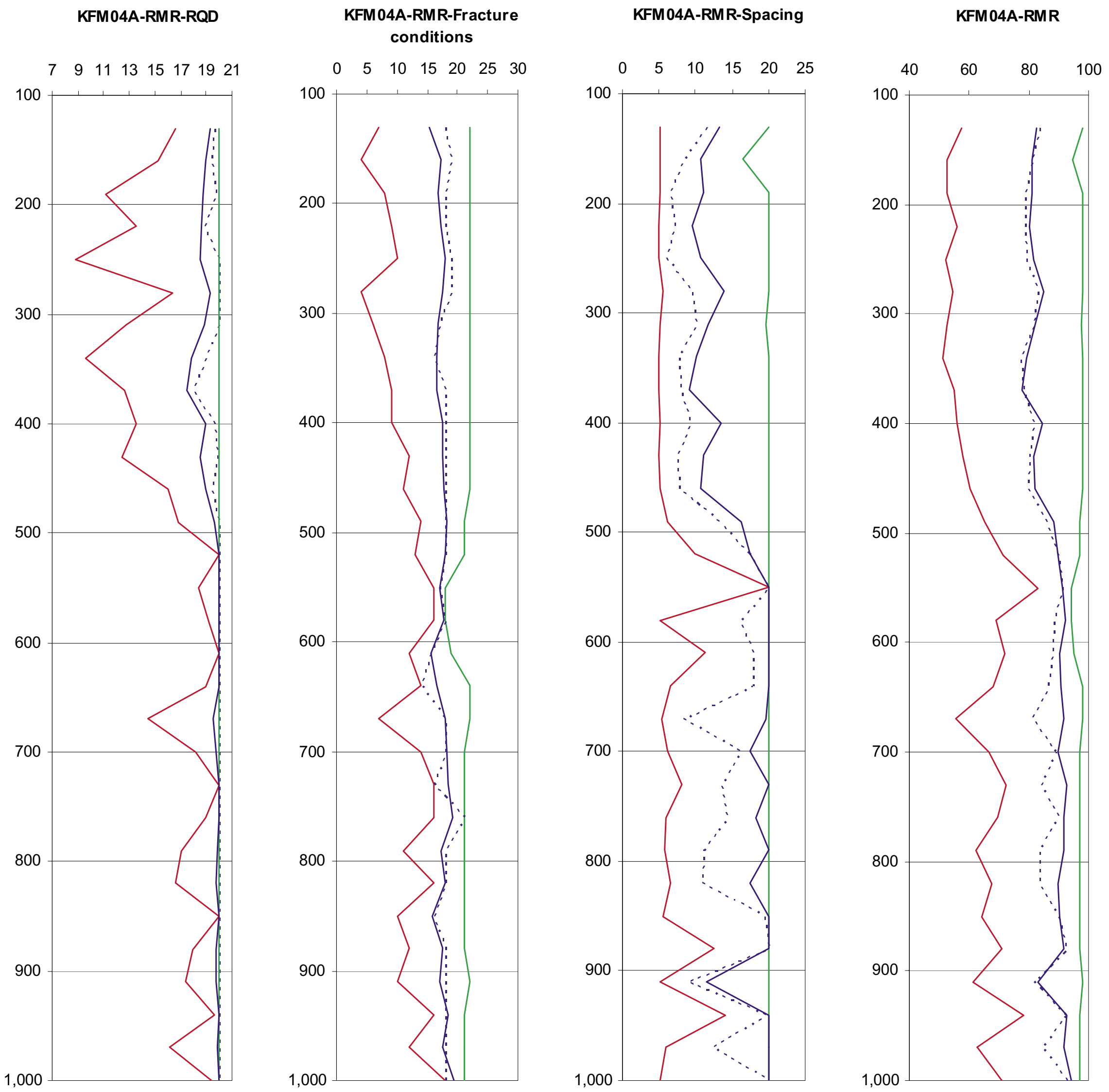

Figure 4-2. *RMR and RMR ratings along borehole KFM04A. Possible minimum, average, most frequent and possible maximum value is plotted in red, blue, dashed blue and green, respectively. Core sections of 30 m are considered.*

is "very good" but towards higher RMR (about 93). More in detail, the rock quality with depth varies as follows:

- "very good" rock (RMR about 80) down to a depth of 215 m and between 275 and 375 m, 395 and 450, and 885 and 910 m.
- "very good" rock (RMR about 87) between 215 and 275 m, and 375 and 395 m, and between 450 and 500.
- "very good" rock (RMR about 90) between 500 and 885, and between 910 and 1,000 m.

There is a difference in rating between the competent and deformation/fractured rock of about 10 points. The rock type Rock Unit 2 to 5 exhibit the same rock quality as the average for the fractured rock along the borehole whereas Rock Unit 6 to 8 show a higher quality of about RMR values of 90 more similar to the RMR value for competent rock.

Table 4-3. Summary of RMR values for borehole KFM04A (core sections of 5 m).

Rock unit	Minimum mean RMR	Average mean RMR	Frequent mean RMR	Maximum mean RMR	Standard deviation	Minimum possible RMR	Maximum possible RMR
RU2	78.7	83.1	81.9	92.7	4.1	56.0	98.0
RU3	79.1	85.8	84.7	94.0	4.4	61.5	98.0
RU4	77.9	82.1	82.5	85.8	2.3	59.7	97.6
RU5	76.5	82.6	82.8	90.8	3.9	51.4	98.0
RU6	76.1	91.6	92.5	98.3	5.0	59.1	100.0
RU7	87.2	92.5	92.6	98.5	4.8	72.5	100.0
RU8	82.2	89.7	90.5	96.1	5.1	68.5	98.0
Competent rock	76.1	88.9	90.3	98.5	5.8	51.4	100.0
Fractured rock	76.5	81.6	81.0	85.8	2.6	59.1	97.0
Whole borehole	76.1	88.2	89.1	98.5	6.0	51.4	100.0

4.4 Characterisation with Q

The input numbers for the Q systems and the resultant rock quality index for 5 m and 30 m are plotted in Figure 4-3 and Figure 4-4, respectively. As for RMR, the Q numbers are obtained through the choice of minimum, average, most frequent and maximum values of the geomechanical parameters logged along the borehole. The fracture-set, roughness and alteration numbers are obtained for each borehole section of 5 or 30 m (see also Appendix B). SRF is assigned to the fractured zones based on consideration about their width, depth, degree of fracturing and alteration, but also based on the ratio between the uniaxial compressive strength of the intact rock and the major rock stress. The deformation/fractured zones listed in Table 4-2 were assigned an SRF of 2.5. The parameter for water in the Q system was assumed equal to 1 (dry borehole) as it is usually done for rock mass characterisation.

According to the Q system, the rock along borehole KFM04A can be classified as “very good rock” as the average Q is much larger than 100 and the most frequent value is about 40. The rock type group A and B show higher quality than the others. On average, the fractured zones can be classified at the limit between the classes “fair” and “good rock”. No “very poor rock” was observed along the borehole.

The rock quality according to Q also varies with depth where the rock quality is “good” to “very good” in the upper 500 m and consistently “very good” in general below 500 m, with an exception of a deformation zone at 655–600 m with “good” quality. Rock Unit 2 display Q values in the lower range of “good” rock (Q number 10–40) and the deformation zone in Rock Unit 2 at 170–175 m shows “fair” quality (Q number 4–10). A general trend of increasing Q value can be seen in the upper 500 m from the “fair” quality of Rock Unit 2 to generally “very good” quality of Rock Unit 6 at 500 m.

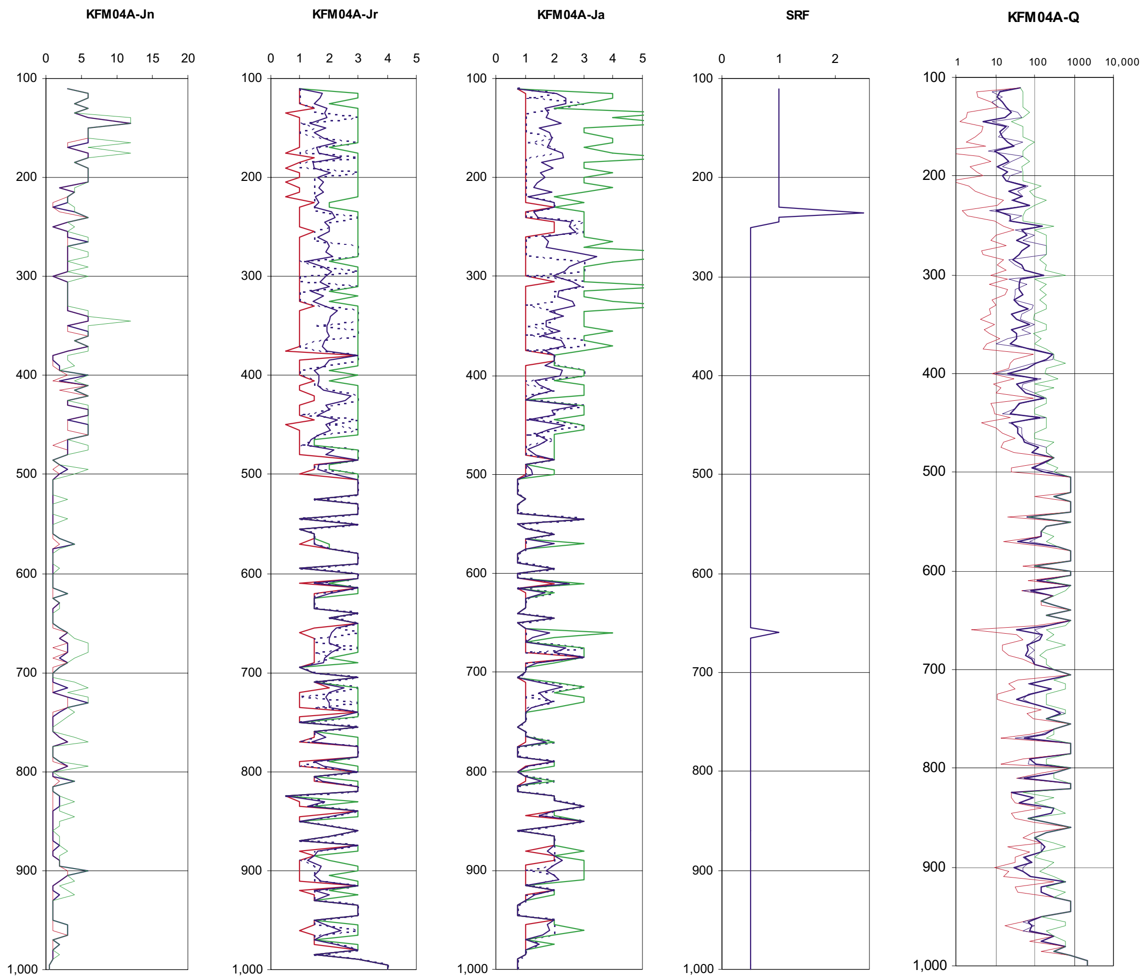

Figure 4-3. Q-numbers for characterisation and resulting Q values for borehole KFM04A. The number for fracture set, fracture roughness, fracture alteration and SRF are plotted along the borehole together with Q. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed for every core section 5 m long, respectively.

Table 4-4. Summary of the Q values for borehole KFM04A (core sections of 5 m).

Rock unit	Minimum Q	Average Q	Frequent Q	Maximum Q	Min possible Q	Max possible Q
RU2	4.7	18.4	16.6	44.4	0.2	100.0
RU3	10.5	63.3	45.3	300.0	0.8	400.0
RU4	26.5	52.6	41.5	168.0	4.8	600.0
RU5	21.2	77.7	43.3	295.2	4.3	600.0
RU6	25.0	367.1	200.0	800.0	2.5	800.0
RU7	35.1	862.6	381.5	2,133.3	11.1	2,133.3
RU8	70.3	236.0	84.5	800.0	18.0	800.0
Competent rock	4.7	265.5	104.1	2,133.3	1.3	2,133.3
Fractured rock	9.7	45.2	34.6	167.3	0.2	300.0
Whole borehole	4.7	243.4	87.5	2,133.3	0.2	2,133.3

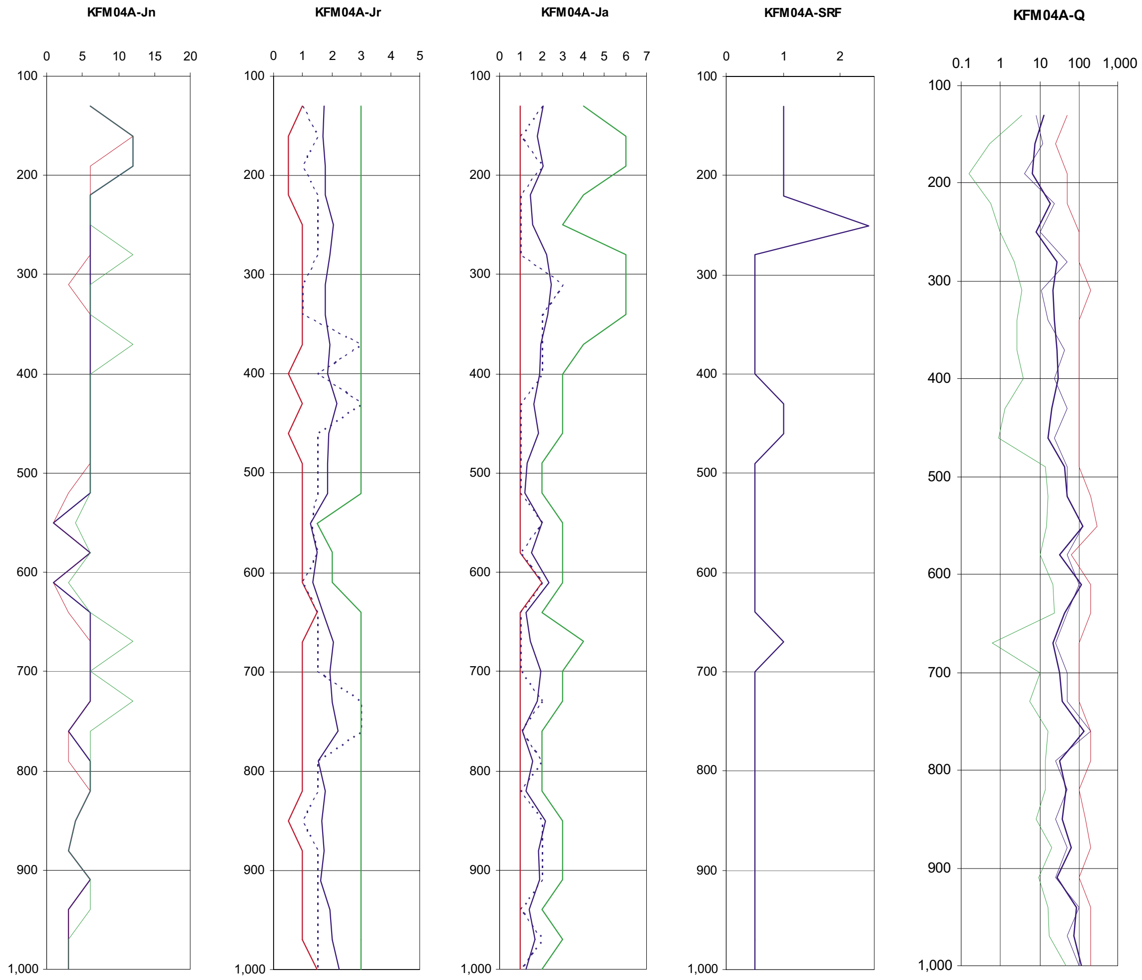

Figure 4-4. *Q and Q-numbers along borehole KFM04A. Minimum, average, most frequent and maximum values are plotted in red, blue, dashed blue and green, respectively. Core lengths of 30 m are considered.*

4.5 Evaluation of the uncertainties

The empirical classification systems for characterisation of the rock mass are affected by the uncertainties on the geological and rock mechanical data and by the intrinsic uncertainties due to the structure of the empirical systems themselves. The uncertainty on a single parameter can widely vary depending on the acquisition technique, subjective interpretation or size of the sample population. But uncertainty can also derive from the way the values of the indexes and ratings are combined with each other. Different operators may obtain and combine the ratings and indices in slightly different ways. The value of Q or RMR for a certain section of borehole may then result from the combination of the possible ratings that range from a minimum to a maximum value in a certain rock mass volume.

In this report, it was decided to correlate the uncertainty on Q and RMR to the range of their possible values derived from the width of the interval between the minimum and maximum occurring value of each index or rating, for each core section. The range of the possible minimum and maximum values of RMR and Q is obtained by combining the ratings and indices in the most unfavourable and favourable way, respectively.

The spatial variability of the geological parameters adds more variability to the indices and ratings and this also mirrors onto the uncertainty of the mean value. For removing the spatial variability, the differences between maximum possible and mean value, and minimum possible and mean value are evaluated for each 5 m borehole section and normalised by means of the mean value. Each obtained value is considered as a sample from a statistical population of variation intervals. The concept of "confidence interval of a population mean" can then be applied to quantify the uncertainty. According to the "Central Limit Theorem" /Peebles, 1993/, the 95% confidence interval of the mean $\Delta_{\text{conf mean}}$ is obtained as:

$$\Delta_{conf\ mean} = \pm \frac{1.96\ \sigma}{\sqrt{n}} \qquad (3)$$

where σ is the standard deviation of the population and n is the number of values in each sample. In KFM04A, there are, on average, 14 sections of 5 m within each rock unit in competent rock, and there are around 4 sections of 5 m within each deformation zone. In practice, two confidence intervals are determined by the proposed technique, one related to the maximum value of RMR and Q, and the other related to the minimum value:

$$\begin{aligned} \Delta P_{+conf\ mean} &= \frac{P_{MAX} - P_{MEAN}}{\sqrt{n}} \\ \Delta P_{-conf\ mean} &= \frac{P_{MEAN} - P_{MIN}}{\sqrt{n}} \end{aligned} \qquad (4)$$

where P is the rating, either RMR or Q, with its possible maximum and minimum values and mean value, respectively. This technique also applies to the rock mechanical parameters derived from the empirical systems (in Chapter 5), such as: deformation modulus, Poisson's ratio, uniaxial compressive strength, friction angle and cohesion of the rock mass.

In Table 4-5, the confidence of the mean value is summarised for the competent and fractured rock along borehole KFM04A. The uncertainty on the mean value is larger for the fractured rock (deformation zones) than for the competent rock. This is due to the local variability of the geological feature that can give rise to different interpretations. The confidence is generally higher on RMR than for Q due to the wide range of variation of the Q values for very good rocks. However, this kind of variations is compatible with the use of Q for design applications.

Table 4-5. Uncertainty on the mean values of RMR and Q for borehole KFM04A and borehole sections of 5 m. The uncertainty is gives as percentage of the mean value.

	Competent rock		Fractured rock	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
RMR	–4%	+2%	–9%	+6%
Q	–13%	+44%	–39%	+133%*

* This is explained because Q spans several orders of magnitude.

5 Mechanical properties of the rock mass

5.1 Deformation modulus of the rock mass

By means of some empirical formulas /Serafim and Pereira, 1983/Barton, 2002/, it is possible to obtain an estimation of the equivalent deformation modulus of the rock mass. In this report, the determination is done for core sections of 5 and 30 m (see also Appendix C). In Figure 5-1, the plots of the minimum, average, most probable and maximum expected deformation modulus (Em) are given. Comparing the mean values obtained independently by means of RMR and Q/Qc, a rather good agreement can be observed below 500 m. It can be noticed that the application of a cut-off of 75 GPa for mean deformation modulus has been applied to consider the physical limit represented by the deformation modulus of the intact rock. This affects the distribution of Em that, for this reason, exhibits a sudden peak for that value in the histograms in Figure 5-2 to Figure 5-4. The trend with depth from lower to higher values that can be seen in Em from Q cannot be seen in Em from RMR. This causes a large difference between Em from Q and from RMR in the upper part of the drill core whereas the difference diminishes continually down to 500 m from where Em from Q and RMR coincides with small discrepancies down to 1,000 m.

In general, Q gives deformation moduli lower and more varying than RMR down to 500 m (Table 5-1). Below 500 m the difference between Em from Q and from RMR is about 10 GPa, whereas above 500 m the difference can be up to 30 GPa. 75% of the differences between Em values from Q and RMR that are larger than 20 GPa occurs above 500 m. The mean deformation modulus from RMR varies in the range 53–65 with extreme values between 45 and 75 GPa. The deformation modulus from Q have a larger range of variation with mean deformation modulus ranging between 34 and 69 GPa and extreme values of 22 and 75 GPa. Below 500 m, about 78% of the rock mass along the borehole exhibits a deformation modulus calculated from RMR of 75 GPa.

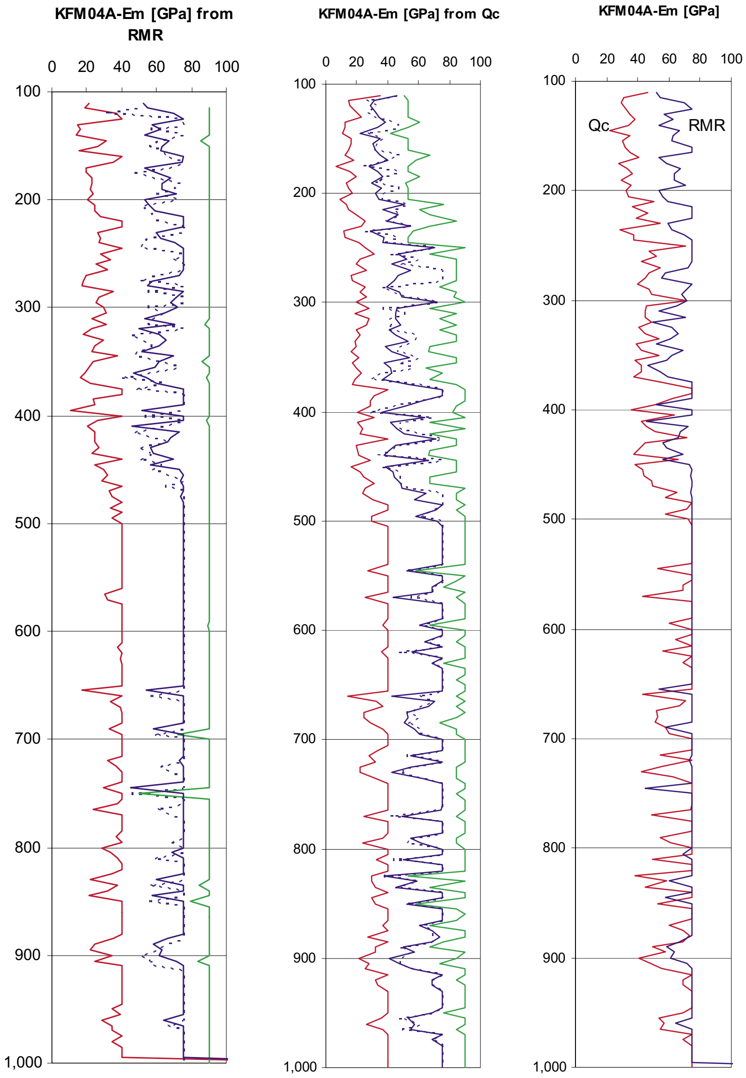

***Figure 5-1.** Deformation modulus of the rock mass derived from RMR and Q values for each core section of 5 m for borehole KFM04A. A comparison of the mean values along the borehole is given in the graph on the right.*

Table 5-1. Summary of the deformation modulus Em derived from RMR and Q for borehole KFM04A (core sections of 5 m).

Rock unit	Average Em from RMR [GPa]	Average Em from Q [GPa]
RU2	63.1	33.4
RU3	69.7	47.4
RU4	63.6	47.3
RU5	63.8	51.2
RU6	73.2	67.5
RU7	75.0	67.5
RU8	72.8	61.9
Competent rock	71.0	59.4
Fractured rock	61.8	43.6
Whole borehole	70.1	57.8

The average Em has a physical threshold in the Young's modulus of the intact rock, which is 75 GPa.

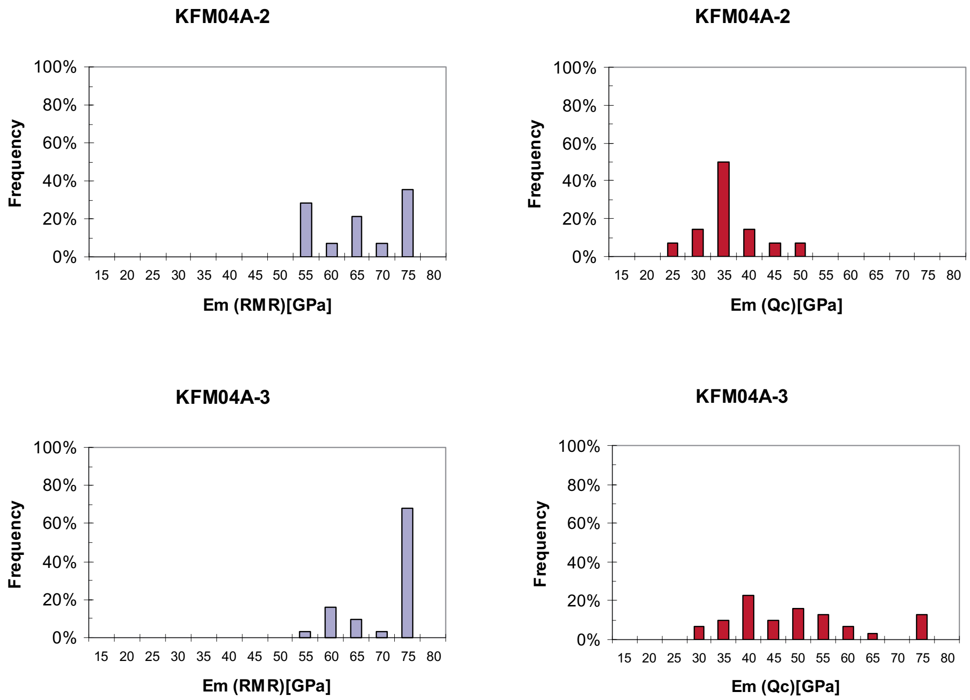

Figure 5-2. *Histograms of the deformation modulus of the rock mass Em derived from RMR and Q (core sections of 5 m) for Rock Unit 2 to 3 in borehole KFM04A.*

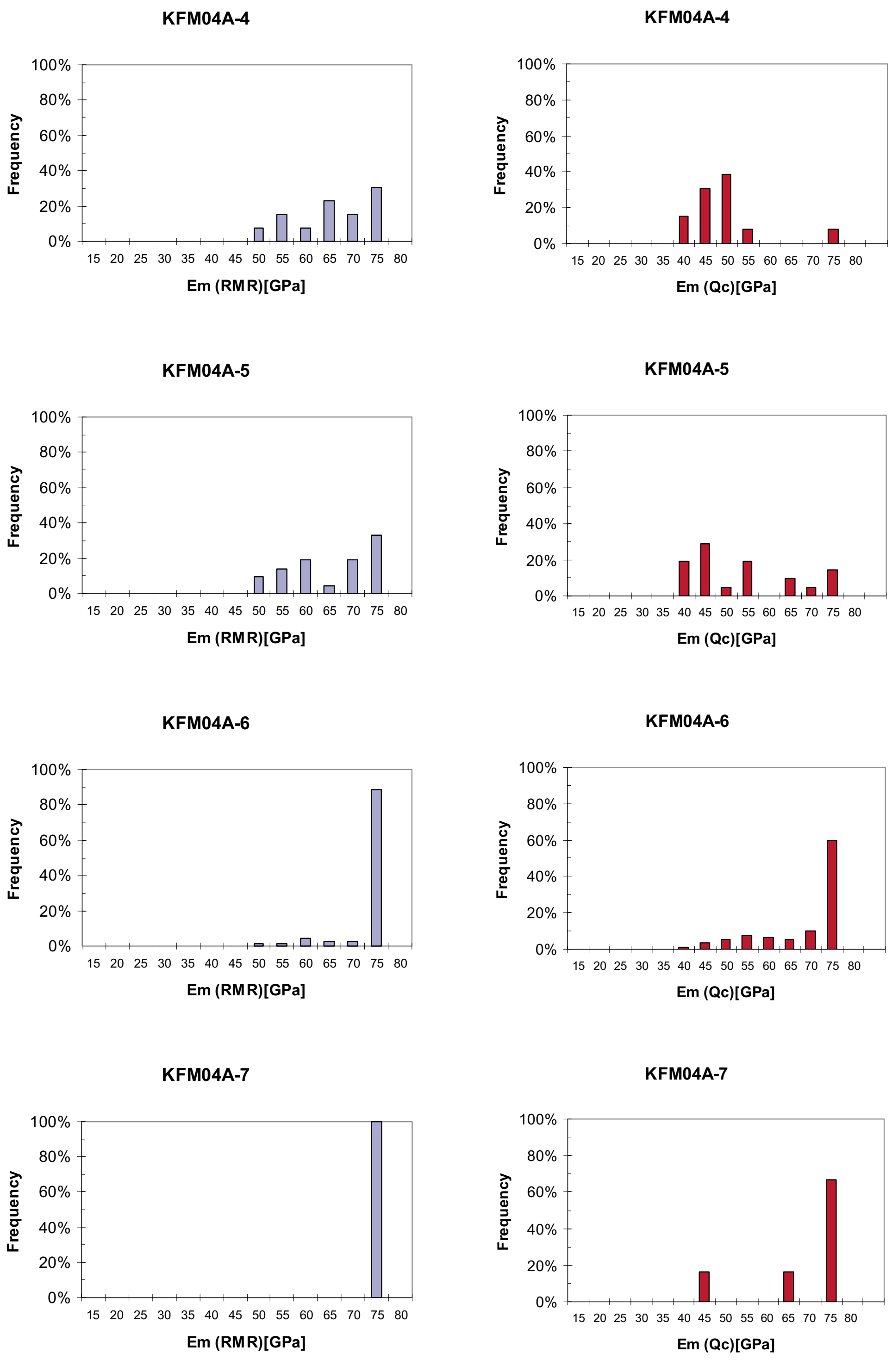

Figure 5-3. *Histograms of the deformation modulus of the rock mass Em derived from RMR and Q (core sections of 5 m) for Rock Unit 4 to 7 in borehole KFM04A.*

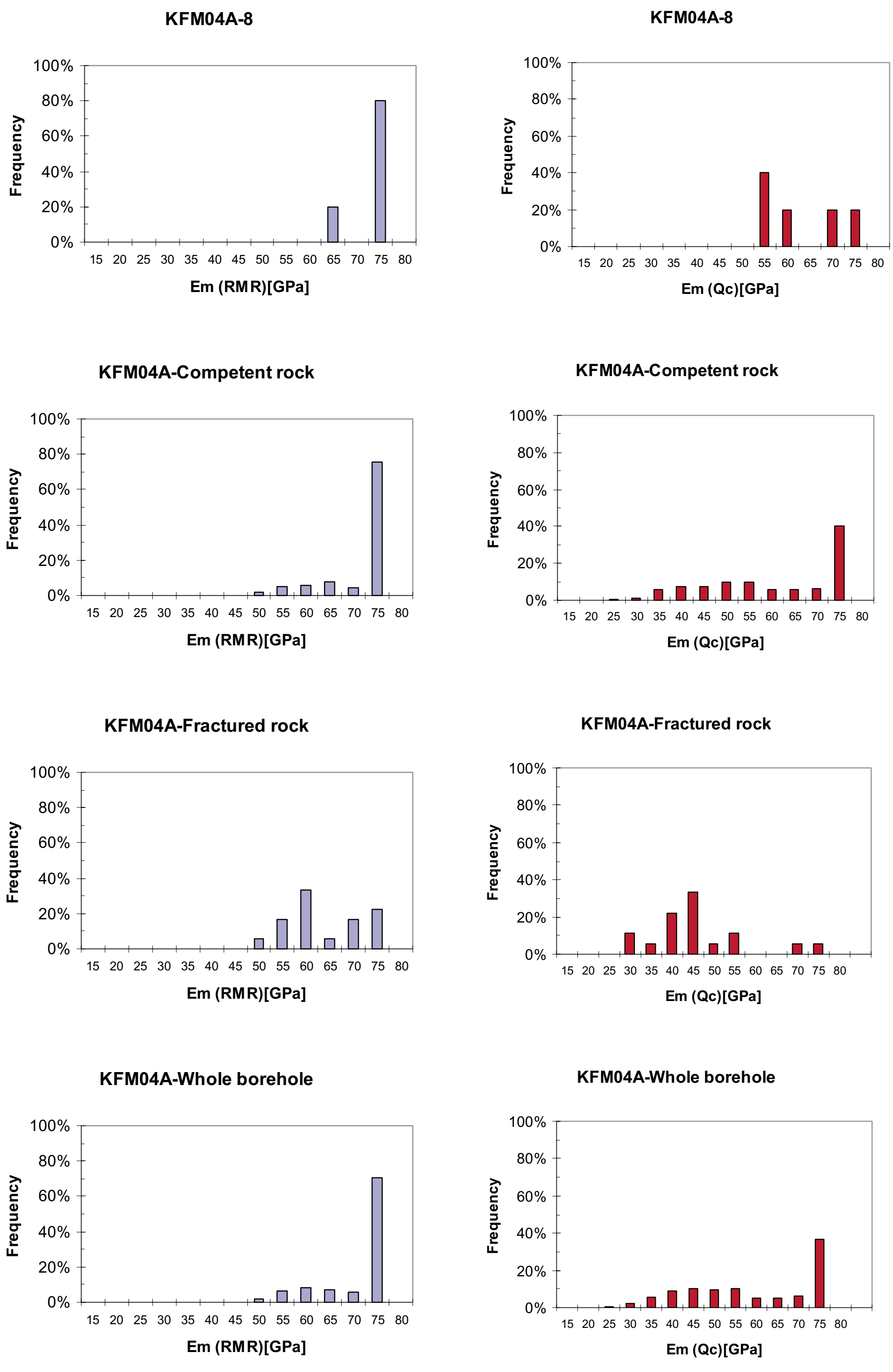

Figure 5-4. *Histograms of the deformation modulus Em derived from RMR and Q (core sections of 5 m) for Rock Unit 8, competent rock, deformation zones/fractured rock, and for the whole borehole KFM04A.*

By applying the technique explained in section 4.5, the uncertainties on the mean value of the deformation modulus from RMR and Q in Table 5-2 can be calculated. It can be observed that the uncertainties of the two methods are rather similar. Moreover, the uncertainty on the deformation modulus of the deformation zones/fractured rock is larger than the uncertainty for the competent rock.

Table 5-2. Confidence on the mean values of the deformation modulus E_m from RMR and Q for borehole KFM04A and borehole sections of 5 m. The uncertainty is gives as percentage of the mean value.

	Competent rock Lower confidence on the mean	Upper confidence on the mean	Fractured rock Lower confidence on the mean	Upper confidence on the mean
E_m(RMR)	–15%	+8%	–29%	+22%
E_m(Q)	–14%	+12%	–28%	+33%

5.2 Poisson's ratio of the rock mass

The Poisson's ratio of the rock mass is often determined as a fraction of that of the intact rock. This fraction is determined by the ratio between the deformation modulus of the rock mass and that of the intact rock. For borehole KFM04A, the Poisson's ratio of the competent rock can be estimated about 0.23, while that of the fractured rock could be about 0.20 (Figure 5-5). The Poisson's ratio of the intact rock matrix is 0.24 (see Table 3-2).

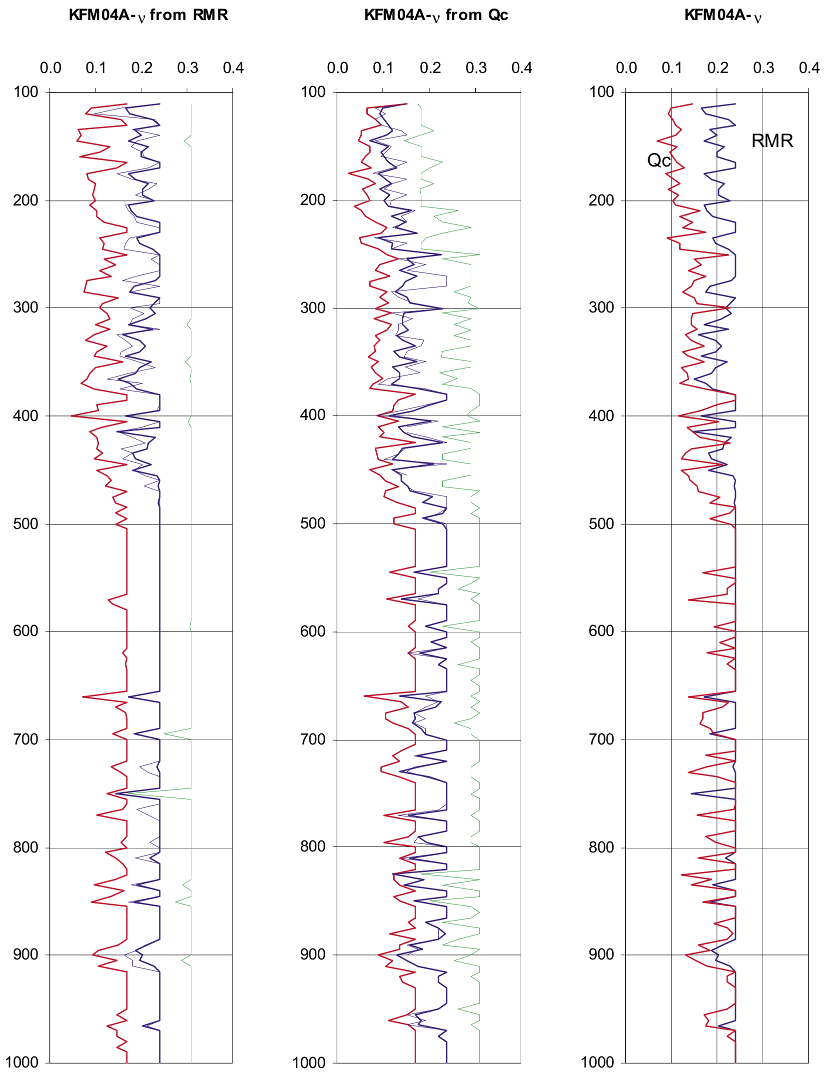

Figure 5-5. Poisson's ratio derived from RMR and Q values for each core section of 5 m for borehole KFM04A. A comparison of the mean values along the borehole is given in the graph on the right.

5.3 Uniaxial compressive strength of the rock mass

The variation of the rock mass compressive strength determined according to RMR /Hoek et al. 2002/ and Q (Qc) can be seen in Figure 5-6. As shown in Table 5-3, the uniaxial compressive strength of the rock mass along KFM04A obtained by means of RMR agrees very well with that determined by means of Q above 500 m. The uniaxial compressive strength of the competent rock mass from RMR is estimated about 95 MPa on average. The uniaxial compressive strength of the deformation zones/fractured rock should be about 60 MPa and displays a variation between 45 and 76 MPa.

Below 500 m, the compressive strength from RMR is consistently lower than that from Q except for two extremely low values. The strength of the Rock Units 6, 7 and 8 is much lower for RMR compared to the strength obtained from Q causing the difference in strength from RMR to deviate from strength from Q much more for competent rock than for fractured rock. It is only for the Rock Unit 2, with generally lower rock quality, where the situation is the opposite. Due to sometimes unrealistic values provided by Q, it is given more credit to the determination based on RMR, since the uniaxial compressive strength of the intact rock matrix is about 225 MPa.

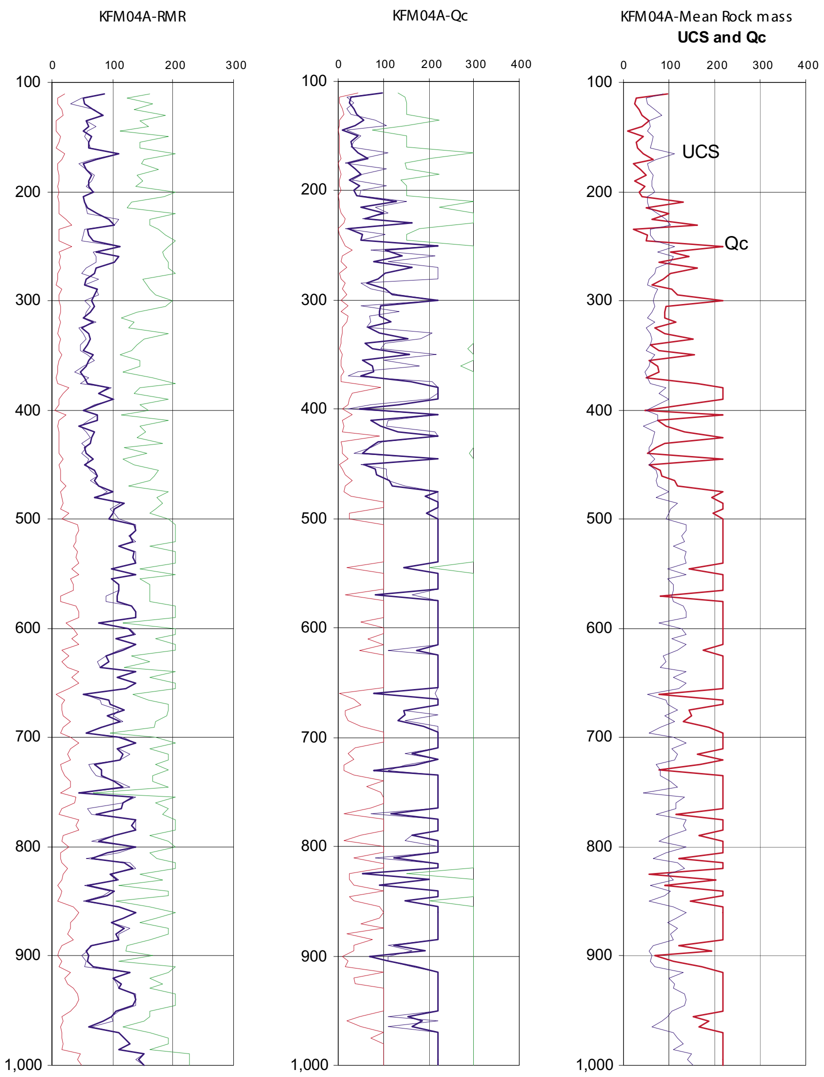

Figure 5-6. *Variation of the rock mass compressive strength from RMR and Q for borehole KFM04A.*

Table 5-3. Summary of the uniaxial compressive strength of the rock mass derived from RMR and Q (core sections of 5 m) for borehole KFM04A.

Rock unit	Average UCS from RMR [MPa]	Average Qc from Q [MPa]
RU2	66.8	40.5
RU3	78.0	139.4
RU4	62.0	115.8
RU5	65.0	170.9
RU6	108.4	(807.6)*
RU7	113.2	(1,897.8)*
RU8	96.9	(519.1)*
Competent rock	94.7	(584.2)*
Fractured rock	60.4	99.5
Whole borehole	91.2	(535.4)*

* Physically unrealistic values.

Table 5-4. Confidence on the mean values of the uniaxial compressive strength from RMR/GSI and Hoek and Brown's Strength Criterion for borehole KFM04A and borehole sections of 5 m. The uncertainty is gives as percentage of the mean value.

	Competent rock		Fractured rock	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
$UCS_{H\ and\ B}$	–22%	+26%	–40%	+75%

In Table 5-4 the uncertainties on the mean uniaxial compressive strength determined by means of RMR are summarised. As usual, the uncertainty is lower for the competent rock (about 25% of the mean value) than for the deformation zones/fractured rock (between 40 and 75%).

5.4 Cohesion and friction angle of the rock mass

Figure 5-7 shows graphically the difference between the cohesion and frictional parameters of the rock mass obtained from RMR and Q and applying for low stresses (between 0 and 5 MPa).

In Table 5-5, the values applying for stresses between 10 and 30 MPa are provided. This can only be obtained from RMR/GSI/Hoek and Brown's Criterion that explicitly takes into account the variation of stress. As for the deformation modulus, some cut-offs are applied to limit the strength of the rock mass to that of the intact rock. The results are shown graphically in Figure 5-8. On average, the cohesion of the rock mass should vary between 22.5 and 29.2 MPa, with the minimum and maximum value for Rock Unit 4 and 7, respectively. The range for the friction angle is between 47.6° and 50°.

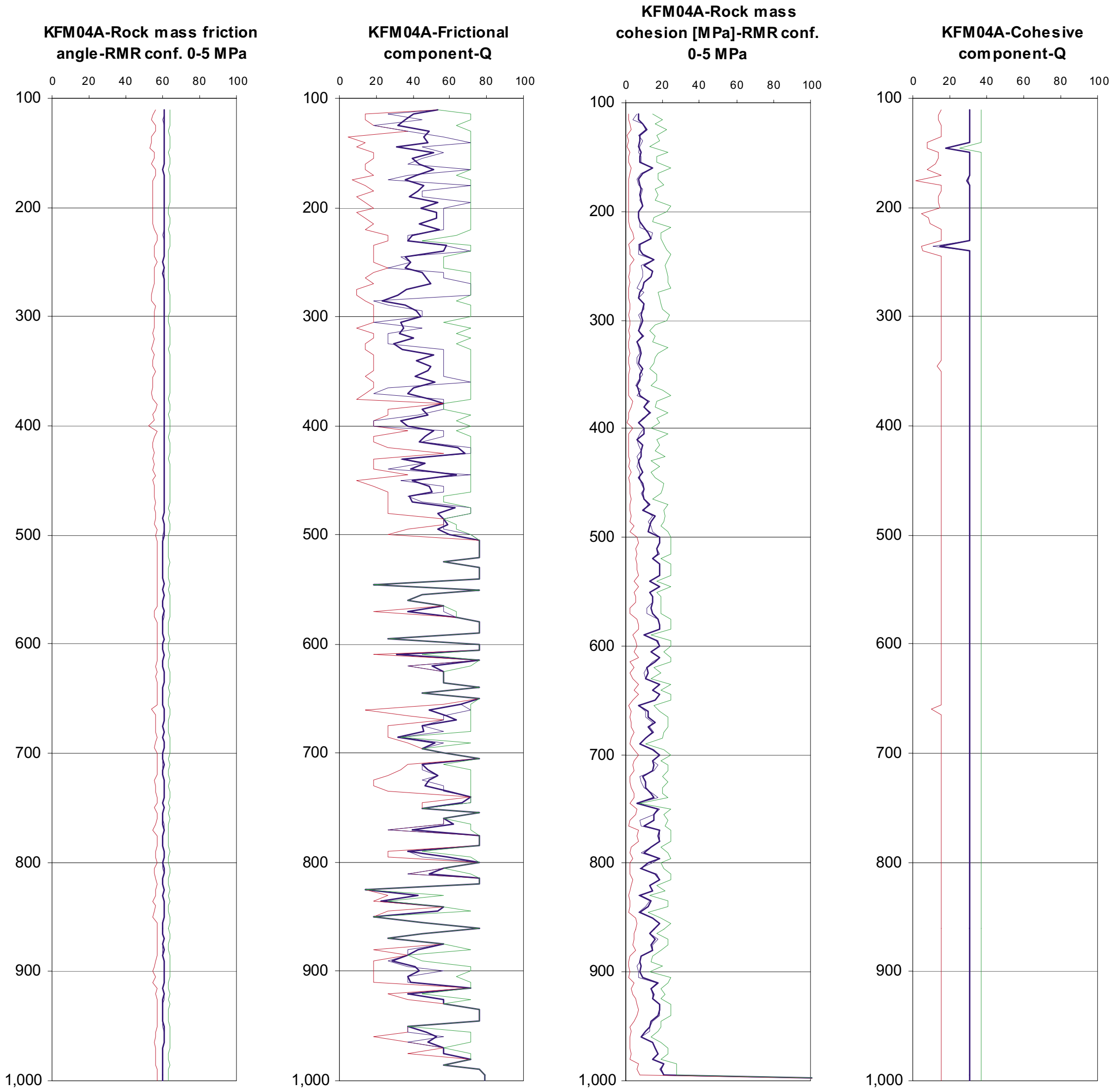

Figure 5-7. *Variation of the rock mass friction angle and cohesion from RMR and Q for borehole KFM04A under stress between 0 and 5 MPa. Core sections of 5 m are considered.*

Table 5-5. Summary of the cohesion and friction angle of the rock mass derived from RMR by means of a linear interpolation (Coulomb's Criterion) of the Hoek and Brown's Strength Criterion for borehole KFM04A (core sections of 5 m) and stress between 10 and 30 MPa.

Rock unit	Average c' [MPa]	Average φ' [°]
RU2	23.1	47.9
RU3	24.6	48.6
RU4	22.5	47.7
RU5	22.9	47.8
RU6	28.6	49.8
RU7	29.2	50.0
RU8	27.1	49.4
Competent rock	26.8	49.2
Fractured rock	22.3	47.6
Whole borehole	26.3	49.1

Table 5-6. Confidence on the mean values of the apparent cohesion and friction angle for borehole KFM04A and borehole sections of 5 m. The uncertainty is gives as percentage of the mean value.

	Competent rock Lower confidence on the mean	Upper confidence on the mean	Fractured rock Lower confidence on the mean	Upper confidence on the mean
c’	–13%	+11%	–21%	+27%
ϕ’	–6%	+3%	–12%	+7%

These values apply for stresses between 10 and 30 MPa.

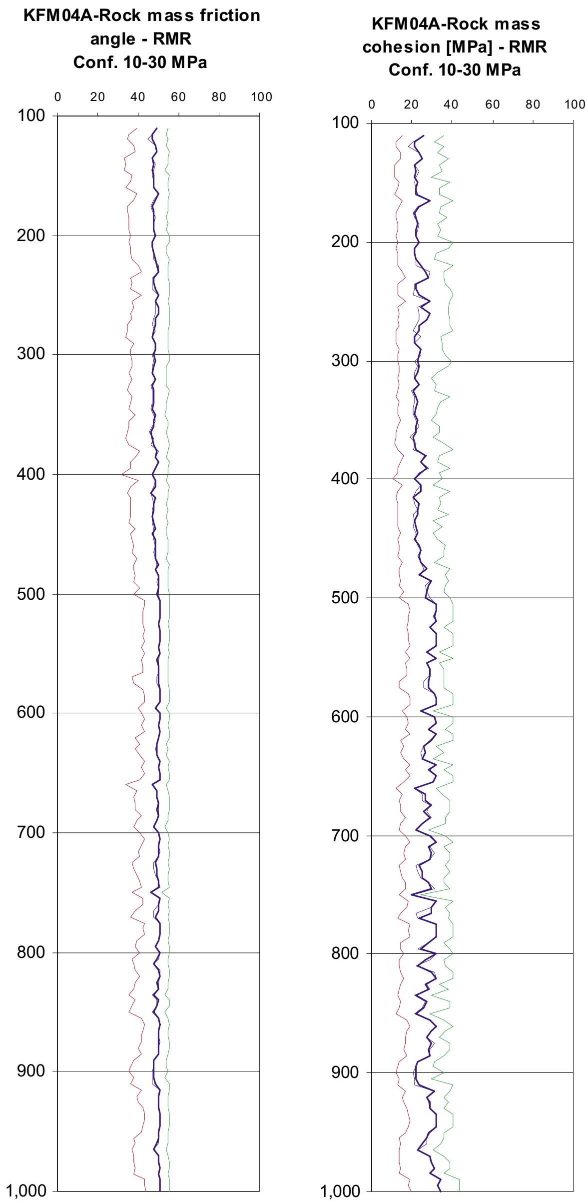

Figure 5-8. *Variation of the rock mass friction angle and cohesion from RMR and Q under stress confinement between 10 and 30 MPa for borehole KFM04A. Core sections of 5 m are considered.*

6 P-wave velocity along the borehole

P-wave velocity measurements were carried out on 37 samples taken from the core of borehole KFM04A at different depths /Chryssanthakis and Tunbridge, 2005/. The measurements were taken along six core diametrical orientation, where the first measurement was taken parallel to the strike of the foliation of the rock. By treating the tensor of the velocity, the principal velocity directions relatively to the foliation and the anisotropy ratio could be determined. In Figure 6-1, the principal P-wave velocities along the borehole are shown. The most significant change of velocity occurs at 400 m where it coincides with the onset of deformation zone 4. It can be observed that the P-wave velocity shows a change to lower values at 500 m. The average velocity changes from about 5,500 to 5,260 m/s. For depths larger than 500 m, the velocity starts to oscillate more than above 500 m.

The absolute orientation of the rock foliation is contained in the BOREMAP data. Only 20% of the measurements are located in the upper 500 m of the bore hole. Thus, the absolute principal velocity orientation is obtained by combining the information from the two sources. The orientation angle of the maximum velocity varies with the dip direction of the foliation in the upper 500 m of the borehole. The correlation between the two angles is rather strong ($R^2 = 0.5$). In the lower part of the borehole, the correlation between the two angles ceases.

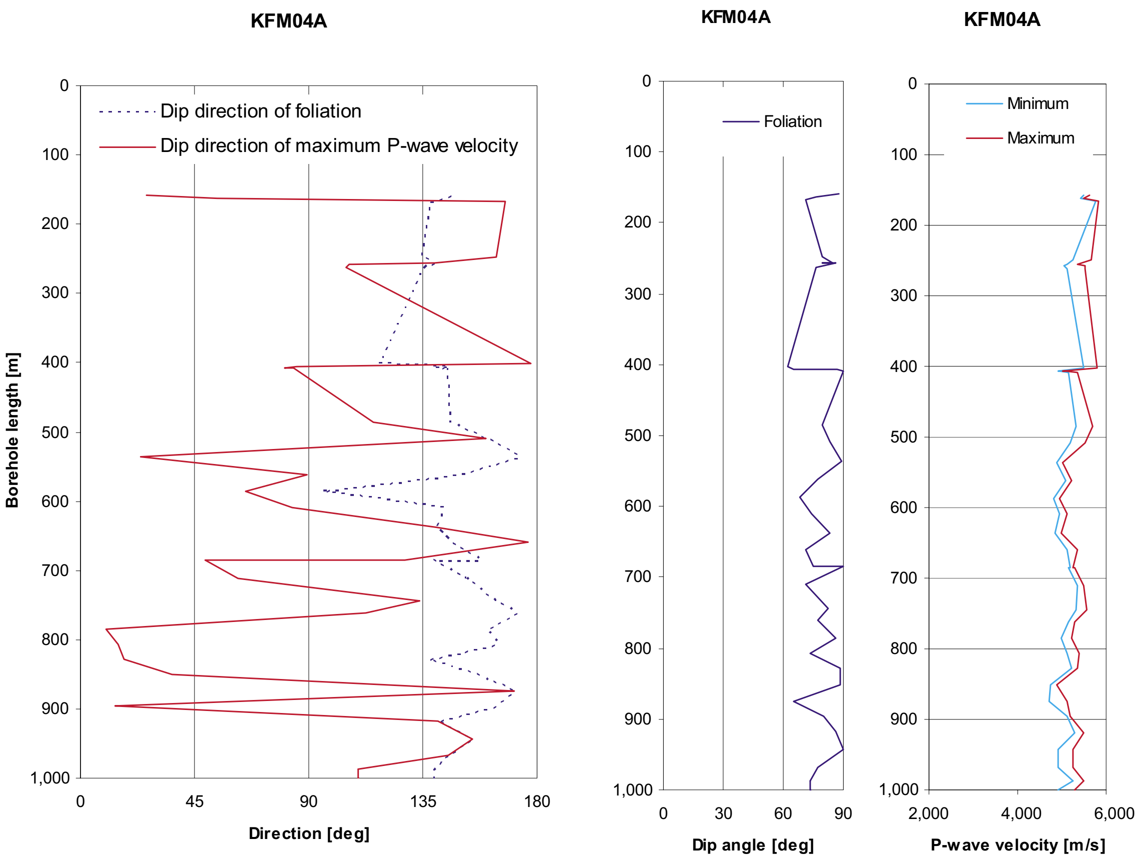

Figure 6-1. *Dip direction of the maximum P-wave compared with the dip direction of the foliation for borehole KFM04A. The dip angle of the foliation and the values of the maximum and minimum P-wave velocities are also shown.*

7 Discussion

In this report, the two independent systems for rock mass quality determination RMR and Q are applied for characterisation of the rock mass along borehole KFM04A. In Figure 7-1, the characterisation results for KFM04A are compared with several other empirical relations between RMR and Q to assess the consistency between the rock mass quality systems and the results previously published in the literature. The diagram for borehole sections of 5 m length, a slight overestimation of RMR as a function of Q can be seen. This is due to the difference between the approach for characterisation of the rock mass and that for design of underground structures. In this version of the Q-system, which takes into consideration the increase of stress confinement with depth by means a favourable SRF factor, higher values than for the original Q-system can be expected especially for larger depth. Considering that the empirical relations apply on average, however, the characterisation results can be considered satisfactory. The linear regression of the data shown in Figure 7-1 and Figure 7-2 can be expressed in mathematical terms as:

$$RMR_{(5m)} = 3.8 \cdot \ln(Q) + 71 \quad (R^2 = 0.672)$$

$$RMR_{(30m)} = 4.7 \cdot \ln(Q) + 71 \quad (R^2 = 0.549)$$

These relations imply that small values of Q (e.g. 0.1) are associated to moderately high values of RMR (e.g. 60–62).

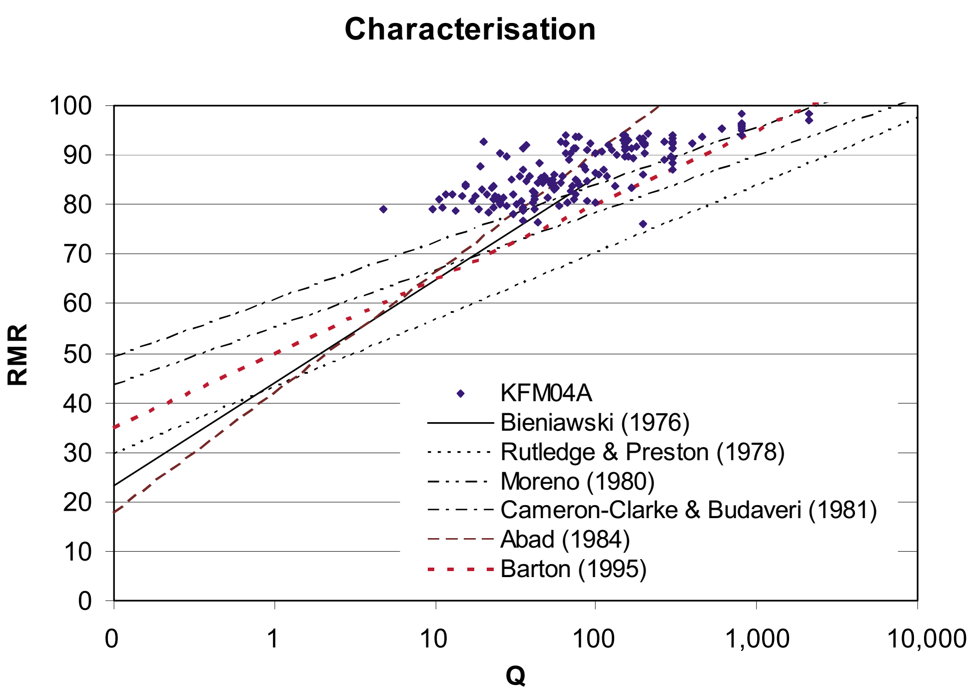

Figure 7-1. *Correlation between RMR and Q for the characterisation of the rock mass along borehole KFM04A (core sections of 5 m). The characterisation results are compared with some relations for design applications from the literature.*

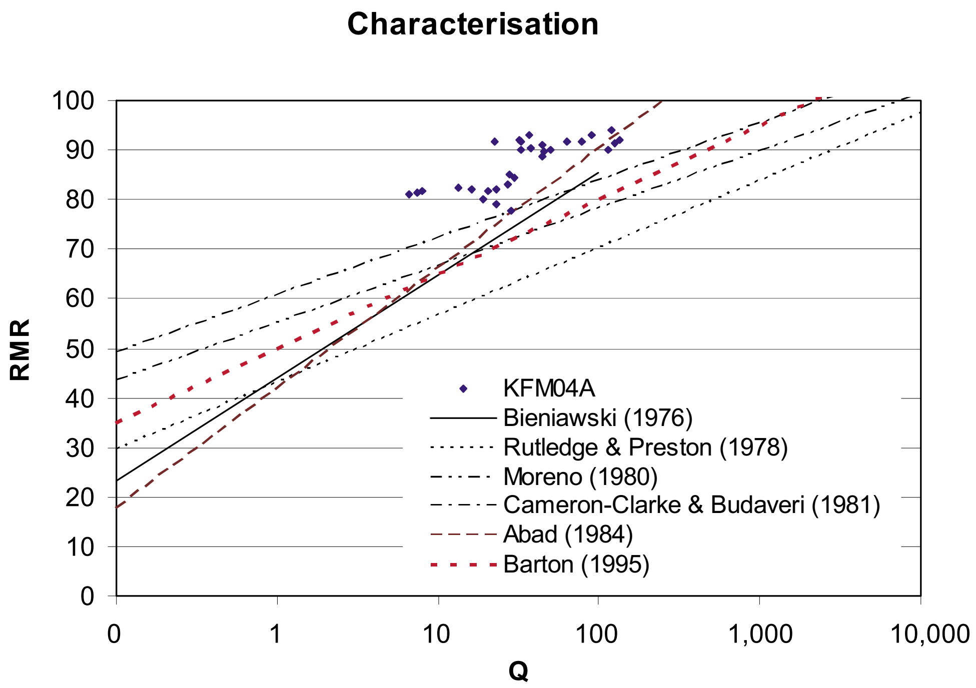

Figure 7-2. *Correlation between RMR and Q for the characterisation of the rock mass along borehole KFM04A (core sections of 30 m). The characterisation results are compared with some relations for design applications from the literature.*

In (Figure 7-3) the averaging effect of analysis over longer core sections (5 and 30 m) can be seen. The longer core sections apply an averaging process that smoothen all the extreme values of most of the geological input parameters. This averaging process affects RMR and Q in different ways. The RMR values show a larger variation in the 30 m analysis compared to the Q values. The values of Q also tend to reduce for larger borehole sections about 40%. This is due to the fact that the number of contemporarily occurring fracture sets increases when the core section length increases, thus Q diminishes. No appreciable reduction occurs for RMR.

The rock mass along the borehole presents a clear improvement of quality below 500 m depth. There is also a marked difference between the competent and the fractured rock. This is shown by Figure 7-4, where the approximated Hoek and Brown's Criterion for the competent and fractured rock is shown.

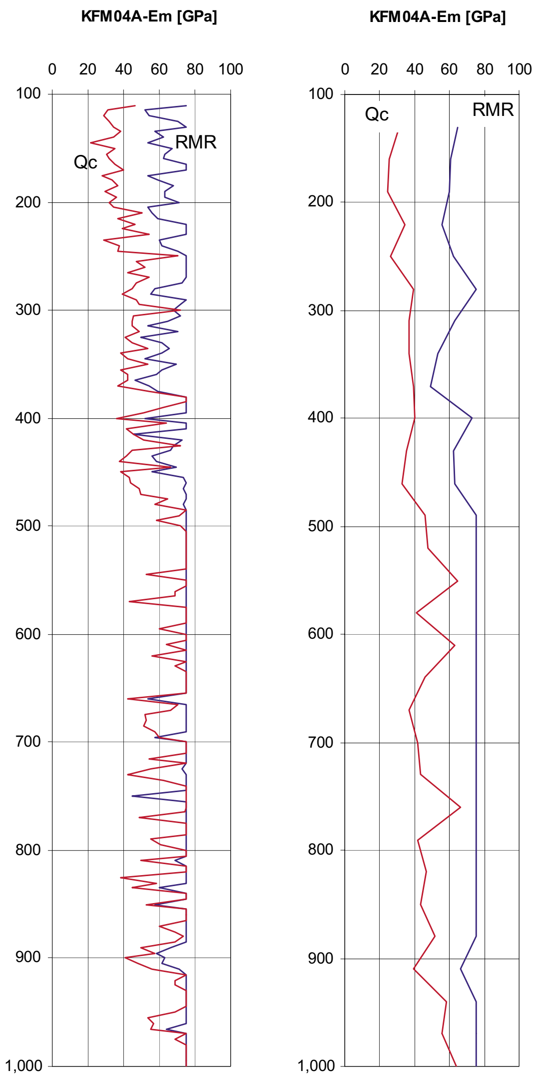

Figure 7-3. *Scale effect on the deformation modulus of the rock mass obtained from RMR and Q/Qc.*

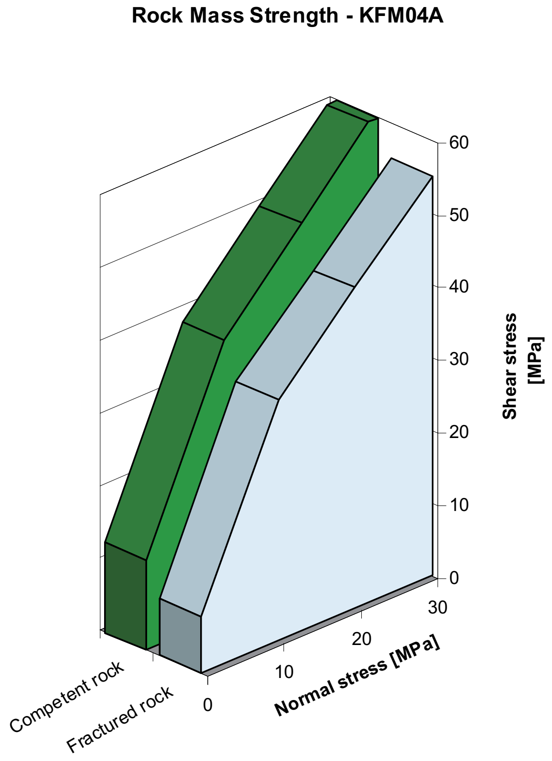

Figure 7-4. *Approximated Hoek and Brown's failure criteria for the "competent rock" and "fractured rock" along borehole KFM04A.*

8 Conclusions

For the purpose of characterisation of the rock mass, the two independent empirical systems Q and RMR were applied to the data from borehole KFM04A in Forsmark. The input data consisted of geomechanical data in digital format stored in SICADA together with the information in graphical form as the BIPS pictures of the borehole wall. The data was processes within core sections of lengths of 5 and 30 m to investigate possible scale effects on the rock mass quality and derived parameters. RMR and Q systems were applied here according to SKB's methodology that implies "characterisation": the boundary conditions in terms of stresses and water pressure are disjointed from the material properties of the rock mass.

The length of the borehole sections affected the characterisation results. It was observed that, while RMR does not seem to be influenced by scale, Q tends to diminish when applied to longer borehole sections. This is due to the fact that longer core section intercepts a larger amount of fractures, thus the number of fracture sets occurring in one section can easily increase of one or two units. Hence, the rock mass appears to have worse conditions when longer sections are analysed.

The application of two independent empirical systems for the characterisation of the rock mass provides the range of possible and expected values of the rock mass quality and derived mechanical properties. Some differences between the two methods arise particularly concerning the fractured zones. This is probably due to the Q factor SRF for fracture zones that take care of the ratio between rock stresses and uniaxial compressive strength of the intact rock. Due to the stepwise structure of the tables providing the values of SRF for the Q system (i.e. SRF jumps from 1 to 2.5 with no intermediate values), it is possible that the quality of the fractured zone is slightly underestimated.

The rock quality varies with depth. In the upper 500 m, it varies between "good" and "very good" (RMR between 80 and 87; Q > 10); below 500 m it becomes "very good" rock (RMR about 90; Q > 40). The deformation zones are characterised on average by a RMR of 82 and Q of 45.

In general, Q gives deformation moduli lower and more varying than RMR down to 500 m. The difference can be up to 30 GPa above 500 m. The mean deformation modulus from RMR varies in the range of 53–65 GPa. The deformation modulus from Q has a larger range of variation with mean deformation modulus ranging between 34 and 69 GPa. About 78% of the rock mass along the borehole exhibits a deformation modulus of 75 GPa (based on RMR).

The Poisson's ratio of the competent rock can be estimated to about 0.23, while that of the fractured rock could be about 0.20.

The uniaxial compressive strength of the rock mass determined by means of RMR/GSI/ Hoek and Brown's Strength Criterion is 95 MPa and 60 MPa on average for the competent rock and deformation zones, respectively. The linear interpolation of the Hoek and Brown's Strength Criterion also gives the apparent cohesion and friction angle of the rock mass for a certain stress interval. For stresses between 10 and 30 MPa, the cohesion is about 27 MPa and the friction angle 49° for the competent rock. For the deformation zones/fractured rock and the same stress interval, the cohesion is about 22 MPa and the friction angle 48°.

Some P-wave velocity measurements are analysed with respect to the orientation of the foliation. The P-wave velocity shows a quite sharp change to lower values at 500 m. For larger depths, the velocity starts to oscillate more than above 500 m. The average velocity varies between 5,500 and 5,260 m/s.

The data contained in the appendices are delivered and input into SKB's database SICADA to complete the single-hole interpretation. This report also contains data that quantify the spatial variability and confidence of the obtained results. The mean value, standard deviation and truncation of the normal distribution describe the spatial variation of the mechanical properties, while the 95% confidence level of the mean values of the properties provides a measure of the uncertainty of the property estimation.

9 Data delivery to SICADA

The results of the rock mass characterisation are delivered to SKB's database SICADA. The characterisation of the rock mass by means of the RMR and Q systems for rock mechanics purposes is assigned to the activity group "Rock Mechanics". For each borehole, data are given for the pseudo-homogenous sections (rock units) of drill-core/borehole and the deformation zones identified by the geological "single-hole" interpretation. For each rock unit or deformation zone, six values of RMR and Q resulting from the characterisation are delivered to the database: the minimum RMR and Q, average RMR/most frequent Q, and the maximum RMR and Q, respectively. Among the rock mechanics properties, the uniaxial compressive strength of the intact rock (UCS) and the deformation modulus (E_m) of the rock mass are also delivered to SICADA. For the deformation modulus, two sets of values are given for each rock unit and deformation zone, one value obtained by means of RMR and one for Q, respectively, each of which consisting of minimum, average and maximum deformation modulus of the rock mass. Before storage into the database, quality assessment routines are performed on the methods and delivered data.

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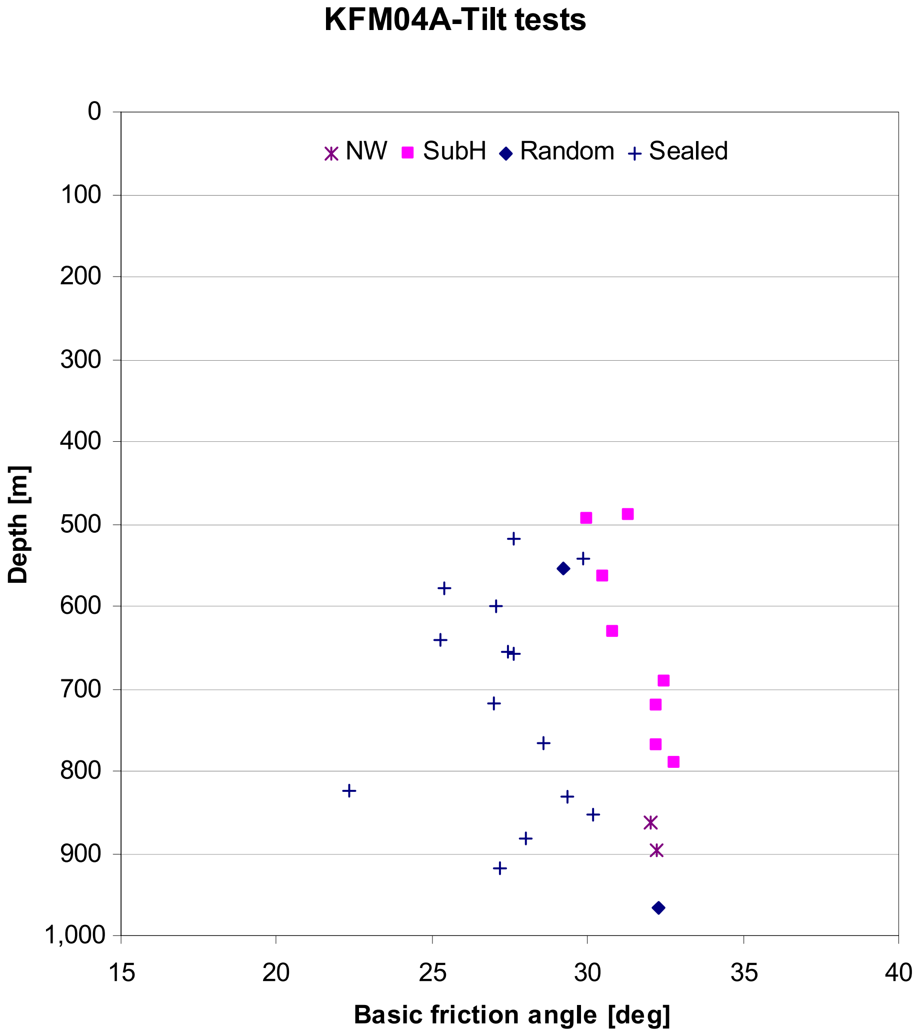
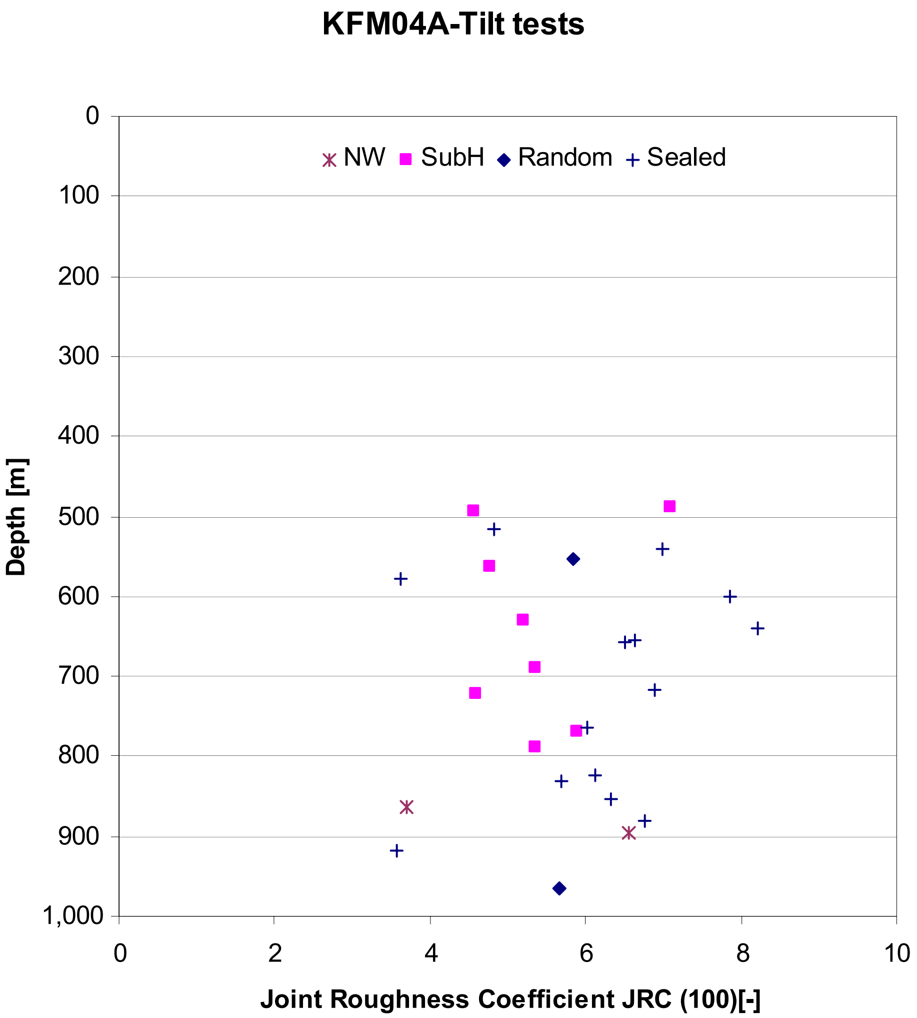
Appendix A

Rock fracture properties

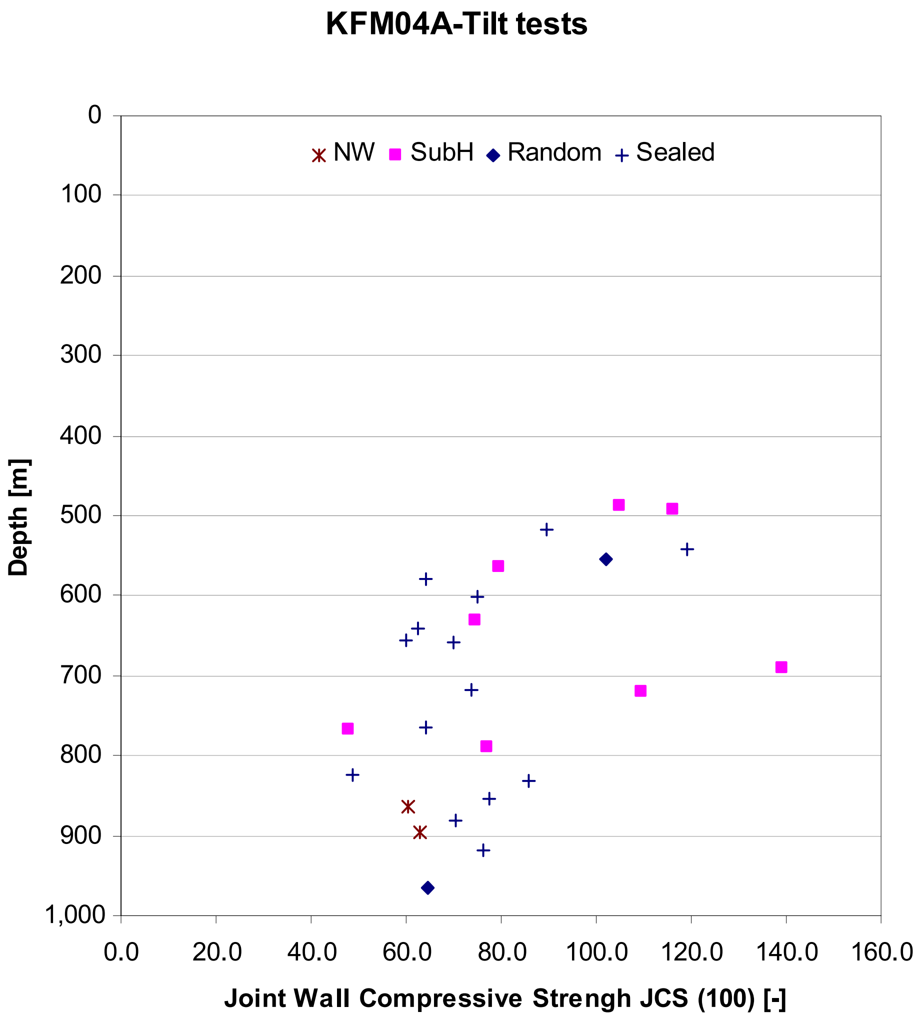
A.1 Tilt test results



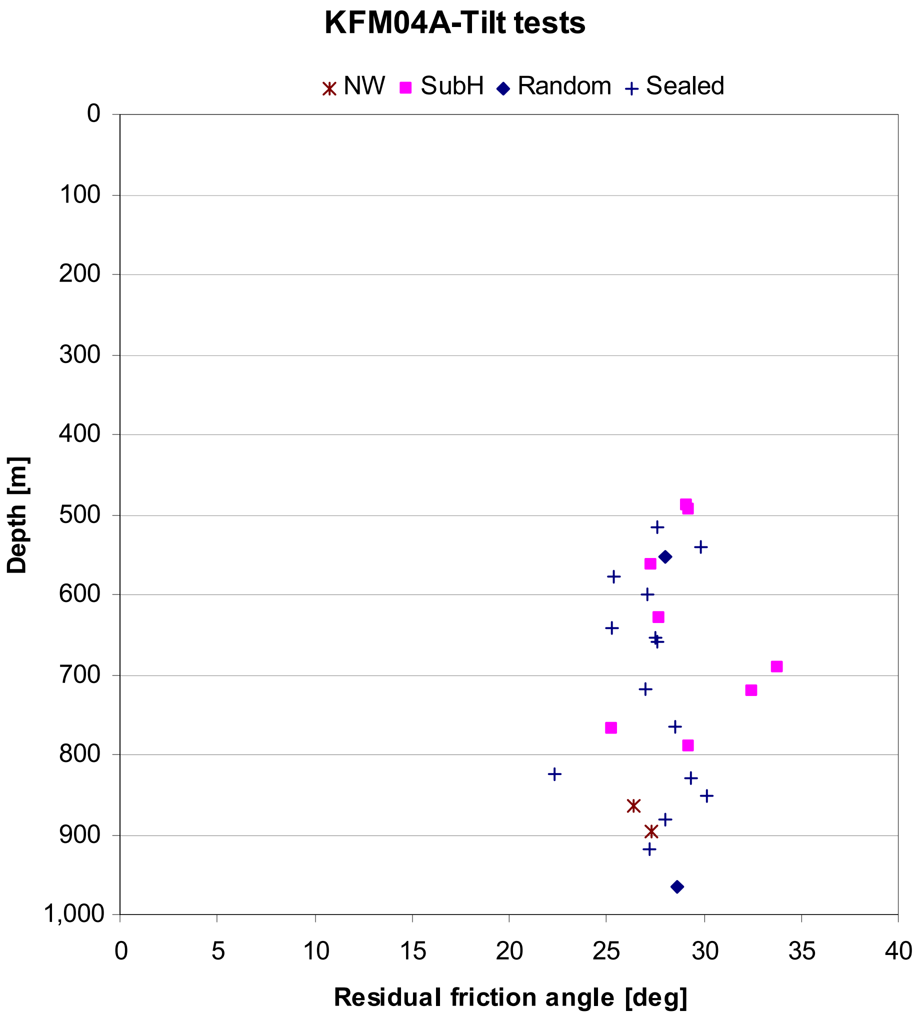
Variation of the basic friction angle of the tested fractures from KFM04A.



Variation of the Joint Roughness Coefficient JRC of the tested fractures from KFM04A.

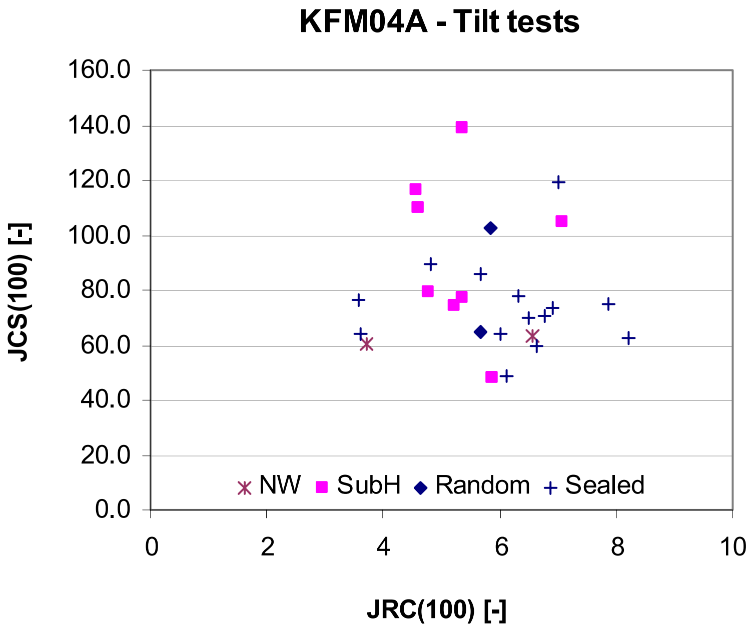


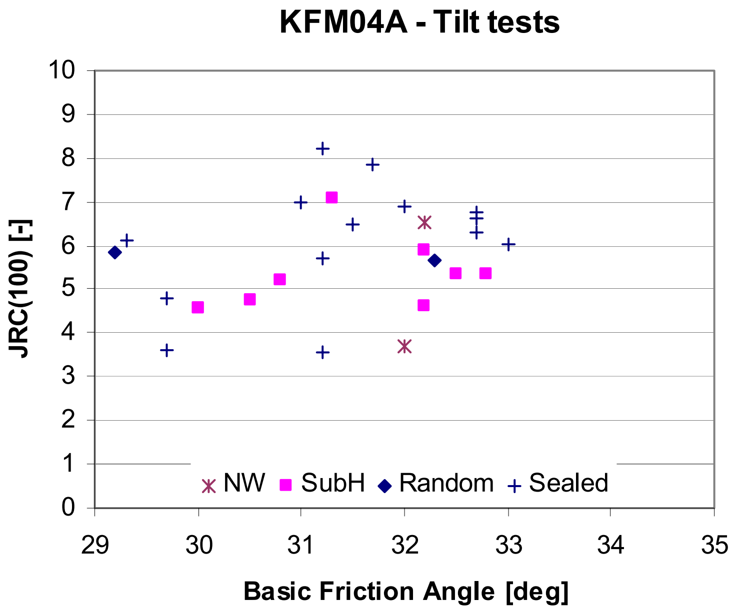
Variation of the Joint Compressive Strength JCS of the tested fractures from KFM04A.

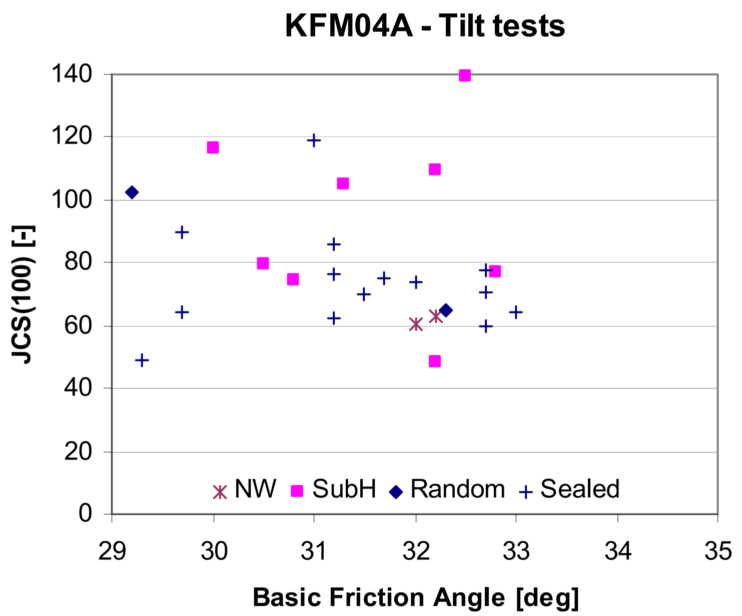


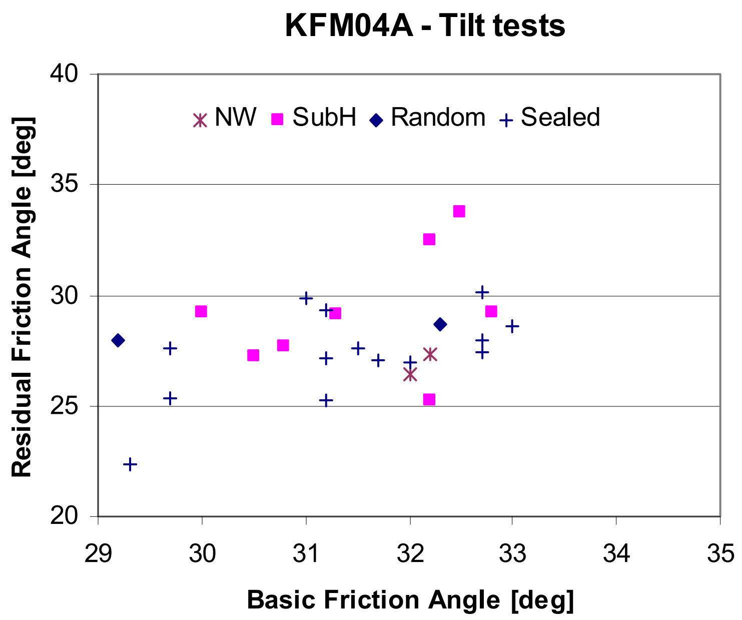
Variation of the residual friction angle of the tested fractures from KFM04A.

A.2 Correlations






KFM04A - Tilt tests
JCS(100) [-]
140
120
100
80
60
40
20
0
NW
SubH
Random
Sealed
29
30
31
32
33
34
35
Basic Friction Angle [deg]


KFM04A - Tilt tests
Residual Friction Angle [deg]
40
35
30
25
20
NW
SubH
Random
Sealed
29
30
31
32
33
34
35
Basic Friction Angle [deg]

Appendix B

Characterisation of the rock mass

B.1 RMR

B.1.1 RMR values along borehole KFM04A (core sections of 5 m).

Depth [m]	Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation	Min possible RMR	Max possible RMR
105–170	78.7	83.4	81.9	92.7	4.1	56.0	98
170–175	79.2	79.2	79.2	79.2	0	61.6	92.2
175–200	80.8	82.4	82.1	84.0	1.2	62.0	98.0
200–215	79.1	80.0	79.9	80.9	0.9	62.6	96.3
215–230	85.4	88.9	89.8	91.5	3.1	67.7	98.0
230–240	81.0	81.3	81.3	81.7	0.5	66.6	96.6
240–275	83.9	87.9	85.3	93.0	4.1	61.5	98.0
275–340	77.9	82.1	82.5	85.8	2.3	59.7	97.6
340–410	76.8	82.9	81.6	90.8	4.4	51.4	98.0
410–445	76.5	82.1	83.0	85.8	3.0	62.4	97.0
445–460	80.0	83.4	84.6	85.6	3.0	65.6	95.3
460–500	84.7	89.0	90.2	94.0	3.5	68.1	97.0
500–655	86.3	93.7	95.1	96.5	3.1	69.3	98.0
655–660	79.2	79.2	79.2	79.2	0	59.1	90.5
660–725	80.5	90.4	92.0	96.5	4.3	70.1	98.0
725–745	87.2	89.9	89.3	93.7	3.3	72.5	97.0
745–940	76.1	90.3	92.3	96.5	5.7	63.4	98.0
940–965	82.2	89.7	90.5	96.1	5.1	68.5	98.0
965–990	92.5	94.6	94.0	98.3	2.4	71.6	100.0
990–1,000	97.1	97.8	97.8	98.5	1.0	89.3	100.0

The shading in yellow indicates the location of the identified potential deformation zones.

B.1.2 RMR for the rock units in borehole KFM04A (core sections of 5 m).

Rock Unit	Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation	Min possible RMR	Max possible RMR
RU2	78.7	83.1	81.9	92.7	4.1	56.0	98.0
RU3	79.1	85.8	84.7	94.0	4.4	61.5	98.0
RU4	77.9	82.1	82.5	85.8	2.3	59.7	97.6
RU5	76.5	82.6	82.8	90.8	3.9	51.4	98.0
RU6	76.1	91.6	92.5	98.3	5.0	59.1	100.0
RU7	87.2	92.5	92.6	98.5	4.8	72.5	100.0
RU8	82.2	89.7	90.5	96.1	5.1	68.5	98.0
Competent rock	76.1	88.9	90.3	98.5	5.8	51.4	100.0
Fractured rock	76.5	81.6	81.0	85.8	2.6	59.1	97.0
Whole borehole	76.1	88.2	89.1	98.5	6.0	51.4	100.0

B.1.3 Summary of RMR values for borehole KFM04A (core sections of 30 m).

Rock Unit	Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation	Min possible RMR	Max possible RMR
RU2	81.2	81.6	81.3	82.3	0.6	52.8	98.0
RU3	77.7	82.2	81.9	88.6	3.2	51.1	98.0
RU4	79.0	80.5	80.5	81.9	2.1	51.1	98.0
RU5	77.7	81.3	81.8	84.5	3.4	55.1	98.0
RU6	82.9	90.9	91.4	94.0	2.5	55.3	98.0
RU7	91.9	91.9	91.9	91.9	0	69.5	97.0
RU8	91.8	91.8	91.8	91.8	0	62.7	97.0
Competent rock	77.7	88.1	90.1	94.0	4.9	51.1	98.0
Fractured rock	79.9	83.1	81.8	91.7	4.3	52.3	98.0
Whole borehole	77.7	87.1	89.9	94.0	5.1	51.1	98.0

B.2 Q

B.2.1 Q values along borehole KFM04A (core sections of 5 m).

Depth [m]	Minimum Q	Average Q	Frequent Q	Maximum Q	Min possible Q	Max possible Q
105–170	4.7	19.1	17.9	44.4	1.3	100.0
170–175	9.7	9.7	9.7	9.7	0.2	49.5
175–200	11.5	17.5	16.8	22.7	2.3	75.0
200–215	18.6	33.6	22.9	59.2	0.8	147.0
215–230	27.8	49.0	45.3	73.8	7.3	200.0
230–240	10.5	17.1	17.1	23.7	1.5	60.0
240–275	23.2	64.3	47.3	158.7	4.6	300.0
275–340	26.5	52.6	41.5	168.0	4.8	600.0
340–410	21.2	84.5	61.6	295.2	4.3	600.0
410–445	24.5	66.7	42.0	167.3	7.6	300.0
445–460	25.3	33.6	37.0	38.4	4.4	200.0
460–500	51.8	130.5	106.6	300.0	14.0	400.0
500–655	37.2	502.0	800.0	800.0	16.0	800.0
655–660	35.5	35.5	35.5	35.5	2.5	200.0
660–725	60.0	183.7	100.0	800.0	11.1	800.0
725–745	35.1	227.3	205.6	462.9	11.1	600.0
745–940	25.0	321.5	185.6	800.0	9.7	800.0
940–965	70.3	236.0	84.5	800.0	18.0	800.0
965–990	149.1	429.8	300.0	800.0	72.8	800.0
990–1,000	2,133.3	2,133.3	2,133.3	2,133.3	2,133.3	2,133.3

The shading in yellow indicates the location of the identified potential deformation zones.

B.2.2 Summary of Q values for borehole KFM04A (core sections of 5 m).

Rock Unit	Minimum Q	Average Q	Frequent Q	Maximum Q	Min possible Q	Max possible Q
RU2	4.7	18.4	16.6	44.4	0.2	100.0
RU3	10.5	63.3	45.3	300.0	0.8	400.0
RU4	26.5	52.6	41.5	168.0	4.8	600.0
RU5	21.2	77.7	43.3	295.2	4.3	600.0
RU6	25.0	367.1	200.0	800.0	2.5	800.0
RU7	35.1	862.6	381.5	2,133.3	11.1	2,133.3
RU8	70.3	236.0	84.5	800.0	18.0	800.0
Competent rock	4.7	265.5	104.1	2,133.3	1.3	2,133.3
Fractured rock	9.7	45.2	34.6	167.3	0.2	300.0
Whole borehole	4.7	243.4	87.5	2,133.3	0.2	2,133.3

B.2.3 Summary of Q values for borehole KFM04A (core section of 30 m).

Rock Unit	Minimum Q	Average Q	Frequent Q	Maximum Q	Min possible Q	Max possible Q
RU2	6.6	9.1	7.4	13.4	0.2	50.0
RU3	8.0	24.1	23.0	45.0	0.6	200.0
RU4	22.9	23.0	23.0	23.2	2.7	200.0
RU5	20.4	26.2	28.2	30.1	1.4	100.0
RU6	22.7	58.3	44.9	124.7	0.6	300.0
RU7	135.3	135.3	135.3	135.3	15.8	200.0
RU8	77.5	77.5	77.5	77.5	18.0	200.0
Competent rock	7.4	52.6	37.2	135.3	0.5	300.0
Fractured rock	6.6	15.5	17.5	22.7	0.2	100.0
Whole borehole	6.6	45.2	32.3	135.3	0.2	300.0

Appendix C

Rock mass properties

C.1 Deformation modulus

C.1.1 RMR

Deformation modulus Em derived from RMR along for borehole KFM04A (core sections of 5 m).

Depth [m]	Minimum Em [GPa]	Average Em [GPa]	Frequent Em [GPa]	Maximum Em [GPa]	Standard deviation	Min possible Em [GPa]	Max possible Em [GPa]
105–170	52.2	63.9	62.7	75.0	8.5	14.1	90.0
170–175	53.6	53.6	53.6	53.6	0	19.5	90.0
175–200	58.9	64.8	63.4	71.0	4.6	20.0	90.0
200–215	53.4	56.2	55.8	59.3	3.0	20.7	90.0
215–230	75.0	75.0	75.0	75.0	0	27.7	90.0
230–240	59.6	60.8	60.8	62.0	1.7	26.0	90.0
240–275	70.3	74.0	75.0	75.0	1.9	19.3	90.0
275–340	49.9	63.6	65.0	75.0	8.0	17.4	90.0
340–410	46.7	63.8	61.5	75.0	10.7	10.8	90.0
410–445	45.9	63.9	66.9	75.0	9.8	20.4	90.0
445–460	56.2	68.1	73.2	75.0	10.4	24.5	90.0
460–500	73.8	74.7	75.0	75.0	0.5	28.4	90.0
500–655	75.0	75.0	75.0	75.0	0	30.4	90.0
655–660	53.8	53.8	53.8	53.8	0	16.9	90.0
660–725	57.9	73.5	75.0	75.0	4.7	31.7	90.0
725–745	75.0	75.0	75.0	75.0	0	36.6	90.0
745–940	45.0	71.9	75.0	75.0	6.8	21.7	90.0
940–965	63.8	72.8	75.0	75.0	5.0	29.1	90.0
965–990	75.0	75.0	75.0	75.0	0	34.6	90.0
990–1,000	75.0	75.0	75.0	75.0	0	40.0	90.0

The shading in yellow indicates the location of the potential deformation zones identified in borehole KFM04A. The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.

Summary of the deformation modulus Em derived from RMR for borehole KFM04A (core sections of 5 m).

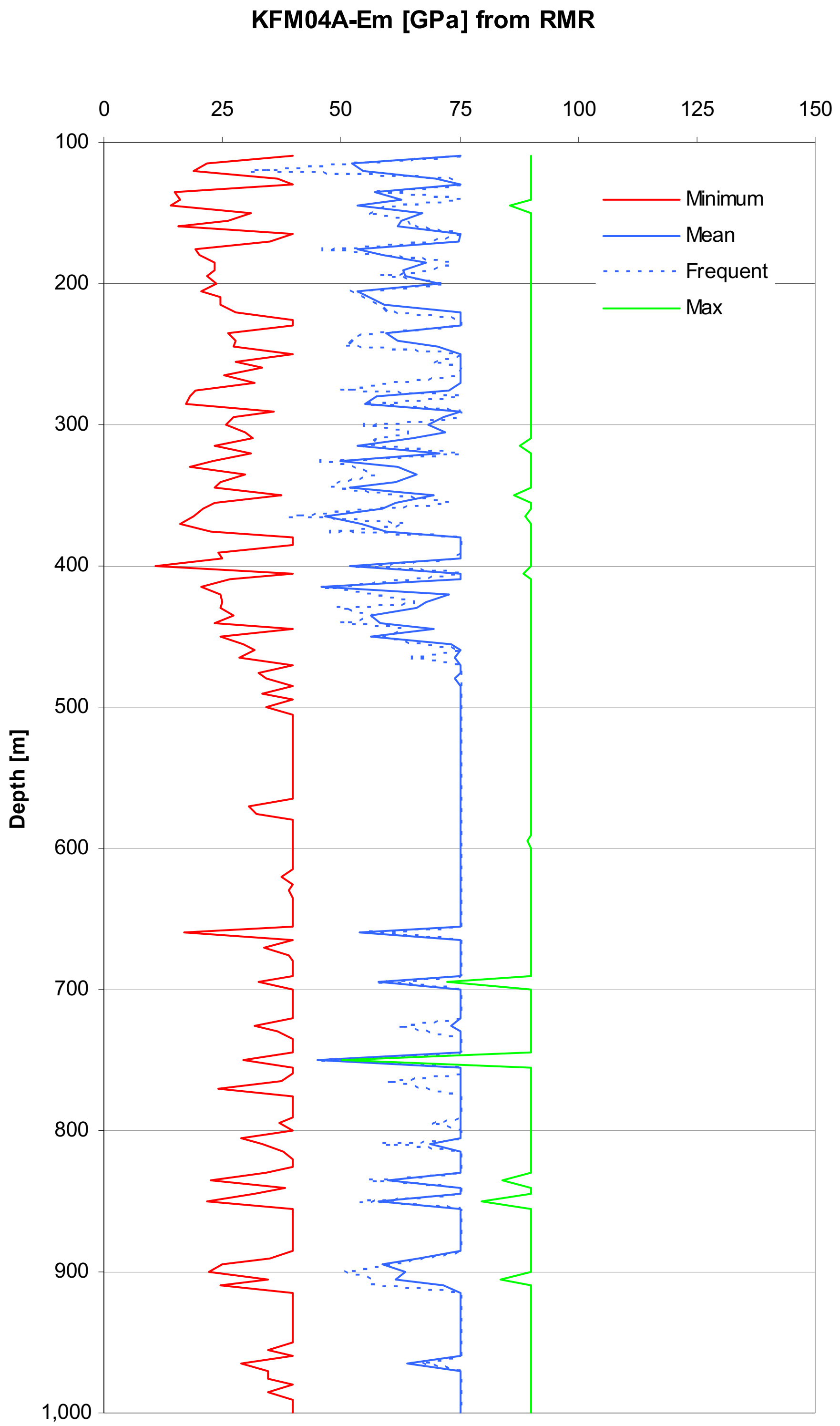
Rock Unit	Minimum Em [GPa]	Average Em [GPa]	Frequent Em [GPa]	Maximum Em [GPa]	Standard deviation	Min possible Em [GPa]	Max possible Em [GPa]
RU2	52.2	63.1	62.6	75.0	8.6	14.1	90.0
RU3	53.4	69.7	73.9	75.0	7.3	19.3	90.0
RU4	49.9	63.6	65.0	75.0	8.0	17.4	90.0
RU5	45.9	63.8	66.0	75.0	10.1	10.8	90.0
RU6	45.0	73.2	75.0	75.0	5.4	16.9	90.0
RU7	75.0	75.0	75.0	75.0	0	36.6	90.0
RU8	63.8	72.8	75.0	75.0	5.0	29.1	90.0
Competent rock	45.0	71.0	75.0	75.0	7.3	10.8	90.0
Fractured rock	45.9	61.8	59.4	75.0	8.7	16.9	90.0
Whole borehole	45.0	70.1	75.0	75.0	7.9	10.8	90.0

The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.

Summary of the deformation modulus Em derived from RMR for borehole KFM04A (core sections of 30 m).

Rock Unit	Minimum Em [GPa]	Average Em [GPa]	Frequent Em [GPa]	Maximum Em [GPa]	Standard deviation	Min possible Em [GPa]	Max possible Em [GPa]
RU2	60.2	61.7	60.6	64.4	2.3	11.7	90.0
RU3	49.4	63.2	62.6	75.0	8.9	10.7	90.0
RU4	53.1	57.9	57.9	62.8	6.9	10.7	90.0
RU5	49.4	61.5	62.2	72.8	11.7	13.4	90.0
RU6	66.6	74.4	75.0	75.0	2.2	13.5	90.0
RU7	75.0	75.0	75.0	75.0	0	30.7	90.0
RU8	75.0	75.0	75.0	75.0	0	20.8	90.0
Competent rock	49.4	71.0	75.0	75.0	7.5	10.7	90.0
Fractured rock	56.1	63.1	62.3	75.0	6.3	11.4	90.0
Whole borehole	49.4	69.5	75.0	75.0	7.9	10.7	90.0

The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.



Variation of the deformation modulus of the rock mass obtained from RMR with depth for borehole KFM04A. The values are given every 5 m.

C.1.2 Q

Deformation modulus Em derived from Q along borehole KFM04A (core sections of 5 m).

Depth [m]	Minimum Em [GPa]	Average Em [GPa]	Frequent Em [GPa]	Maximum Em [GPa]	Standard deviation	Min possible Em [GPa]	Max possible Em [GPa]
105–170	21.8	33.8	34.0	46.1	5.8	10.8	66.9
170–175	27.7	27.7	27.7	27.7	0	6.2	53.0
175–200	29.4	33.5	33.3	36.8	3.0	13.2	60.8
200–215	34.4	40.7	36.9	50.7	8.8	9.1	76.1
215–230	39.4	46.8	46.4	54.6	7.6	19.4	84.3
230–240	28.4	32.9	32.9	37.3	6.3	11.4	56.5
240–275	37.1	50.1	47.0	70.4	10.7	16.6	90.0
275–340	38.8	47.3	45.0	71.8	8.4	16.9	90.0
340–410	36.0	51.9	51.4	75.0	13.7	16.2	90.0
410–445	37.8	50.1	45.2	71.7	12.3	19.6	90.0
445–460	38.2	41.8	43.3	43.9	3.1	16.4	84.3
460–500	48.5	62.1	61.5	75.0	10.3	24.1	90.0
500–655	43.4	71.2	75.0	75.0	7.9	25.2	90.0
655–660	42.8	42.8	42.8	42.8	0	13.6	84.3
660–725	50.9	63.1	60.4	75.0	9.9	22.3	90.0
725–745	42.6	63.8	68.8	75.0	15.3	22.3	90.0
745–940	38.0	65.9	74.2	75.0	11.8	21.3	90.0
940–965	53.7	61.9	57.1	75.0	9.5	26.2	90.0
965–990	69.0	73.8	75.0	75.0	2.7	40.0	90.0
990–1,000	75.0	75.0	75.0	75.0	0	40.0	90.0

The shading in yellow indicates the location of the potential deformation zones identified in Borehole KFM04A. The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.

Summary of the deformation modulus Em derived from Q for borehole KFM04A (core sections of 5 m).

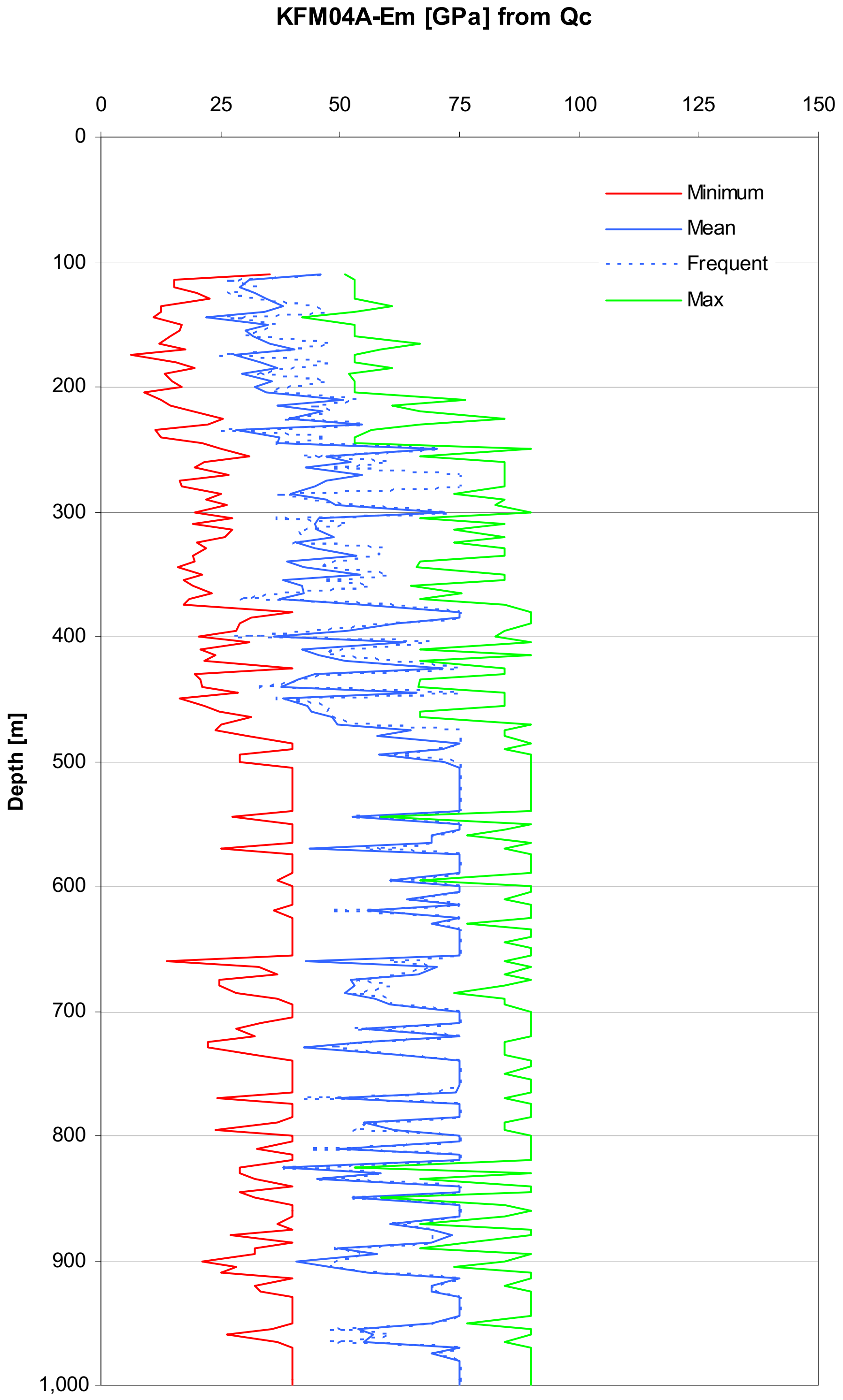
Rock Unit	Minimum Em [GPa]	Average Em [GPa]	Frequent Em [GPa]	Maximum Em [GPa]	Standard deviation	Min possible RMR	Max possible Em [GPa]
RU2	21.8	33.4	33.2	46.1	5.8	6.2	66.9
RU3	28.4	47.4	46.4	75.0	13.2	9.1	90.0
RU4	38.8	47.3	45.0	71.8	8.4	16.9	90.0
RU5	36.0	51.2	45.7	75.0	12.9	16.2	90.0
RU6	38.0	67.5	75.0	75.0	10.6	13.6	90.0
RU7	42.6	67.5	75.0	75.0	13.2	22.3	90.0
RU8	53.7	61.9	57.1	75.0	9.5	26.2	90.0
Competent rock	21.8	59.4	61.2	75.0	15.4	10.8	90.0
Fractured rock	27.7	43.6	42.4	71.7	11.2	6.2	90.0
Whole borehole	21.8	57.8	57.7	75.0	15.8	6.2	90.0

The shading in yellow indicates the location of the potential deformation zones identified in Borehole KFM04A. The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.

Summary of the deformation modulus Em derived from Q for borehole KFM04A (core sections of 30 m).

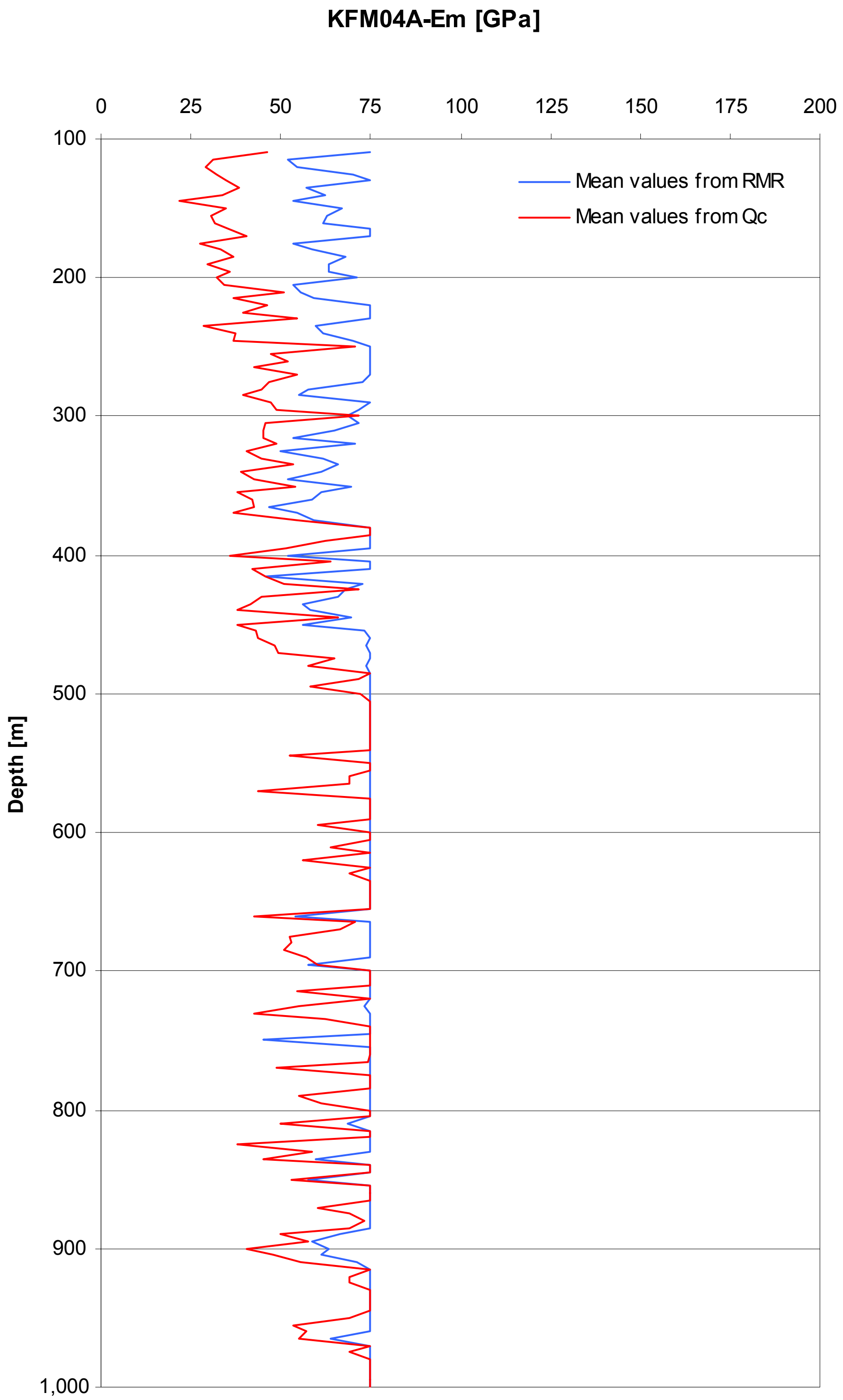
Rock Unit	Minimum Em [GPa]	Average Em [GPa]	Frequent Em [GPa]	Maximum Em [GPa]	Standard deviation	Min possible Em [GPa]	Max possible Em [GPa]
RU2	24.4	26.9	25.3	30.9	3.5	5.4	53.1
RU3	26.0	36.9	37.0	46.3	5.3	8.3	84.3
RU4	36.9	37.0	37.0	37.1	0.1	13.9	84.3
RU5	35.5	38.5	39.6	40.4	2.6	11.1	66.9
RU6	36.8	48.7	46.2	65.0	9.5	8.4	90.0
RU7	66.8	66.8	66.8	66.8	0	25.1	84.3
RU8	55.4	55.4	55.4	55.4	0	26.2	84.3
Competent rock	25.3	46.3	43.4	66.8	10.9	8.1	90.0
Fractured rock	24.4	31.7	33.8	36.8	5.2	5.4	66.9
Whole borehole	24.4	43.4	41.4	66.8	11.6	5.4	90.0

The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.



Variation of the deformation modulus of the rock mass obtained from Q_c with depth for borehole KFM04A. The values are given every 5 m.

C.1.3 Comparison



Comparison between the mean values of the deformation modulus E_m *obtained from RMR and Qc for different depths for borehole KFM04A.*

C.2 Poisson's ratio

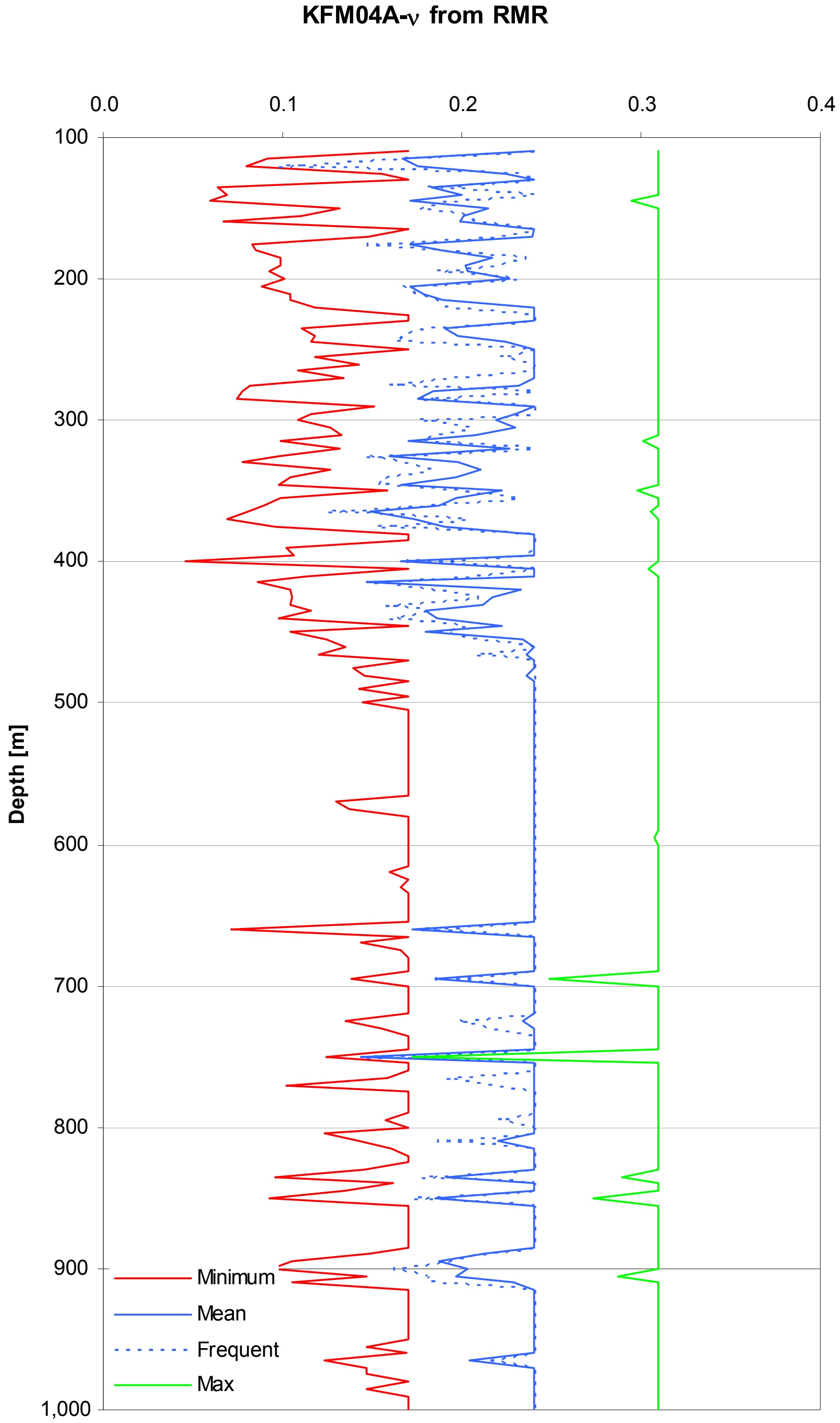
C.2.1 RMR

Summary of Poisson's ratio (v) derived from RMR for borehole KFM04A (core sections of 5 m).

Depth [m]	Minimum v	Average v	Frequent v	Maximum v	Standard deviation	Min possible v	Max possible v
105–170	0.17	0.21	0.20	0.24	0.03	0.06	0.31
170–175	0.17	0.17	0.17	0.17	0	0.08	0.31
175–200	0.19	0.21	0.20	0.23	0.01	0.08	0.31
200–215	0.17	0.18	0.18	0.19	0.01	0.09	0.31
215–230	0.24	0.24	0.24	0.24	0	0.12	0.31
230–240	0.19	0.19	0.19	0.20	0.01	0.11	0.31
240–275	0.22	0.24	0.24	0.24	0.01	0.08	0.31
275–340	0.16	0.20	0.21	0.24	0.03	0.07	0.31
340–410	0.15	0.20	0.20	0.24	0.03	0.05	0.31
410–445	0.15	0.20	0.21	0.24	0.03	0.09	0.31
445–460	0.18	0.22	0.23	0.24	0.03	0.10	0.31
460–500	0.24	0.24	0.24	0.24	0	0.12	0.31
500–655	0.24	0.24	0.24	0.24	0	0.13	0.31
655–660	0.17	0.17	0.17	0.17	0	0.07	0.31
660–725	0.19	0.24	0.24	0.24	0.02	0.13	0.31
725–745	0.24	0.24	0.24	0.24	0	0.16	0.31
745–940	0.14	0.23	0.24	0.24	0.02	0.09	0.31
940–965	0.20	0.23	0.24	0.24	0.02	0.12	0.31
965–990	0.24	0.24	0.24	0.24	0	0.15	0.31
990–1,000	0.24	0.24	0.24	0.24	0	0.17	0.31

Poisson's ratio (v) from RMR for the rock units in borehole KFM04A (core sections of 5 m).

Rock Unit	Minimum v	Average v	Frequent v	Maximum v	Standard deviation	Min possible v	Max possible v
RU2	0.17	0.20	0.20	0.24	0.03	0.06	0.31
RU3	0.17	0.22	0.24	0.24	0.02	0.08	0.31
RU4	0.16	0.20	0.21	0.24	0.03	0.07	0.31
RU5	0.15	0.20	0.21	0.24	0.03	0.05	0.31
RU6	0.14	0.23	0.24	0.24	0.02	0.07	0.31
RU7	0.24	0.24	0.24	0.24	0	0.16	0.31
RU8	0.20	0.23	0.24	0.24	0.02	0.12	0.31
Competent rock	0.14	0.23	0.24	0.24	0.02	0.05	0.31
Fractured rock	0.15	0.20	0.19	0.24	0.03	0.07	0.31
Whole borehole	0.14	0.22	0.24	0.24	0.03	0.05	0.31



Variation of Poisson's ratio (ν) with depth for borehole KFM04A. The values are given every 5 m.

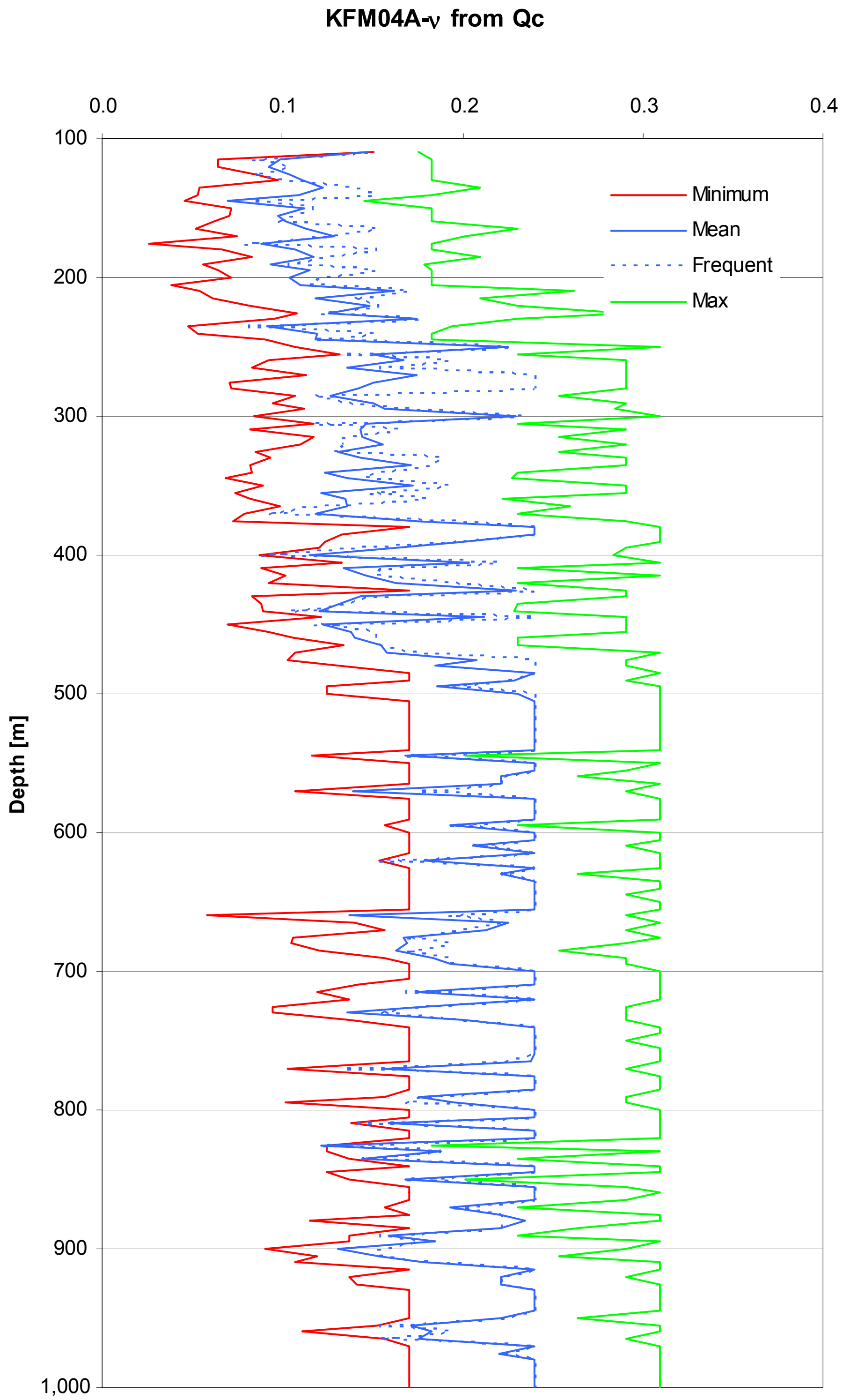
C.2.2 Q

Summary of Poisson's ratio (v) derived from Qc for borehole KFM04A (core sections of 5 m).

Depth [m]	Minimum v	Average v	Frequent v	Maximum v	Standard deviation	Min possible v	Max possible v
105–170	0.07	0.11	0.11	0.15	0.02	0.05	0.23
170–175	0.09	0.09	0.09	0.09	0	0.03	0.18
175–200	0.09	0.11	0.11	0.12	0.01	0.06	0.21
200–215	0.11	0.13	0.12	0.16	0.03	0.04	0.26
215–230	0.13	0.15	0.15	0.17	0.02	0.08	0.29
230–240	0.09	0.11	0.11	0.12	0.02	0.05	0.19
240–275	0.12	0.16	0.15	0.23	0.03	0.07	0.31
275–340	0.12	0.15	0.14	0.23	0.03	0.07	0.31
340–410	0.12	0.17	0.16	0.24	0.04	0.07	0.31
410–445	0.12	0.16	0.14	0.23	0.04	0.08	0.31
445–460	0.12	0.13	0.14	0.14	0.01	0.07	0.29
460–500	0.16	0.20	0.20	0.24	0.03	0.10	0.31
500–655	0.14	0.23	0.24	0.24	0.03	0.11	0.31
655–660	0.14	0.14	0.14	0.14	0	0.06	0.29
660–725	0.16	0.20	0.19	0.24	0.03	0.09	0.31
725–745	0.14	0.20	0.22	0.24	0.05	0.09	0.31
745–940	0.12	0.21	0.24	0.24	0.04	0.09	0.31
940–965	0.17	0.20	0.18	0.24	0.03	0.11	0.31
965–990	0.22	0.24	0.24	0.24	0.01	0.17	0.31
990–1,000	0.24	0.24	0.24	0.24	0	0.17	0.31

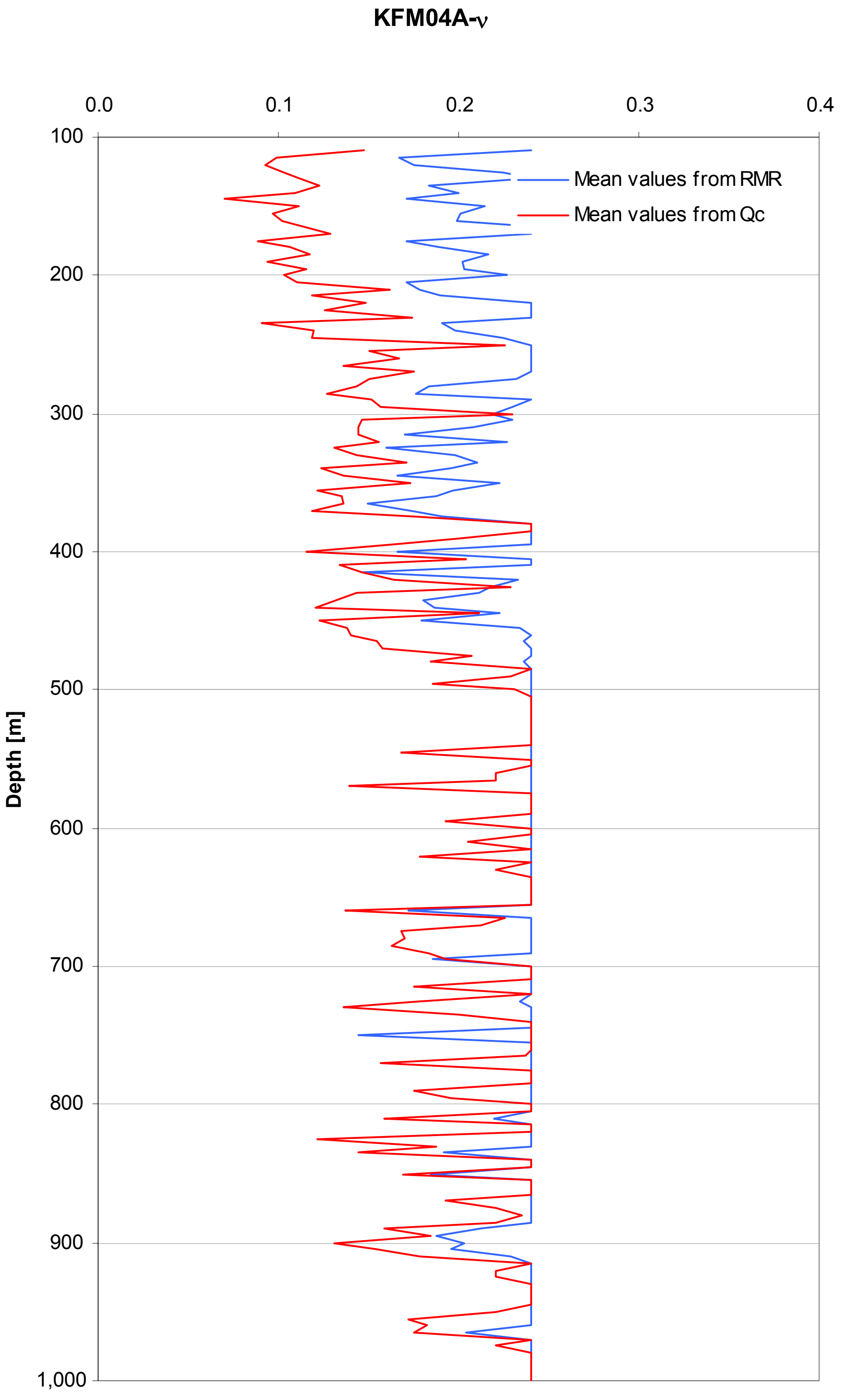
Poisson's ratio (v) from Qc for the rock units in borehole KFM04A (core sections of 5 m).

Rock Unit	Minimum v	Average v	Frequent v	Maximum v	Standard deviation	Min possible v	Max possible v
RU2	0.07	0.11	0.11	0.15	0.02	0.03	0.23
RU3	0.09	0.15	0.15	0.24	0.04	0.04	0.31
RU4	0.12	0.15	0.14	0.23	0.03	0.07	0.31
RU5	0.12	0.16	0.15	0.24	0.04	0.07	0.31
RU6	0.12	0.22	0.24	0.24	0.03	0.06	0.31
RU7	0.14	0.22	0.24	0.24	0.04	0.09	0.31
RU8	0.17	0.20	0.18	0.24	0.03	0.11	0.31
Competent rock	0.07	0.19	0.20	0.24	0.05	0.05	0.31
Fractured rock	0.09	0.14	0.14	0.23	0.04	0.03	0.31
Whole borehole	0.07	0.19	0.18	0.24	0.05	0.03	0.31



Variation of Poisson's ratio (ν) with depth for borehole KFM04A. The values are given every 5 m.

C.2.3 Comparison



Comparison between the mean values of Poisson's ratio (ν) obtained from RMR and Qc for different depths for borehole KFM04A.

C.3 Uniaxial compressive strength

C.3.1 RMR

Summary of the uniaxial compressive strength of the rock mass derived from RMR for borehole KFM04A (core sections of 5 m).

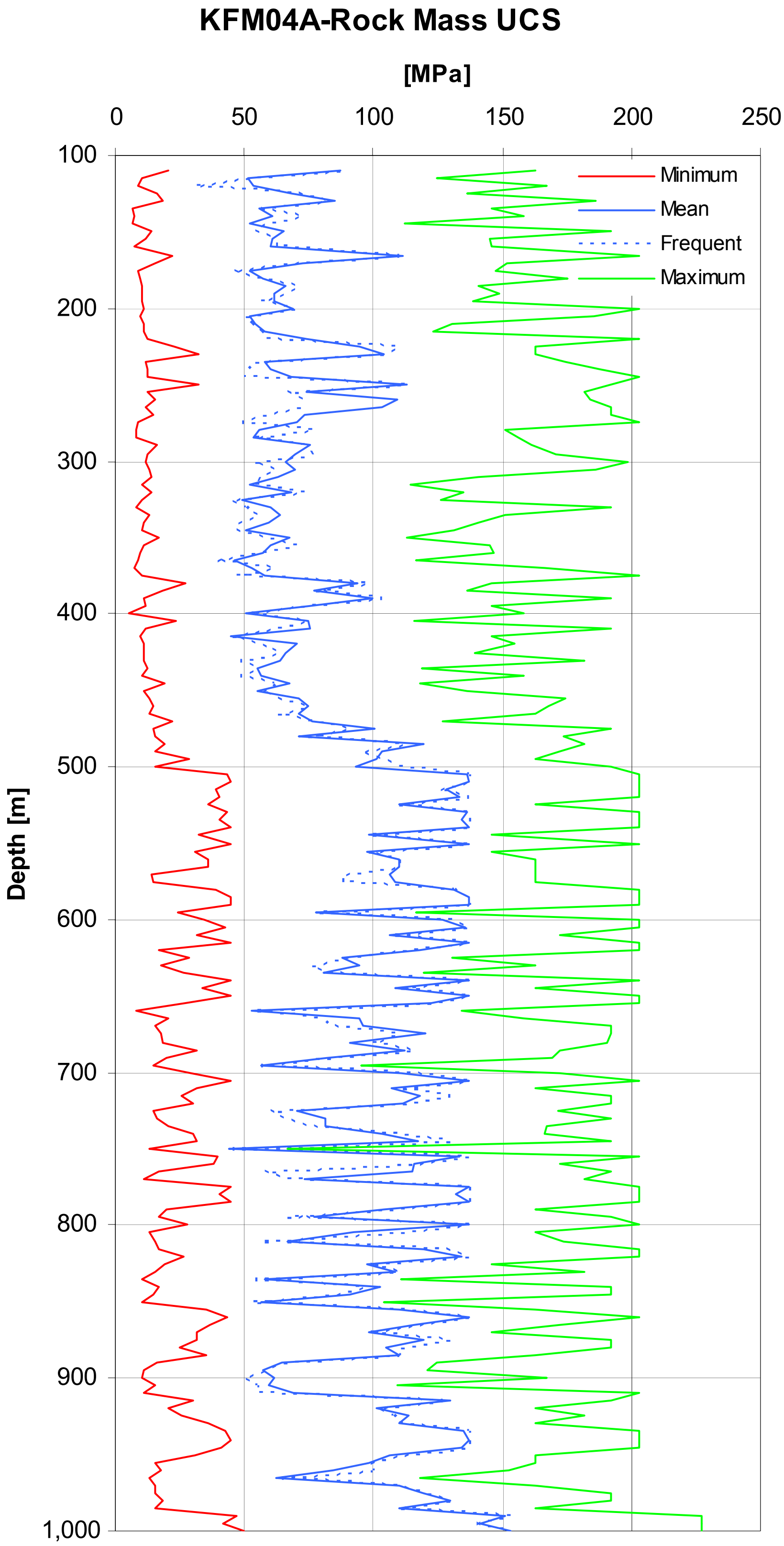
Depth [m]	Minimum UCS	Average UCS	Frequent UCS	Maximum UCS	Standard deviation	Min possible UCS	Max possible UCS
105–170	51.0	67.9	61.1	111.2	17.3	6.6	203.3
170–175	52.4	52.4	52.4	52.4	0	9.0	147.5
175–200	57.4	62.9	61.6	68.7	4.4	9.2	202.8
200–215	52.2	54.8	54.5	57.7	2.8	9.5	185.5
215–230	74.1	90.9	94.7	103.9	15.3	12.6	203.3
230–240	58.0	59.1	59.1	60.2	1.6	11.9	187.7
240–275	68.0	87.2	73.8	113.0	20.1	8.9	203.3
275–340	48.9	62.0	63.1	75.5	7.9	8.1	198.9
340–410	45.8	66.5	59.8	99.9	17.0	5.1	203.3
410–445	45.1	62.5	64.9	75.8	9.8	9.4	192.4
445–460	54.8	66.8	70.8	74.7	10.5	11.2	174.6
460–500	71.4	92.1	96.7	119.5	17.5	12.9	192.4
500–655	77.7	119.3	126.6	137.2	18.9	13.8	137.2
655–660	52.6	52.6	52.6	52.6	0	7.8	133.9
660–725	56.4	100.4	107.0	137.2	21.9	14.3	203.3
725–745	81.6	96.0	92.5	117.5	17.6	16.5	192.4
745–940	44.3	101.8	108.6	137.2	28.5	9.9	203.3
940–965	62.0	96.9	98.3	133.9	26.6	13.2	203.3
965–990	109.9	124.0	119.4	151.3	17.3	15.6	227.2
990–1,000	141.8	147.6	147.6	153.3	8.1	41.8	227.2

Uniaxial compressive strength of the rock mass from RMR for the rock units in borehole KFM04A (core sections of 5 m).

Rock Unit	Minimum UCS	Average UCS	Frequent UCS	Maximum UCS	Standard deviation	Min possible UCS	Max possible UCS
RU2	51.0	66.8	61.0	111.2	17.1	6.6	203.3
RU3	52.2	78.0	71.4	119.5	19.9	8.9	203.3
RU4	48.9	62.0	63.1	75.5	7.9	8.1	198.9
RU5	45.1	65.0	64.0	99.9	14.5	5.1	203.3
RU6	44.3	108.4	109.9	151.3	25.9	7.8	227.2
RU7	81.6	113.2	110.5	153.3	30.1	16.5	227.2
RU8	62.0	96.9	98.3	133.9	26.6	13.2	203.3
Competent rock	44.3	94.7	97.4	153.3	29.1	5.1	227.2
Fractured rock	45.1	60.4	57.9	75.8	8.7	7.8	192.4
Whole borehole	44.3	91.2	90.9	153.3	29.6	5.1	227.2

Summary of the compressive strength of the rock mass derived from RMR for borehole KFM04A (core sections of 30 m).

Rock Unit	Minimum UCS	Average UCS	Frequent UCS	Maximum UCS	Standard deviation	Min possible UCS	Max possible UCS
RU2	58.6	60.0	59.0	62.5	2.1	5.5	203.3
RU3	48.4	63.0	60.8	88.4	11.6	5.0	203.3
RU4	51.9	56.4	56.4	61.0	6.5	5.0	203.3
RU5	48.4	59.8	60.5	70.4	11.0	6.3	203.3
RU6	64.6	101.1	103.6	119.2	12.4	6.3	203.3
RU7	106.4	106.4	106.4	106.4	0	13.9	192.4
RU8	106.0	106.0	106.0	106.0	0	9.6	192.4
Competent rock	48.4	89.1	96.0	119.2	21.6	5.0	203.3
Fractured rock	54.7	66.8	60.5	104.9	18.8	5.4	203.3
Whole borehole	48.4	84.6	94.9	119.2	22.6	5.0	203.3

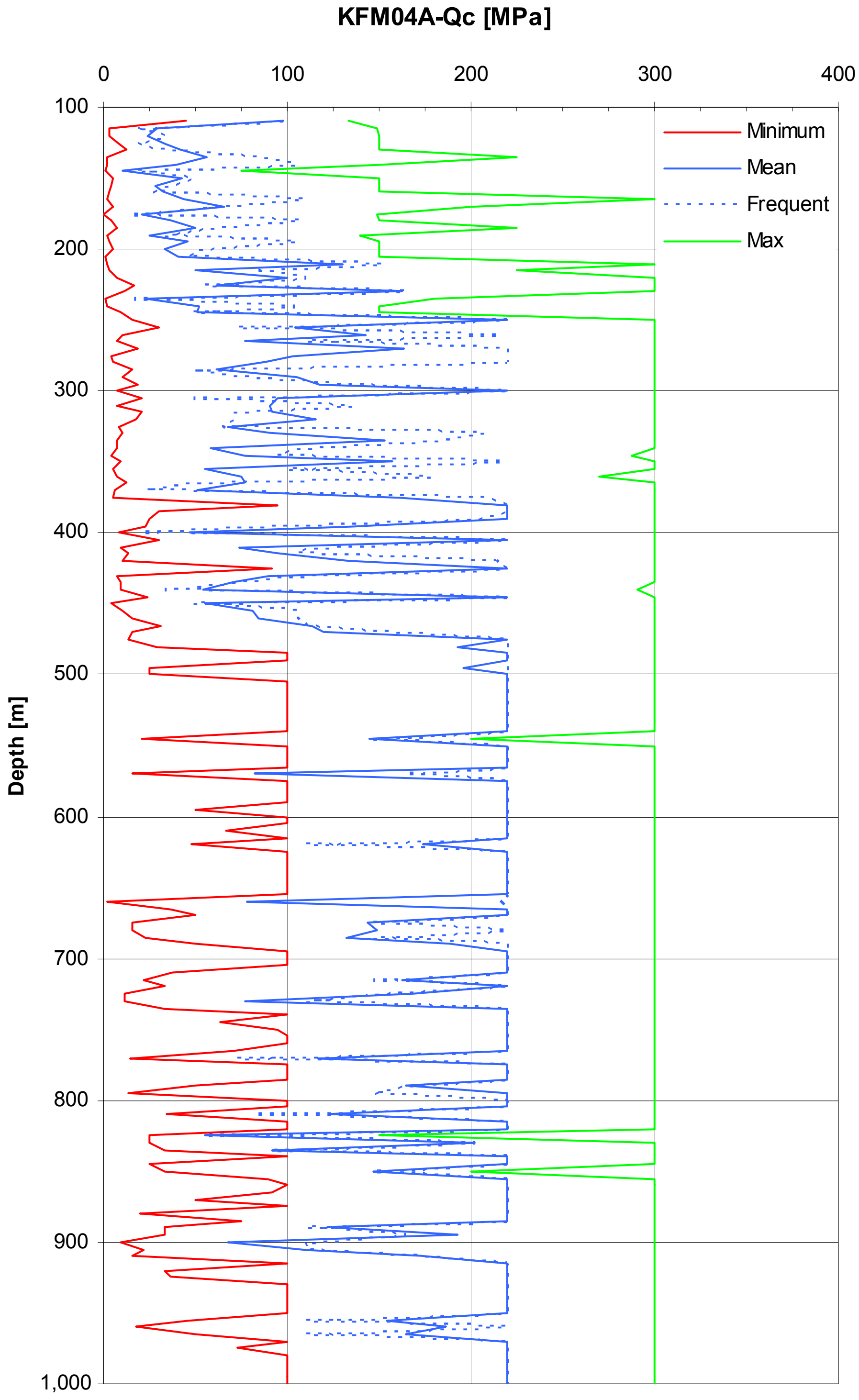


Variation of the uniaxial compressive strength of the rock mass with depth for borehole KFM04A. The values are given every 5 m.

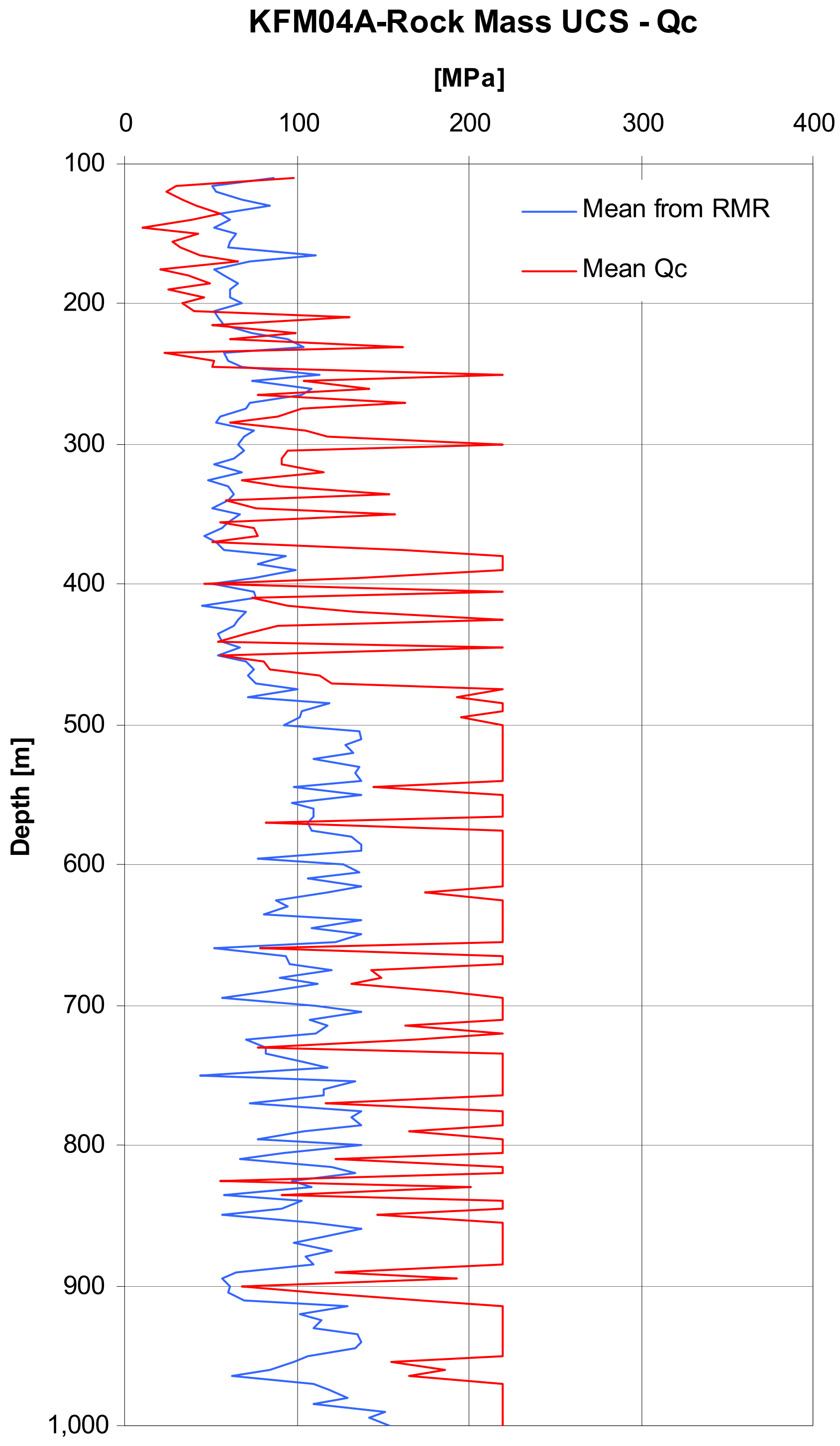
C.3.2 Q

Summary of Qc derived from Q for borehole KFM04A (core sections of 5 m).

Rock Unit	Minimum Qc	Average Qc	Frequent Qc	Maximum Qc	Standard deviation	Min possible Qc	Max possible QC
RU2	10.4	40.5	36.6	97.8	21.6	0.2	300.0
RU3	23.0	139.4	99.6	660.0	138.2	0.8	1,200.0
RU4	58.4	115.8	91.3	369.5	80.4	4.8	1,800.0
RU5	46.6	170.9	95.2	649.4	154.9	4.3	1,800.0
RU6	55.0	807.6	440.0	1,760.0	686.3	2.5	2,400.0
RU7	77.2	1,897.8	839.2	4,693.3	2,190.1	11.1	6,400.0
RU8	154.6	519.1	186.0	1,760.0	697.3	18.0	2,400.0
Competent rock	10.4	584.2	229.0	4,693.3	773.3	1.3	6,400.0
Fractured rock	21.3	99.5	76.1	368.0	89.7	0.2	900.0
Whole borehole	10.4	535.4	192.5	4,693.3	748.1	0.2	6,400.0



Variation of Q_c with depth for borehole KFM04A. The values are given every 5 m.



Comparison of the rock mass compressive strength from RMR and Q for borehole KFM04A.

C.4 Friction angle and cohesion and of the rock mass

C.4.1 RMR

Summary of the friction angle (φ') of the rock mass derived from RMR for borehole KFM04A (10–30 MPa) (core sections of 5 m).

Depth [m]	Minimum ϕ' [deg]	Average ϕ' [deg]	Frequent ϕ' [deg]	Maximum ϕ' [deg]	Standard deviation	Min possible ϕ' [deg]	Max possible ϕ' [deg]
105–170	46.9	48.0	47.7	50.1	1.0	33.1	55.3
170–175	47.0	47.0	47.0	47.0	0	34.8	54.3
175–200	47.4	47.8	47.7	48.2	0.3	34.9	55.3
200–215	47.0	47.2	47.2	47.4	0.2	35.1	55.0
215–230	48.5	49.3	49.5	49.8	0.7	36.6	55.3
230–240	47.5	47.6	47.6	47.6	0.1	36.3	55.1
240–275	48.2	49.1	48.5	50.1	0.9	34.7	55.3
275–340	46.7	47.7	47.8	48.6	0.6	34.2	55.2
340–410	46.4	47.9	47.6	49.7	1.0	31.7	55.3
410–445	46.3	47.7	48.0	48.6	0.7	35.0	55.1
445–460	47.2	48.0	48.3	48.6	0.7	36.0	54.9
460–500	48.4	49.3	49.6	50.3	0.7	36.7	55.1
500–655	48.7	50.2	50.5	50.8	0.6	37.1	55.3
655–660	47.0	47.0	47.0	47.0	0	34.0	54.0
660–725	47.3	49.6	49.9	50.8	0.9	37.3	55.3
725–745	48.9	49.5	49.4	50.3	0.7	38.0	55.1
745–940	46.2	49.5	50.0	50.8	1.2	35.3	55.3
940–965	47.8	49.4	49.6	50.7	1.1	36.8	55.3
965–990	50.0	50.4	50.3	51.0	0.4	37.7	55.5
990–1,000	50.9	51.0	51.0	51.1	0.2	42.7	55.5

Friction angle (φ') of the rock mass from RMR for the rock units in borehole KFM04A (10–30 MPa) (core sections of 5 m).

Rock Unit	Minimum ϕ' [deg]	Average ϕ' [deg]	Frequent ϕ' [deg]	Maximum ϕ' [deg]	Standard deviation ϕ' [deg]	Min possible ϕ' [deg]	Max possible ϕ' [deg]
RU2	46.9	47.9	47.7	50.1	1.0	33.1	55.3
RU3	47.0	48.6	48.4	50.3	1.0	34.7	55.3
RU4	46.7	47.7	47.8	48.6	0.6	34.2	55.2
RU5	46.3	47.8	47.9	49.7	0.9	31.7	55.3
RU6	46.2	49.8	50.0	51.0	1.1	34.0	55.5
RU7	48.9	50.0	50.1	51.1	0.9	38.0	55.5
RU8	47.8	49.4	49.6	50.7	1.1	36.8	55.3
Competent rock	46.2	49.2	49.6	51.1	1.3	31.7	55.5
Fractured rock	46.3	47.6	47.5	48.6	0.6	34.0	55.1
Whole borehole	46.2	49.1	49.3	51.1	1.3	31.7	55.5

Summary of the friction angle of the rock mass derived from RMR (10–30 MPa) (core sections of 30 m).

Rock Unit	Minimum ϕ' [deg]	Average ϕ' [deg]	Frequent ϕ' [deg]	Maximum ϕ' [deg]	Standard deviation ϕ' [deg]	Min possible ϕ' [deg]	Max possible ϕ' [deg]
RU2	47.5	47.6	47.5	47.8	0.2	32.1	55.3
RU3	46.6	47.8	47.7	49.2	0.8	31.6	55.3
RU4	47.0	47.3	47.3	47.7	0.5	31.6	55.3
RU5	46.6	47.5	47.7	48.3	0.8	32.8	55.3
RU6	47.9	49.7	49.8	50.3	0.5	32.9	55.3
RU7	49.9	49.9	49.9	49.9	0	37.1	55.1
RU8	49.9	49.9	49.9	49.9	0	35.1	55.1
Competent rock	46.6	49.1	49.6	50.3	1.1	31.6	55.3
Fractured rock	47.2	47.9	47.7	49.9	1.0	32.0	55.3
Whole borehole	46.6	48.9	49.5	50.3	1.2	31.6	55.3

Summary of the cohesion of the rock mass derived from RMR for borehole KFM04A (10–30 MPa) (core sections of 5 m).

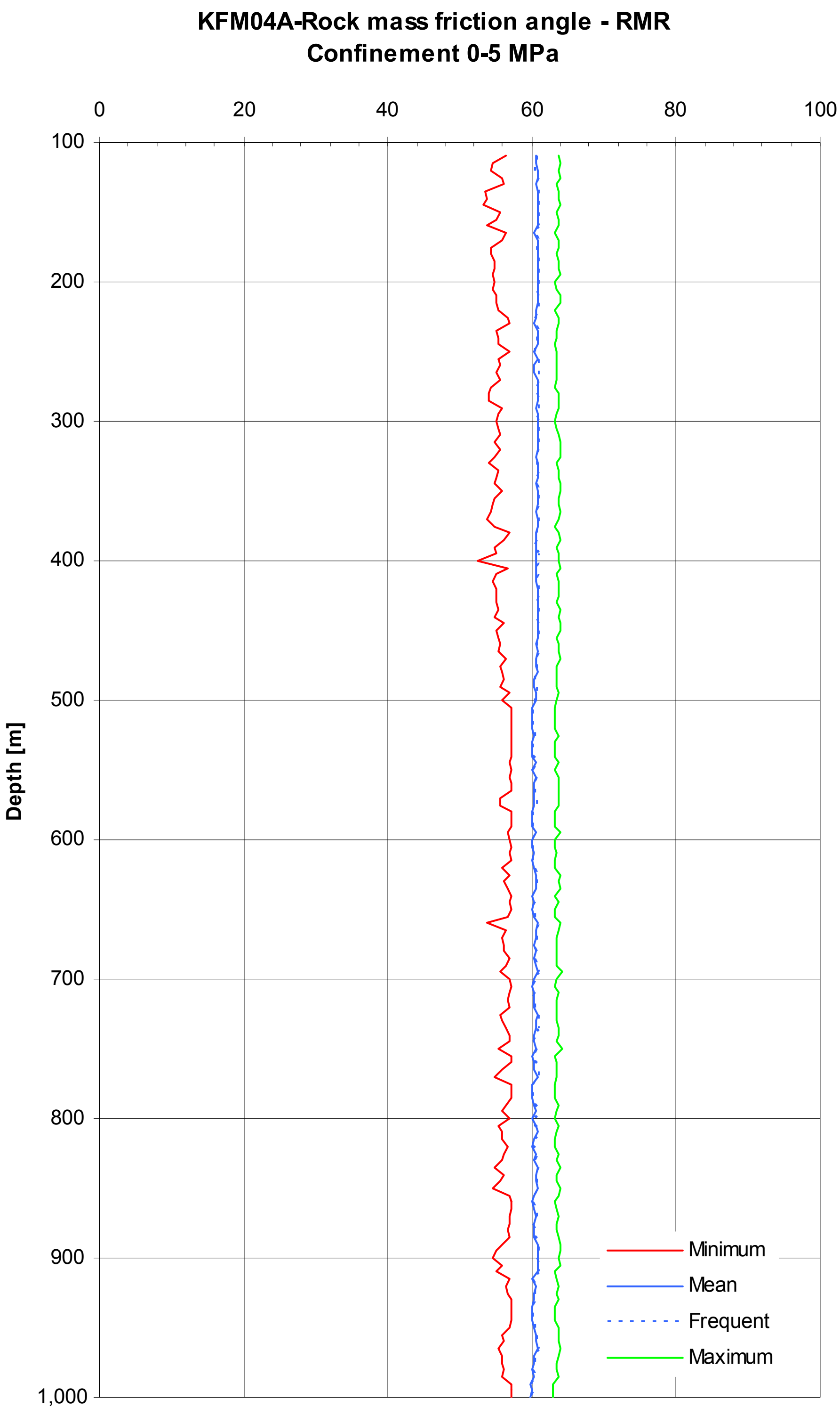
Depth [m]	Minimum c'	Average c'	Frequent c'	Maximum c'	Standard deviation	Min possible c'	Max possible c'
105–170	21.1	23.3	22.4	28.9	2.3	11.4	40.4
170–175	21.2	21.2	21.2	21.2	0	12.3	33.8
175–200	21.9	22.6	22.5	23.4	0.6	12.3	40.4
200–215	21.2	21.6	21.5	22.0	0.4	12.4	38.3
215–230	24.1	26.3	26.8	28.0	2.0	13.2	40.4
230–240	22.0	22.1	22.1	22.3	0.2	13.1	38.6
240–275	23.3	25.8	24.1	29.1	2.6	12.2	40.4
275–340	20.8	22.5	22.7	24.3	1.0	12.0	39.9
340–410	20.4	23.1	22.2	27.4	2.2	10.8	40.4
410–445	20.3	22.6	22.9	24.3	1.3	12.4	39.1
445–460	21.6	23.1	23.7	24.2	1.4	12.9	37.0
460–500	23.7	26.4	27.0	30.0	2.3	13.3	39.1
500–655	24.6	30.0	31.0	32.4	2.5	13.5	40.4
655–660	21.3	21.3	21.3	21.3	0	11.9	32.3
660–725	21.8	27.5	28.4	32.4	2.9	13.7	40.4
725–745	25.1	26.9	26.5	29.7	2.3	14.1	39.1
745–940	20.1	27.7	28.6	32.4	3.7	12.5	40.4
940–965	22.5	27.1	27.2	31.9	3.5	13.4	40.4
965–990	28.7	30.6	30.0	34.3	2.3	13.9	43.3
990–1,000	33.0	33.8	33.8	34.6	1.1	18.4	43.3

Cohesion of the rock mass from RMR for the rock units in borehole KFM04A (10–30 MPa) (core sections of 5 m).

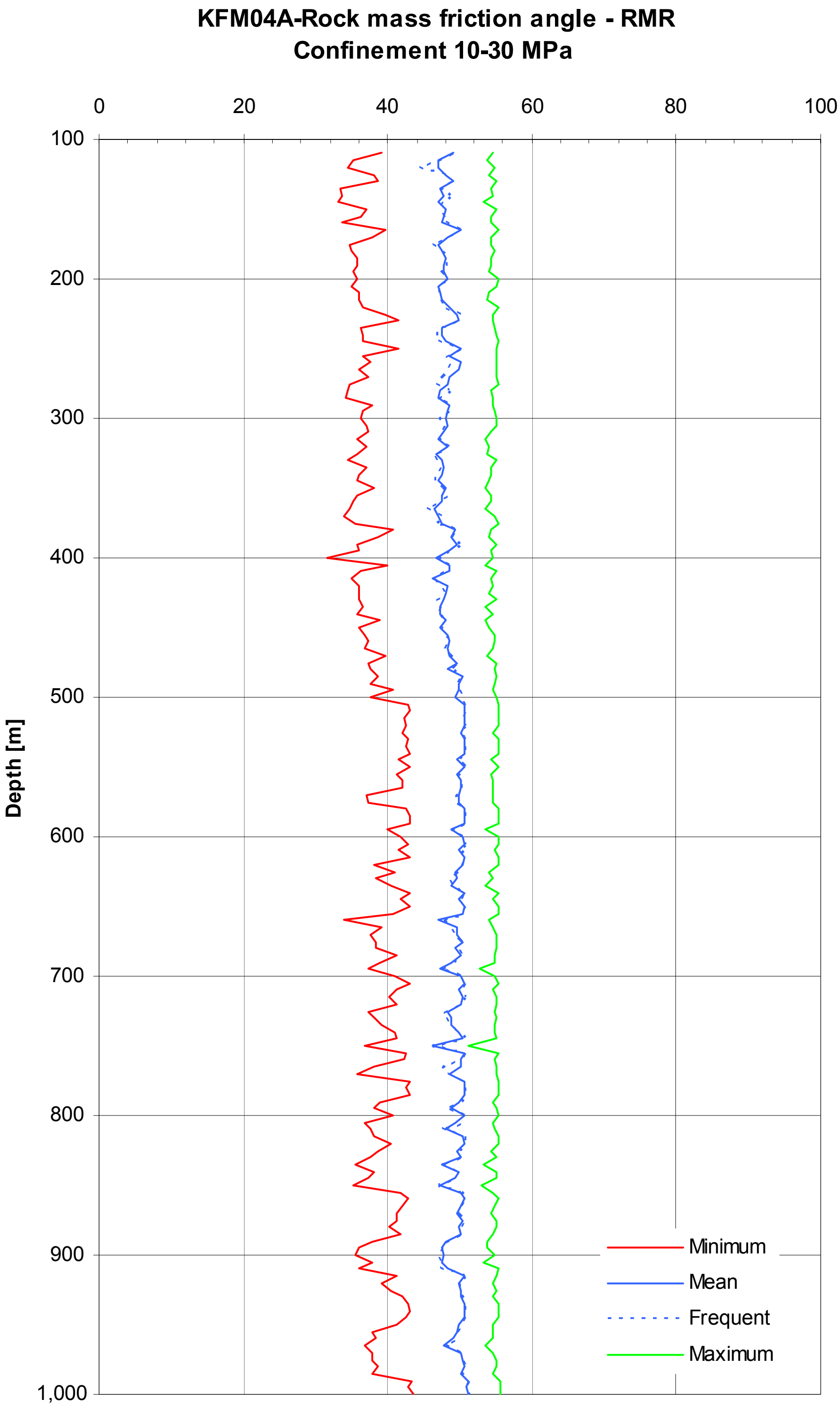
Rock Unit	Minimum c' [MPa]	Average c' [MPa]	Frequent c' [MPa]	Maximum c' [MPa]	Standard deviation c' [MPa]	Min possible c' [MPa]	Max possible c' [MPa]
RU2	21.1	23.1	22.4	28.9	2.2	11.4	40.4
RU3	21.2	24.6	23.8	30.0	2.6	12.2	40.4
RU4	20.8	22.5	22.7	24.3	1.0	12.0	39.9
RU5	20.3	22.9	22.8	27.4	1.9	10.8	40.4
RU6	20.1	28.6	28.7	34.3	3.4	11.9	43.3
RU7	25.1	29.2	28.8	34.6	4.0	14.1	43.3
RU8	22.5	27.1	27.2	31.9	3.5	13.4	40.4
Competent rock	20.1	26.8	27.1	34.6	3.8	10.8	43.3
Fractured rock	20.3	22.3	22.0	24.3	1.1	11.9	39.1
Whole borehole	20.1	26.3	26.3	34.6	3.9	10.8	43.3

Summary of the cohesion of the rock mass derived from RMR (10–30 MPa) (core sections of 30 m).

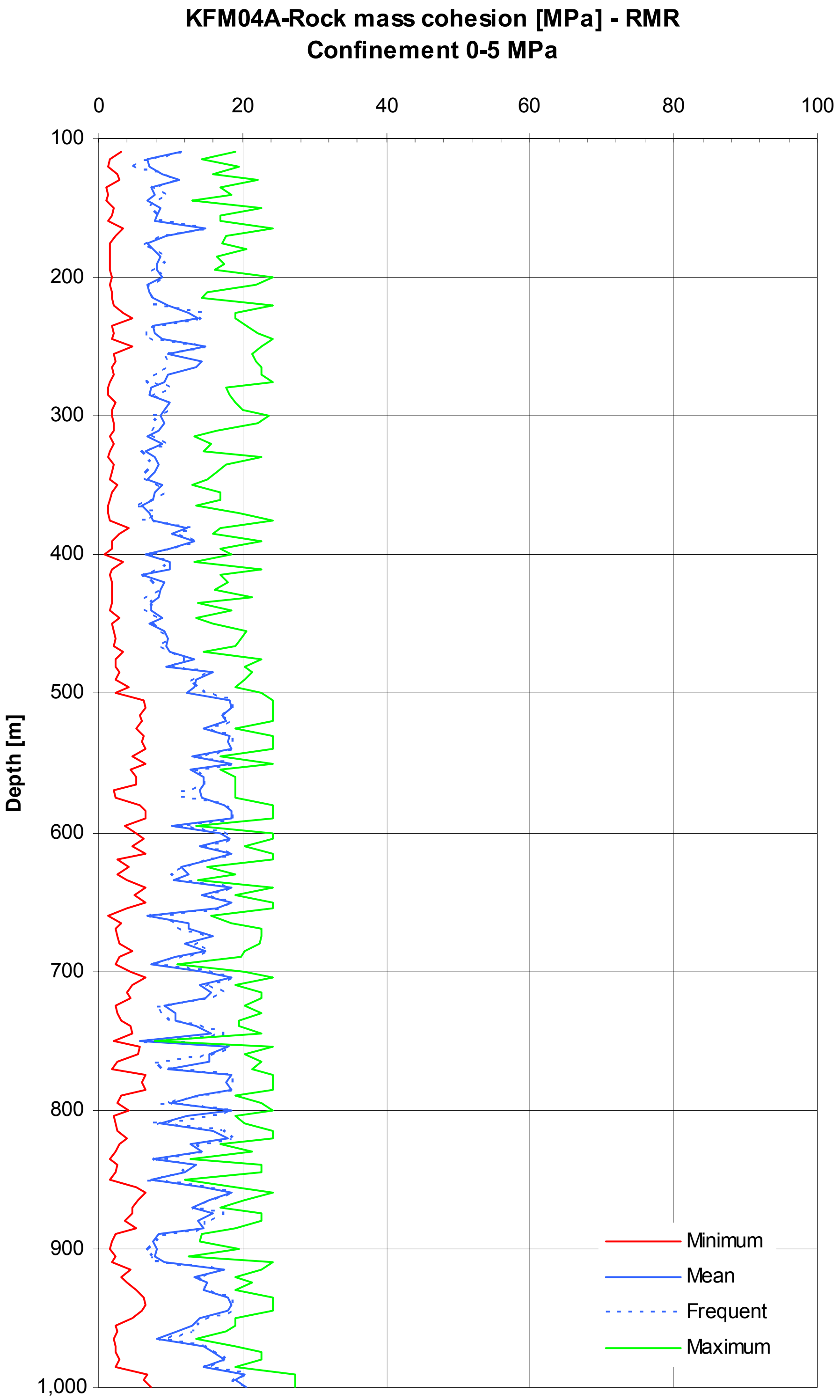
Rock Unit	Minimum c' [MPa]	Average c' [MPa]	Frequent c' [MPa]	Maximum c' [MPa]	Standard deviation c' [MPa]	Min possible c' [MPa]	Max possible c' [MPa]
RU2	22.1	22.3	22.1	22.6	0.3	11.0	40.4
RU3	20.7	22.6	22.4	26.0	1.5	10.8	40.4
RU4	21.2	21.8	21.8	22.4	0.9	10.8	40.4
RU5	20.7	22.2	22.3	23.6	1.5	11.3	40.4
RU6	22.9	27.6	27.9	30.0	1.6	11.3	40.4
RU7	28.3	28.3	28.3	28.3	0	13.6	39.1
RU8	28.2	28.2	28.2	28.2	0	12.4	39.1
Competent rock	20.7	26.0	26.9	30.0	2.8	10.8	40.4
Fractured rock	21.6	23.1	22.3	28.1	2.5	10.9	40.4
Whole borehole	20.7	25.5	26.8	30.0	2.9	10.8	40.4



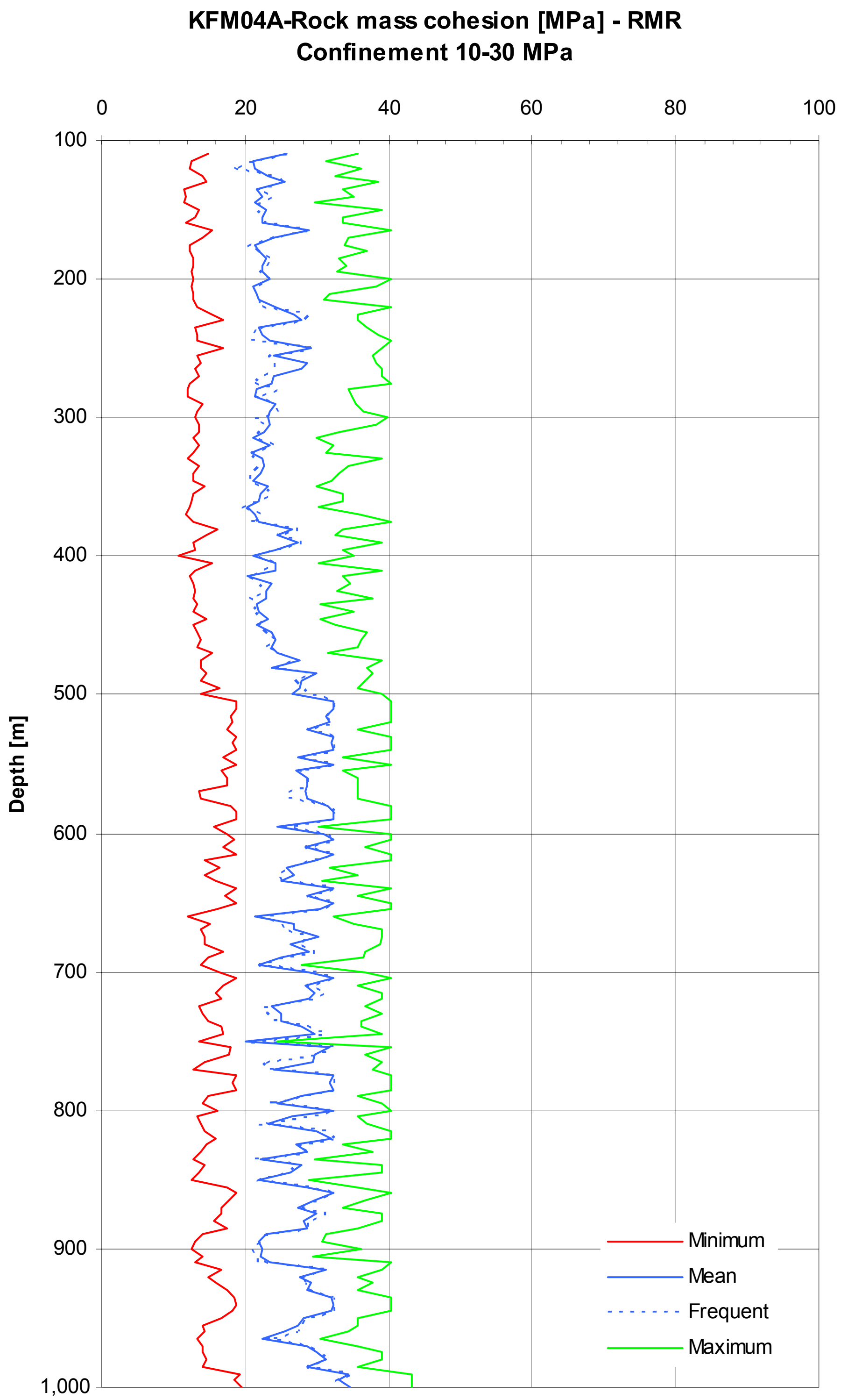
Variation of the rock mass friction angle from RMR for borehole KFM04A under stress confinement 0–5 MPa.



Variation of the rock mass friction angle from RMR for borehole KFM04A under stress confinement 10–30 MPa.



Variation of the rock mass cohesion from RMR for borehole KFM04A under stress confinement 0–5 MPa.



Variation of the rock mass cohesion from RMR for borehole KFM04A under stress confinement 10–30 MPa.

C.4.2 Q

Summary of the frictional component FC of the rock mass derived from Qc for borehole KFM04A (core sections of 5 m).

Rock Unit	Minimum FC [deg]	Average FC [deg]	Frequent FC [deg]	Maximum FC [deg]	Standard deviation FC [deg]	Min possible FC [deg]	Max possible FC [deg]
RU2	30.6	42.7	42.6	53.1	7.4	4.8	71.6
RU3	35.8	47.3	47.6	62.9	8.2	9.5	71.6
RU4	22.9	36.5	34.7	51.3	7.3	9.5	71.6
RU5	33.7	47.4	46.8	68.6	9.7	9.5	71.6
RU6	14.0	56.0	56.3	76.0	17.2	14.0	76.0
RU7	46.5	67.1	69.2	79.4	12.7	18.4	79.4
RU8	32.9	52.2	48.4	76.0	14.5	18.4	76.0
Competent rock	14.0	51.5	49.1	79.4	15.7	4.8	79.4
Fractured rock	34.2	49.5	48.7	68.6	9.8	7.1	71.6
Whole borehole	14.0	51.3	49.0	79.4	15.2	4.8	79.4

Summary of the frictional component FC of the rock mass derived from Q (core sections of 30 m).

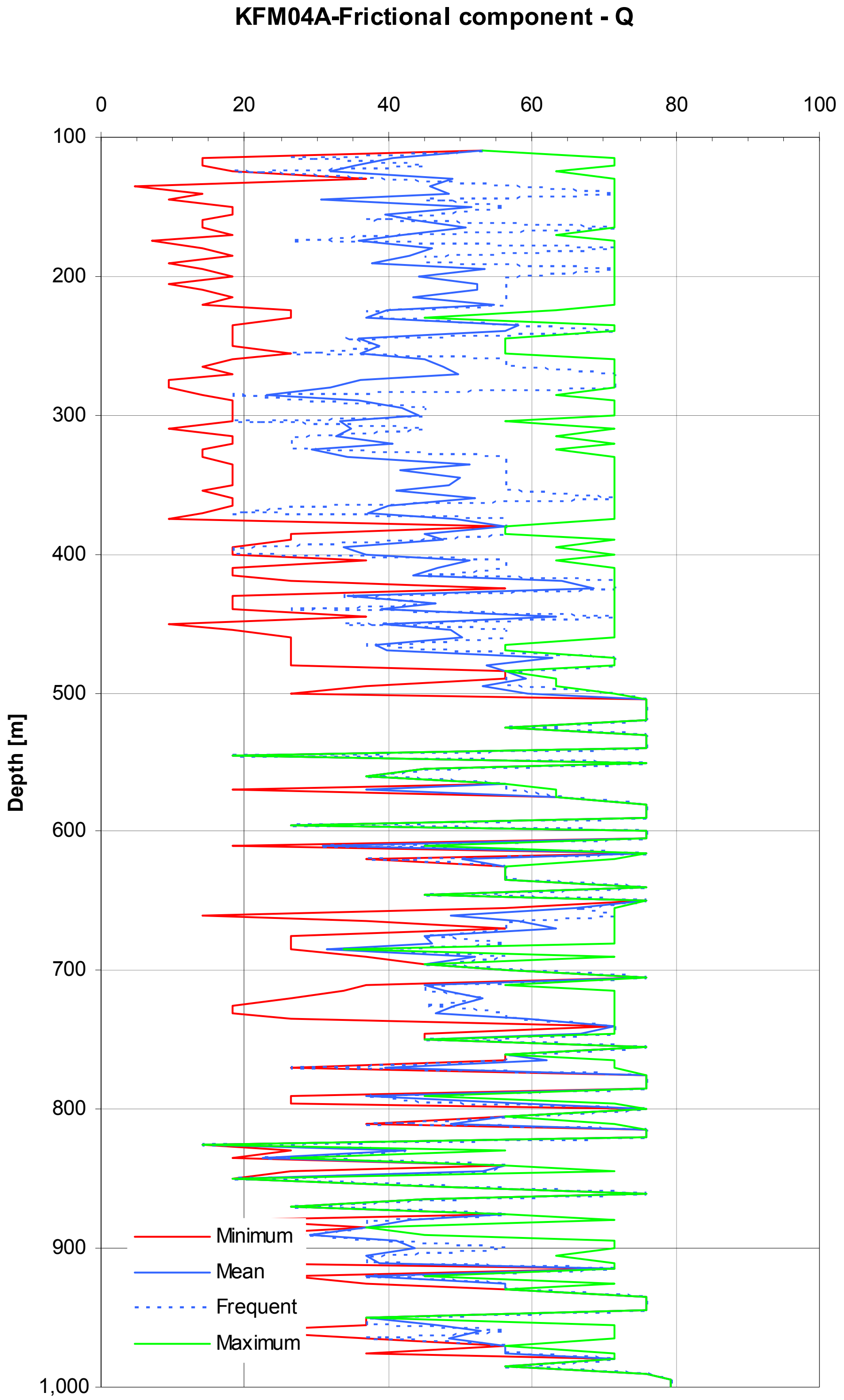
Rock Unit	Minimum mean FC [deg]	Average mean FC [deg]	Frequent mean FC [deg]	Maximum mean FC [deg]	Standard deviation FC [deg]	Conf. Min FC [deg]	Conf. Max FC [deg]
Competent rock	29.7	45.6	44.0	63.8	8.7	4.8	71.6
Fractured rock	40.4	49.4	51.7	54.3	5.4	4.8	71.6
Whole borehole	29.7	46.4	44.6	63.8	8.2	4.8	71.6

Summary of the cohesive component CC of the rock mass derived from Qc for borehole KFM04A (core sections of 5 m).

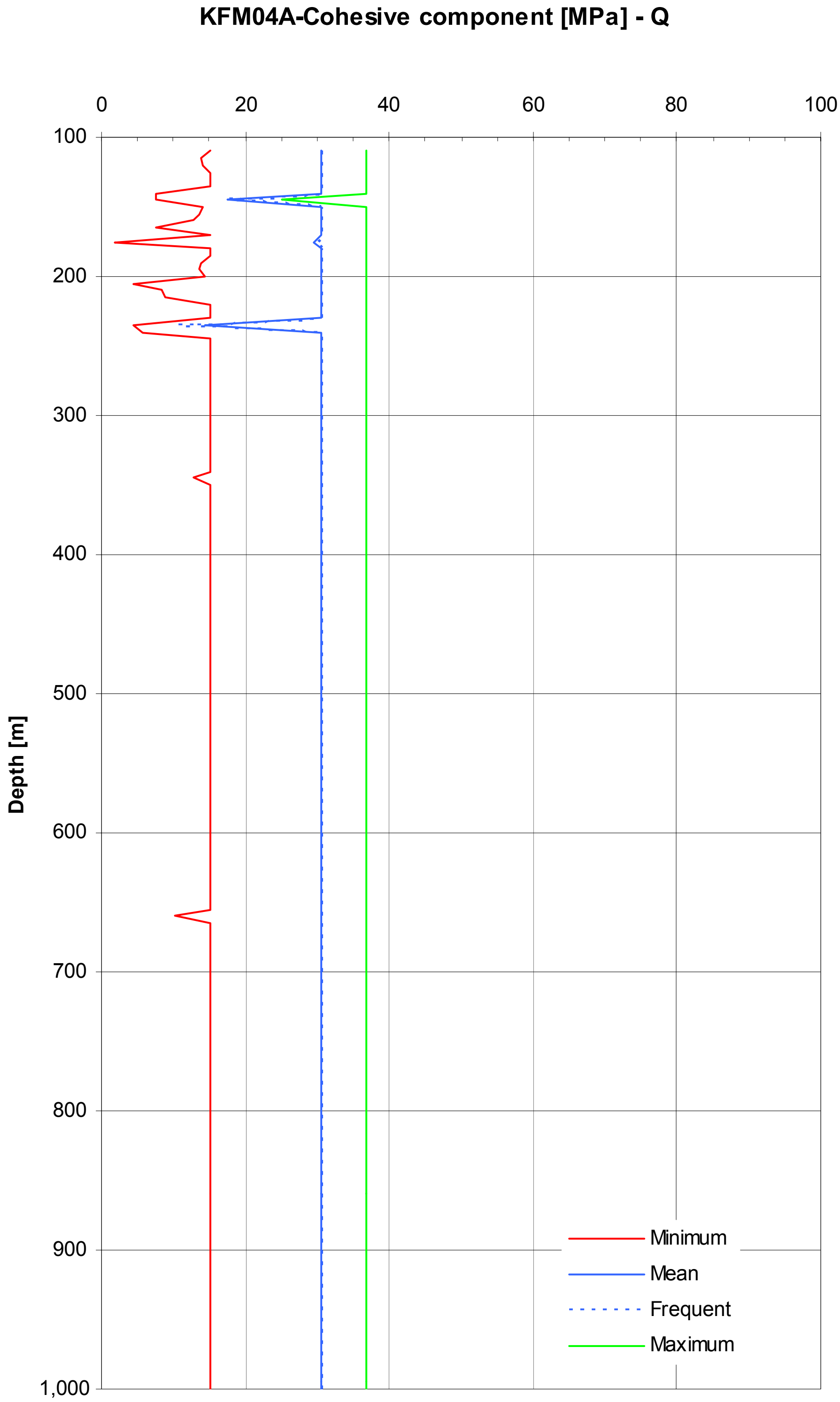
Rock Unit	Minimum CC [MPa]	Average CC [MPa]	Frequent CC [MPa]	Maximum CC [MPa]	Standard deviation CC [MPa]	Min possible CC [MPa]	Max possible CC [MPa]
RU2	17.6	29.6	30.6	30.6	3.5	1.9	36.9
RU3	14.3	30.1	30.6	30.6	2.9	4.4	36.9
RU4	30.6	30.6	30.6	30.6	0	15.1	36.9
RU5	30.6	30.6	30.6	30.6	0	12.8	36.9
RU6	30.6	30.6	30.6	30.6	0	10.1	36.9
RU7	30.6	30.6	30.6	30.6	0	15.1	36.9
RU8	30.6	30.6	30.6	30.6	0	15.1	36.9
Competent rock	17.6	30.6	30.6	30.6	1.0	7.5	36.9
Fractured rock	14.3	29.7	30.6	30.6	3.8	1.9	36.9
Whole borehole	14.3	30.5	30.6	30.6	1.6	1.9	36.9

Summary of the cohesive component CC of the rock mass derived from Q (core sections of 30 m).

Rock Unit	Minimum mean CC [MPa]	Average mean CC [MPa]	Frequent mean CC [MPa]	Maximum mean CC [MPa]	Standard deviation CC [MPa]	Poss. Min CC [MPa]	Poss. Max CC [MPa]
Competent rock	17.4	42.5	43.9	43.9	5.6	6.3	52.5
Fractured rock	13.5	28.2	34.1	35.9	10.1	1.9	52.5
Whole borehole	13.5	39.6	43.9	43.9	8.7	1.9	52.5

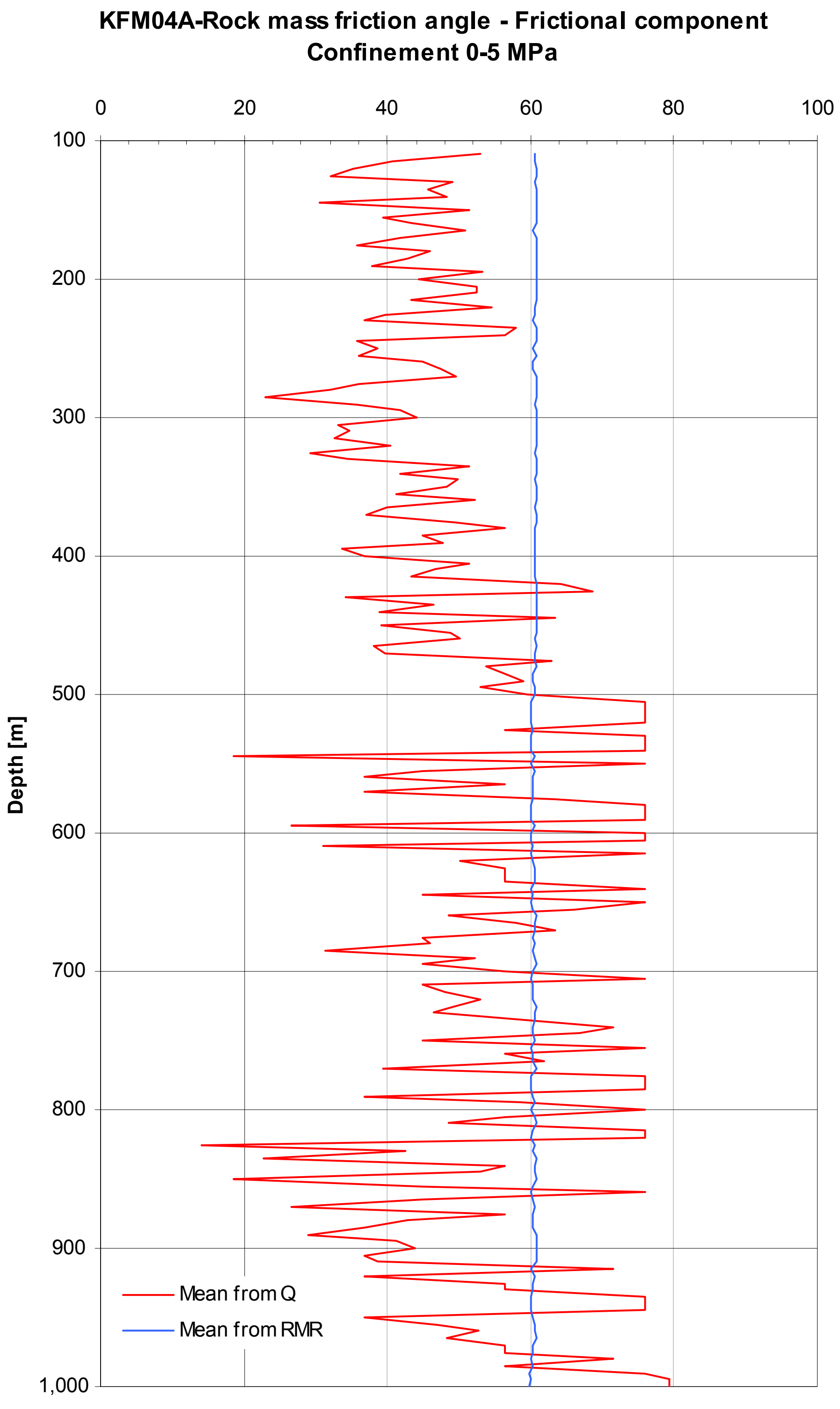


Variation of the frictional component FC from Q for borehole KFM04A.

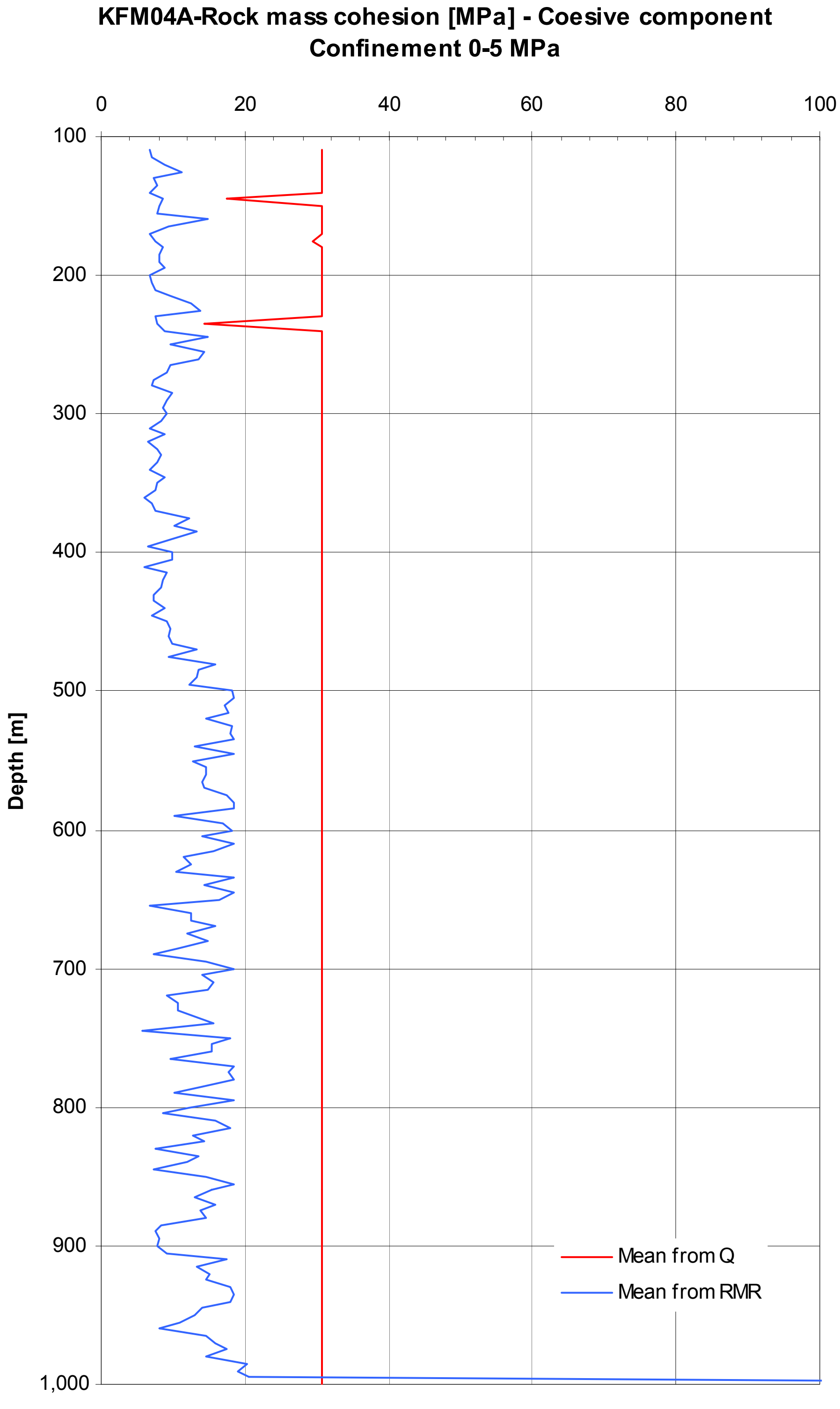


Variation of the cohesive component from Q for borehole KFM04A.

C.4.3 Comparison



Comparison of the rock mass friction angle from RMR and Q for borehole KFM04A under stress confinement 0–5 MPa.



Comparison of the rock mass cohesion from RMR and Q for borehole KFM04A under stress confinement 0–5 MPa.