P-05-04

Forsmark site investigation

Borehole KFM06A

Determination of P-wave velocity, transverse borehole core

Panayiotis Chryssanthakis, Lloyd Tunbridge
Norwegian Geotechnical Institute, Oslo

May 2005

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1651-4416
SKB P-05-04

Forsmark site investigation

Borehole KFM06A

Determination of P-wave velocity, transverse borehole core

Panayiotis Chryssanthakis, Lloyd Tunbridge
Norwegian Geotechnical Institute, Oslo

May 2005

Keywords: Rock mechanics, P-wave velocity, Anisotropy.

Summary

The Norwegian Geotechnical Institute has carried out P-wave velocity measurements on drill cores from borehole KFM06A at Forsmark in November–December 2004. Thirty P-wave velocity measurements have been performed from a total of 900 m core.

The results from the P-wave velocity measurements over the whole length of the borehole show maximum velocities between 5,358–5,893 m/s and an anisotropy ratio between 1.03 and 1.16. There is little variation in the maximum velocity, which lies between 5,772–5,840 m/s down to 266 m borehole length. From 266 m to 415 m the maximum velocity is more variable between 5,358–5,893 m/s. Below 415 m there is again little variation in the maximum velocity which lies between 5,508–5,704 m/s with an outlying low value of 5,365 m/s at 525 m depth.

The anisotropy ratio is quite variable, but there appears to be a trend of a slight increase of the anisotropy ratio with depth with values between 1.03 to 1.10 at the upper end and 1.07–1.16 at the lower end.

The orientation of the maximum velocity is quite variable relative to the foliation direction, with no consistent or preferred orientation, though there are very few values oriented between 55° and 130°. It is neither parallel nor perpendicular to the foliation as might been expected.

Sammanfattning

Norges Geotekniske Institutt (NGI) har under november–december 2004 utfört P-vågsmätningar på borrkärnor från borrhål KFM06A i Forsmark. Sammanlagt har det utförts 30 st hastighetsbestämningar av P-vågen på kärnprover från en ca 900 m lång borrkärna.

Resultaten visar för hela borrhålets längd en maximalhastighet som varierer mellan 5 358–5 893 m/s och en anisotropikvot på 1,03–1,16. Ned till 266 m borrhålslängd är maximihastigheten relativt konstant, kring 5 772–5 840 m/s. Mellan 266 m och 415 m djup är variationen större, och varierar kring 5 358–5 893 m/s. Från 415 m och djupare visar resultaten åter på liten variation, mellan 5 508–5 893 m/s, med undantag av ett resultat på 5 365 m/s vid 525 m djup.

Anisotropikvoten är något varierande, men det ser ut att vara en ökande tendens mot djupet. Kvoten varierer mellan 1,03–1,10 i den övre delen av borrhålet och mellan 1,07–1,16 i den nedre delen.

Orienteringen på maximihastigheten är relativt varierande med avseende på folitions-riktningen. Det finns ingen konsekvent eller dominerende riktning, trots att det förekommer väldigt få värden mellan 55° och 130°. Orienteringen av maximihastigheten är varken parallell eller vinkelrätt mot foliationen, vilket möjligen kunde förväntas.

Contents

1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on drill cores from borehole KFM06A at Forsmark in Sweden, see Figure 1-1 in accordance with the SKB Activity Plan AP PF 400-04-122, version 1.0, which refers to SKB's Method Description MD 190 002 version 1.0. The Activity Plan and Method Description are both SKB internal controlling documents. The work was carried out by Panayiotis Chryssanthakis and Pavel Jankowski in November and December 2004. Borehole KFM06A is inclined c 60° from the horizontal plane, entailing that there is a difference between borehole (or drill core) lenght and vertical depth of approximately the factor 0.87.

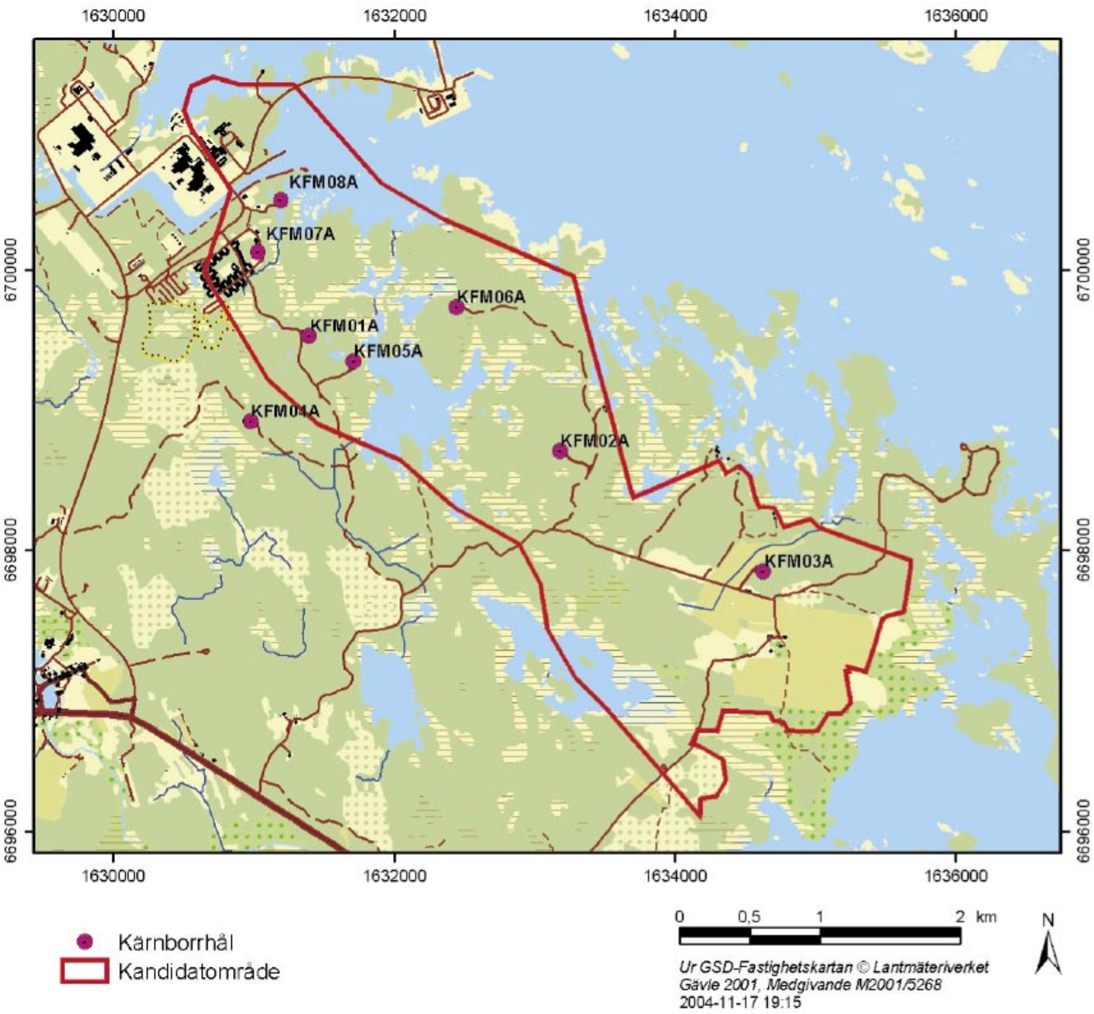


Figure 1-1. *Location of the first eight deep boreholes including borehole KFM06A at the Forsmark site.*

2 Objective and scope

The purpose of the testing was to determine the P-wave velocity transverse the core axis. The P-wave velocity is a parameter used in the rock mechanical model which will be established for the candidate area selected for site investigations at Forsmark.

The number of core specimens tested and the number of tests performed are given in Table 2-1.

The results from the P-wave velocity measurements are presented in this report by means of tables, figures and spreadsheets.

Table 2-1. Total number of P-wave velocity specimens and measurements.

Borehole	P-wave velocity test specimens	P-wave velocity measurements
KFM06A	27	30

3 Equipment

The measurements were conducted using Panametrics Videoscan transducers with a natural frequency of 0.5 MHz. These were mounted in a special frame to hold them in contact with the core (see Figure 3-1). Special wave guides, metal shoes with a concave radius similar to the core, were installed between the transducers and the core. The equipment was designed and constructed specially for this contract by NGI, based on the information presented in the SKB report entitled “Detection of Anisotropy by Diametral Measurements of Longitudinal Wave Velocities on Rock Cores” /Eitzenberger, 2002/.

A strong sine-wave pulse at the natural frequency of the transducers was used as the acoustic signal source. The arrival of the signals was measured using a PC with a high speed data acquisition board and software to emulate an oscilloscope (see Figures 3-2 and 3-3). The time pick for the first break was taken as the beginning of the first transition, i.e. the point where the received signal first diverges from the zero volt line. In order to provide consistent interpretation of the time pick, one operator (PC) made all the interpretations. The time pick was measured with a precision better than 0.01 μs. The instrumentation was calibrated using a cylinder of aluminium of known acoustic velocity of the same diameter as the core. Several measurements were taken each day on the calibration piece to check the operation of the system.

A thin layer of a thick honey was used as a coupling medium, as this proved to be one of the most effective of different media tested and was easily removed by washing without damaging or contaminating the cores.

***Figure 3-1.** Detail of NGI’s apparatus for measuring acoustic P-wave travel time transverse a foliated borehole core. The aluminium cylinder for calibration of the device is on the left.*

Figure 3-2. NGI's equipment set-up for measuring acoustic P-wave travel time transverse a foliated borehole core.

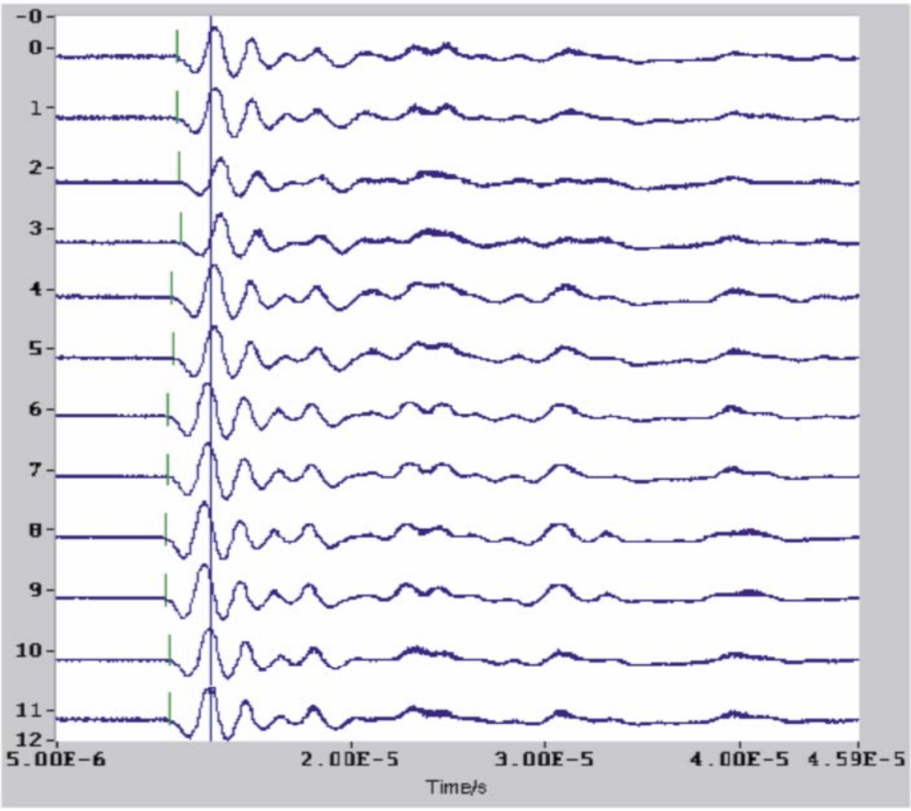


Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse a borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Twenty-seven core specimens of lengths approximately 200–500 mm and a diameter about 50 mm were selected from borehole KFM06A while the complete length of the borehole was displayed on the racks in the core shed at Forsmark. The specimens were selected together by NGI and Thomas Jansson representing SKB.

These specimens represent the foliated metamorphic granite down to about 580 m depth, and the fine-grained granite-granodiorite below this depth, with some veins of amphibolite and pegmatite, found over most of the length of the borehole. Geological logging of cores has been carried out by SKB. No detailed geological description has been attempted by NGI.

The depths used to describe the location are those marked on the core and core boxes at the time. Detailed description of the specimens is available from the detailed core log by SKB. At the time of sampling, the core had been exposed to the atmosphere at room temperature for an extended period and may be presumed to be air-dried, though no measurements of the moisture content were made.

4.2 Test method

Tests were made at 30° intervals around the core, starting at 0° parallel with the foliation. However, where the foliation was not identifiable, the first test was made at a random orientation. The cores were all oriented such that successive measurements were made clockwise looking down the borehole (see Figure 4-1). The cores were marked by attaching a piece of self-adhesive tape that had been previously cut to the appropriate lengths and marked up with the locations for the tests. These marks were then transferred to the core with a permanent marker. The cores may thus be checked at any time to ascertain the location and orientation of the tests.

Each test sample comprised a minimum of two consecutive determinations of acoustic pulse travel time at each of six locations around the core (at 0°, 30°, 60°, 90°, 120° and 150°) at one cross section. The seating of the transducers and application of the coupling medium was adjusted in cases where there was a significant difference between the time picks, and additional measurements were made until two similar time picks were obtained. The average of the two measured time picks was recorded.

As the travel time includes a number of other factors, such as travel through the wave guides, time pick method, and delay due to the oscilloscope triggering on the rising part of the sine-wave, the determination of the true travel time was calibrated using an aluminium cylinder with known P-wave velocity. The correction factor determined in the calibration tests was subtracted from all the measurements on the rock cores.

The diameter of the core was measured using a calliper with an accuracy of 0.01 mm and the P-wave velocity was determined by dividing the diameter (in mm) by the travel time was (in µs) and multiplying by 1,000 to obtain the velocity in m/s.

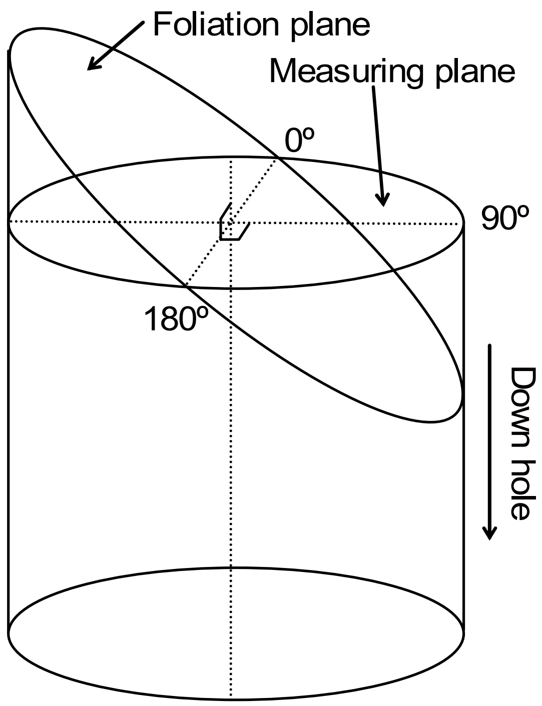


Figure 4-1. *Orientation of measurements.*

Analysis

Since the acoustic velocity is dependent on the elastic properties of the material, the results were analysed similarly for determining the stress or strain tensor in the material. In this case the velocity in the orientation θ is given by:

$$V_\theta = V_x\cos^2\theta + V_y\sin^2\theta + 2 \cdot V_{xy}\sin\theta\cos\theta \quad (1)$$

A simple regression analysis of the six measurements was used to determine the values of V_x, V_y, and V_{xy} (where the X-axis is parallel with the foliation where identifiable).

These values were used to model the complete velocity profile around the core.

The magnitude and orientation of the principal velocities were determined from the Eigen values and vectors of the 2D tensor matrix:

$$\begin{vmatrix} V_x & V_{xy} \\ V_{xy} & V_y \end{vmatrix} \quad (2)$$

4.3 Nonconformities

Tests were made at 30° intervals around the core instead of 45° intervals, which were suggested in the Method Description. This was the only nonconformity to the controlling documents.

5 Results

5.1 Summary of results

The results of the determinations of the travel time and velocity for all the tests are presented in Table 5-1, and the velocity and anisotropy are shown diagrammatically versus borehole length in Figures 5-1 and 5-2.

Table 5-1. Measurements of acoustic velocity, transverse core in borehole KFM06A, Forsmark. (Orientation clockwise looking down hole, 0° is parallel with foliation).

Drill core length m	Diameter mm	Parallel foliation			Corrected time, mS Perendicular foliation			Parallel foliation			Velocity m/S Perendicular foliation			Aniso-tropy ratio
		0°	30°	60°	90°	120°	150°	0°	30°	60°	90°	120°	150°	
153.95	50.77	8.78	8.93	9.15	9.24	9.02	8.82	5,785	5,688	5,551	5,497	5,631	5,759	1.05
172.90	50.70	8.95	8.71	8.79	8.98	9.01	9.14	5,667	5,824	5,771	5,649	5,630	5,550	1.05
194.35	50.82	9.50	9.39	9.07	8.79	8.86	9.23	5,352	5,415	5,606	5,784	5,739	5,508	1.08
222.70	50.80	8.79	9.07	9.33	9.34	8.87	8.76	5,782	5,603	5,447	5,441	5,730	5,802	1.07
243.75	50.82	8.85	8.89	9.17	9.32	9.17	8.91	5,745	5,719	5,545	5,455	5,545	5,706	1.05
266.10	50.75	8.75	8.94	8.95	8.94	8.77	8.73	5,803	5,679	5,673	5,679	5,790	5,816	1.03
286.55	50.81	9.51	9.43	10.47	10.22	10.29	9.89	5,345	5,391	4,855	4,974	4,940	5,140	1.11
308.50	50.88	9.14	9.49	9.88	9.83	9.38	9.10	5,569	5,364	5,152	5,178	5,427	5,594	1.09
329.40	50.70	8.76	8.90	8.87	8.70	8.61	8.67	5,790	5,699	5,719	5,830	5,891	5,851	1.03
350.45	50.73	8.74	8.80	8.96	9.12	9.00	8.83	5,807	5,768	5,664	5,565	5,639	5,748	1.04
372.20	50.85	9.11	9.04	9.38	9.64	9.63	9.31	5,584	5,628	5,424	5,277	5,283	5,464	1.07
392.13	50.67	9.51	9.20	9.15	9.33	9.69	9.83	5,330	5,510	5,540	5,433	5,231	5,157	1.07
415.20	50.74	9.75	10.29	10.31	9.70	9.44	9.72	5,206	4,933	4,923	5,233	5,377	5,222	1.09
437.30	50.72	9.50	9.19	9.26	9.51	9.80	9.72	5,341	5,522	5,480	5,336	5,178	5,220	1.07
458.90	50.52	9.17	9.10	9.59	9.99	9.79	9.31	5,512	5,554	5,270	5,059	5,163	5,429	1.10
480.75	50.50	9.59	9.88	9.65	9.30	9.09	9.20	5,268	5,114	5,235	5,433	5,558	5,492	1.09
502.60	50.74	9.09	9.39	9.77	9.96	9.64	9.20	5,585	5,406	5,196	5,097	5,266	5,518	1.10
525.08	50.60	9.71	9.47	9.48	9.96	10.18	9.96	5,213	5,346	5,340	5,082	4,973	5,082	1.08
544.50	50.50	9.20	9.51	10.03	9.84	9.50	9.26	5,492	5,313	5,037	5,134	5,318	5,456	1.09
565.07	50.69	9.08	9.48	10.24	10.51	9.91	9.23	5,574	5,339	4,942	4,815	5,107	5,484	1.16
589.60	50.52	10.14	9.94	9.32	9.02	9.26	9.91	4,984	5,085	5,423	5,603	5,458	5,100	1.12
607.60	50.76	9.07	9.18	9.80	10.26	9.89	9.24	5,599	5,532	5,182	4,949	5,135	5,496	1.13
633.15	50.71	9.87	9.36	9.22	9.58	10.12	10.26	5,140	5,420	5,503	5,296	5,013	4,945	1.11
652.80	50.57	9.08	9.22	9.59	9.76	9.54	9.30	5,572	5,487	5,276	5,184	5,303	5,440	1.07
673.85	50.68	9.47	9.14	9.10	9.53	10.05	9.85	5,354	5,547	5,572	5,320	5,045	5,147	1.10
699.30	50.66	9.02	9.30	9.83	10.07	9.77	9.31	5,619	5,450	5,156	5,033	5,187	5,444	1.12
715.95	50.76	9.35	8.94	8.96	9.45	9.89	9.66	5,431	5,681	5,668	5,374	5,135	5,257	1.11
286.55	50.79	9.41	9.42	10.10	10.41	10.22	9.75	5,400	5,394	5,031	4,881	4,972	5,211	1.11
458.90	50.53	9.04	9.10	9.56	9.93	9.87	9.42	5,592	5,555	5,288	5,091	5,122	5,367	1.10
633.15	50.69	9.85	9.42	9.16	9.46	10.20	10.28	5,148	5,384	5,536	5,361	4,972	4,933	1.12

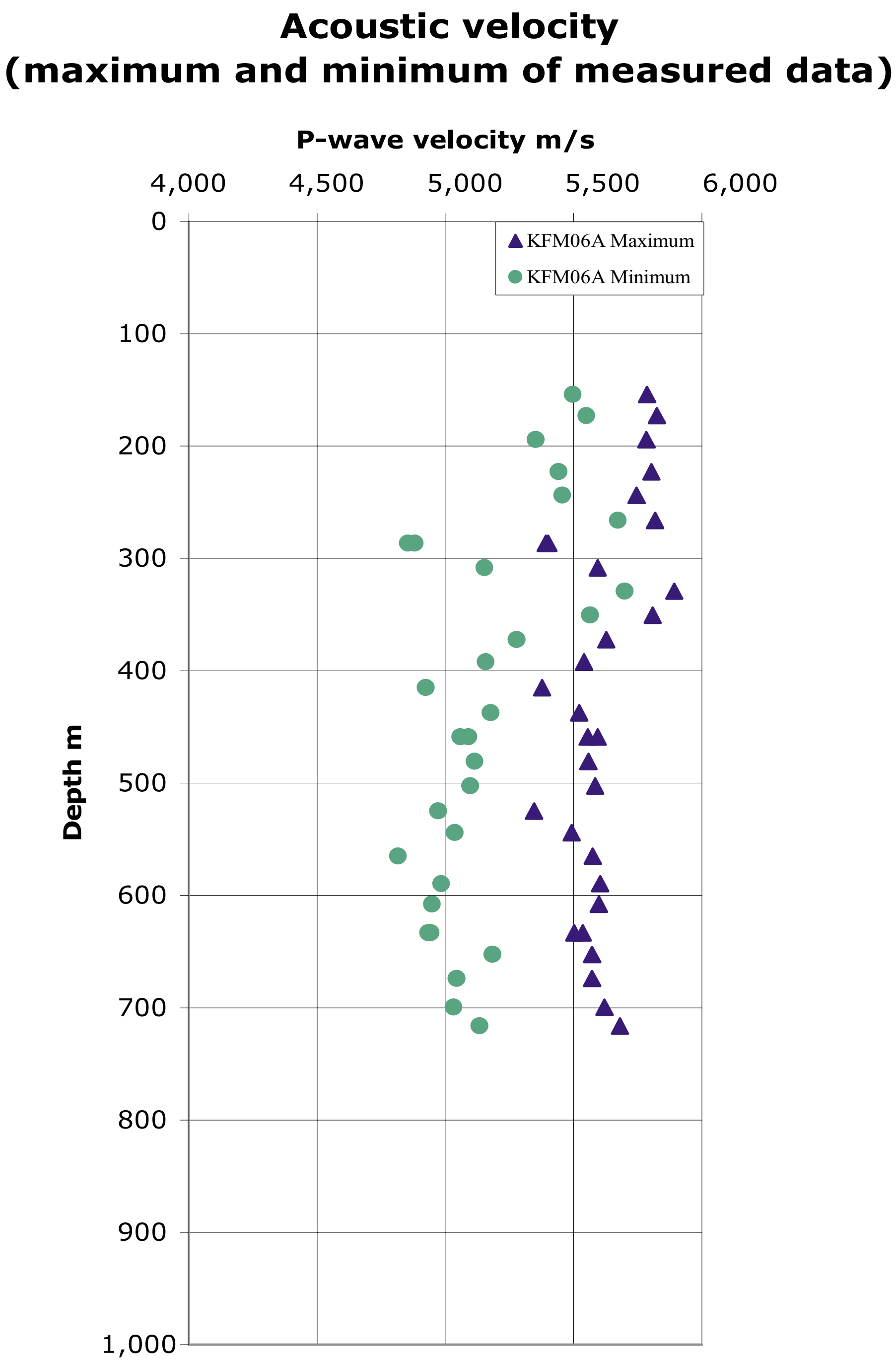


Figure 5-1. *Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KFM06A.*

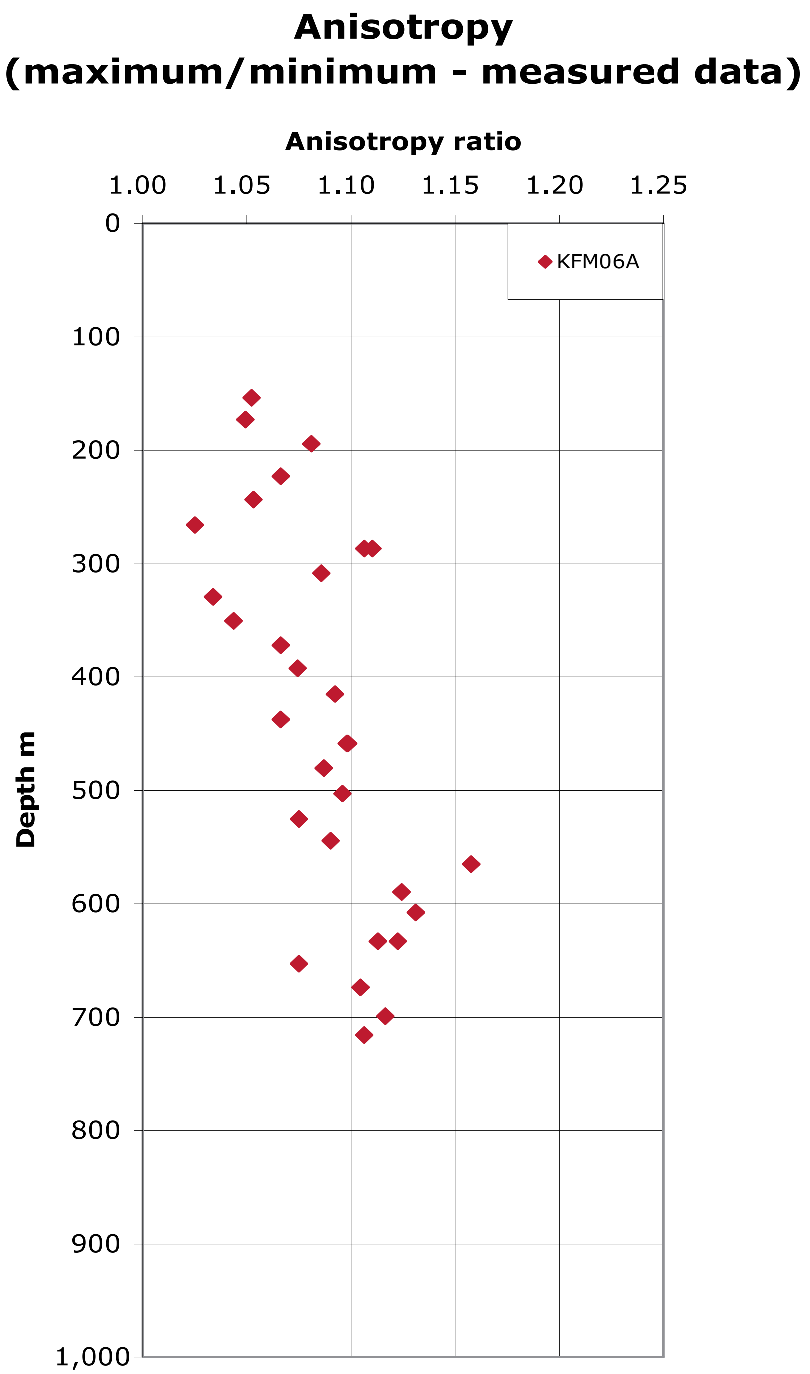


Figure 5-2. *Measured values of acoustic velocities anisotropy plotted versus borehole length in KFM06A.*

The results of calculated principal velocities and their orientations, and the anisotropy ratio are presented in Table 5-2, and shown diagrammatically versus borehole length in Figures 5-3 to 5-5.

The results of calibration determinations for the system are shown in Appendix A. The results are also reported to SICADA (FN 426).

Table 5-2. Determinations of principal velocity and orientation, transverse core in borehole KFM06A, Forsmark. (Orientation clockwise looking down hole, 0° is parallel with foliation where identified).

Depth m	Maximum velocity m/s	Orientation	Minimum velocity m/s	Orientation	Anisotropy ratio	Foliation	
153.95	5,799	170°	5,505	80°	1.05	f	f = foliation (clearly identifiable).
172.90	5,801	45°	5,562	135°	1.04	f	n = no identifiable foliation.
194.35	5,791	100°	5,343	10°	1.08	f	w = weak foliation (no good).
222.70	5,840	160°	5,429	70°	1.08	f	s = strong foliation (good).
243.75	5,772	0°	5,466	90°	1.06	f	
266.10	5,827	150°	5,653	60°	1.03	f	
286.55	5,358	5°	4,856	95°	1.10	f	
308.50	5,623	160°	5,138	70°	1.09	f	
329.40	5,893	130°	5,700	40°	1.03	f	
350.45	5,815	5°	5,582	95°	1.04	f	
372.20	5,632	15°	5,255	105°	1.07	f	
392.13	5,565	55°	5,169	145°	1.08	f	
415.20	5,366	130°	4,932	40°	1.09	f	
437.30	5,521	40°	5,171	130°	1.07	f	
458.90	5,583	10°	5,079	100°	1.10	f	
480.75	5,570	125°	5,130	35°	1.09	f	
502.60	5,590	175°	5,099	85°	1.10	f	
525.08	5,365	35°	4,980	125°	1.08	f	
544.50	5,516	165°	5,067	75°	1.09	f	
565.07	5,602	175°	4,818	85°	1.16	s	
589.60	5,598	90°	4,953	0°	1.13	f	
607.60	5,651	0°	4,979	90°	1.13	f	
633.15	5,508	55°	4,930	145°	1.12	f	
652.80	5,565	0°	5,189	90°	1.07	f	
673.85	5,600	40°	5,062	130°	1.11	f	
699.30	5,602	0°	5,028	90°	1.11	f	
715.95	5,704	40°	5,145	130°	1.11	f	
286.55	5,430	5°	4,866	95°	1.12	f	Repeat
458.90	5,608	10°	5,063	100°	1.11	f	Repeat
633.15	5,533	55°	4,912	145°	1.13	f	Repeat

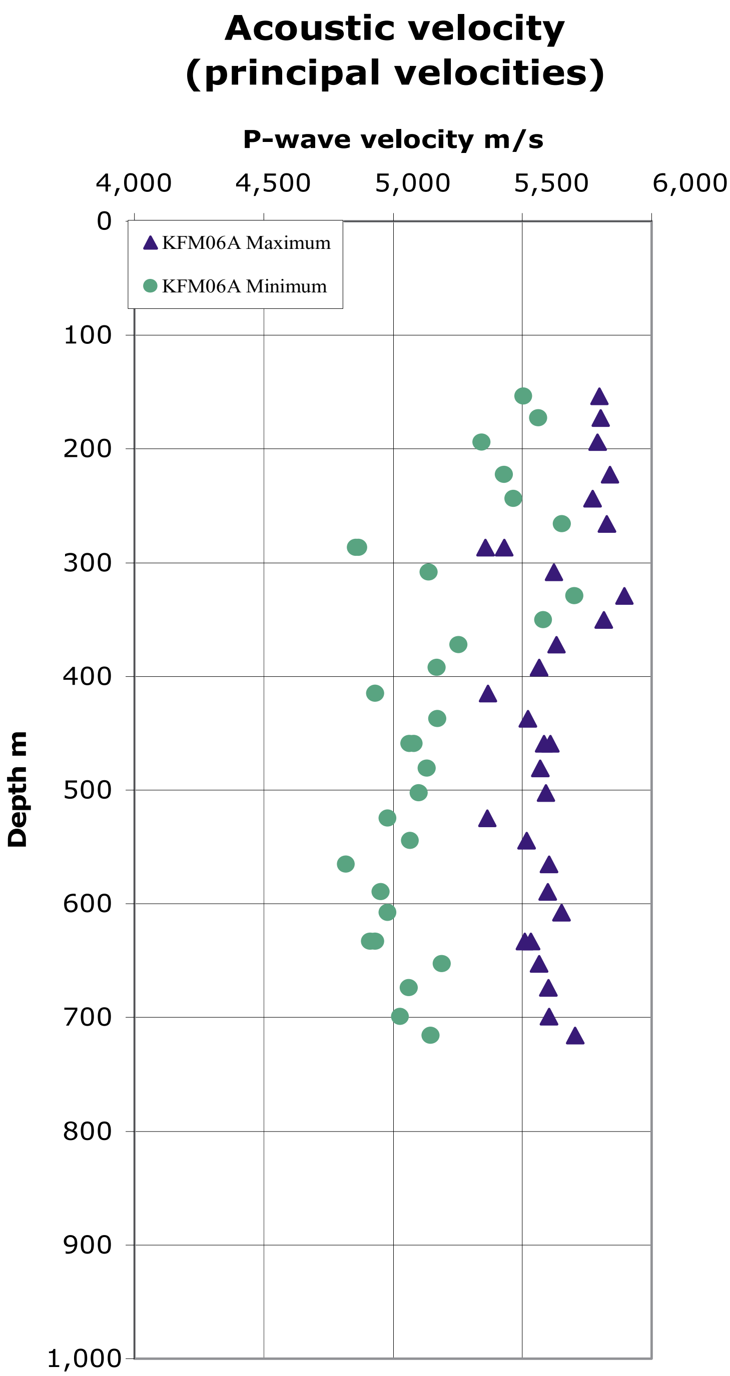


Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KFM06A.*

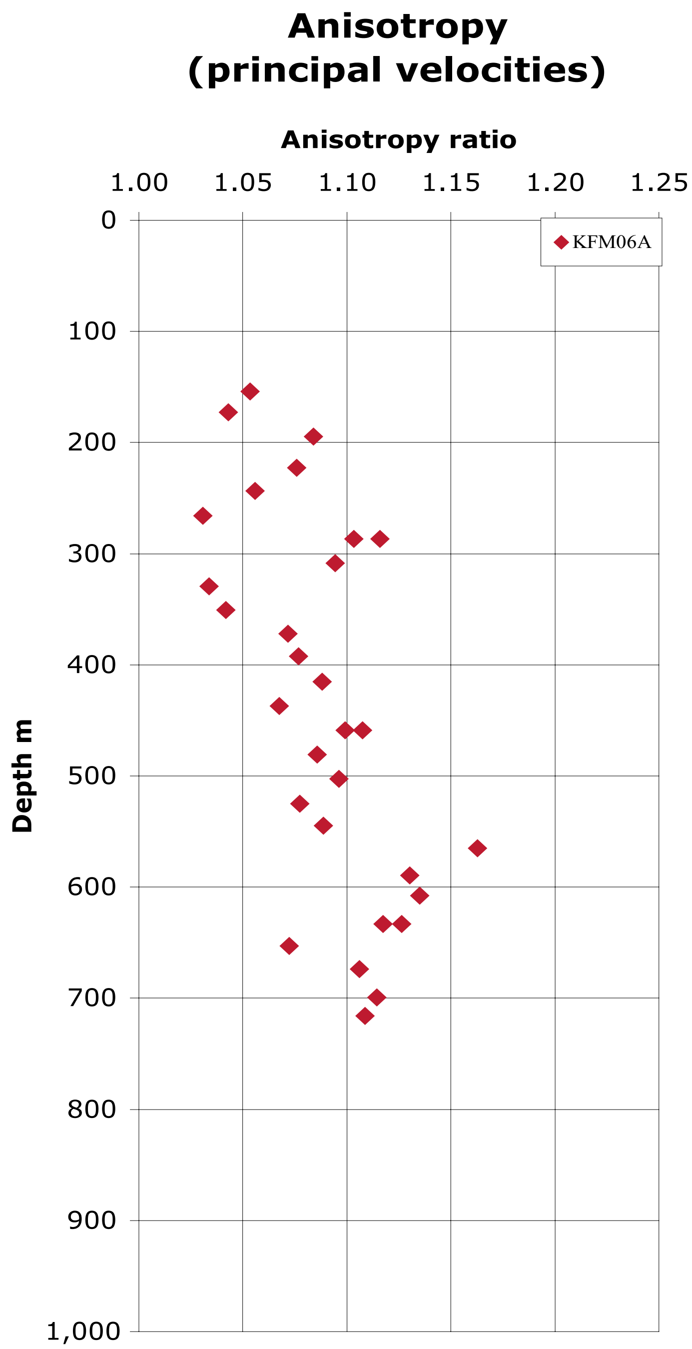


Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KFM06A.*

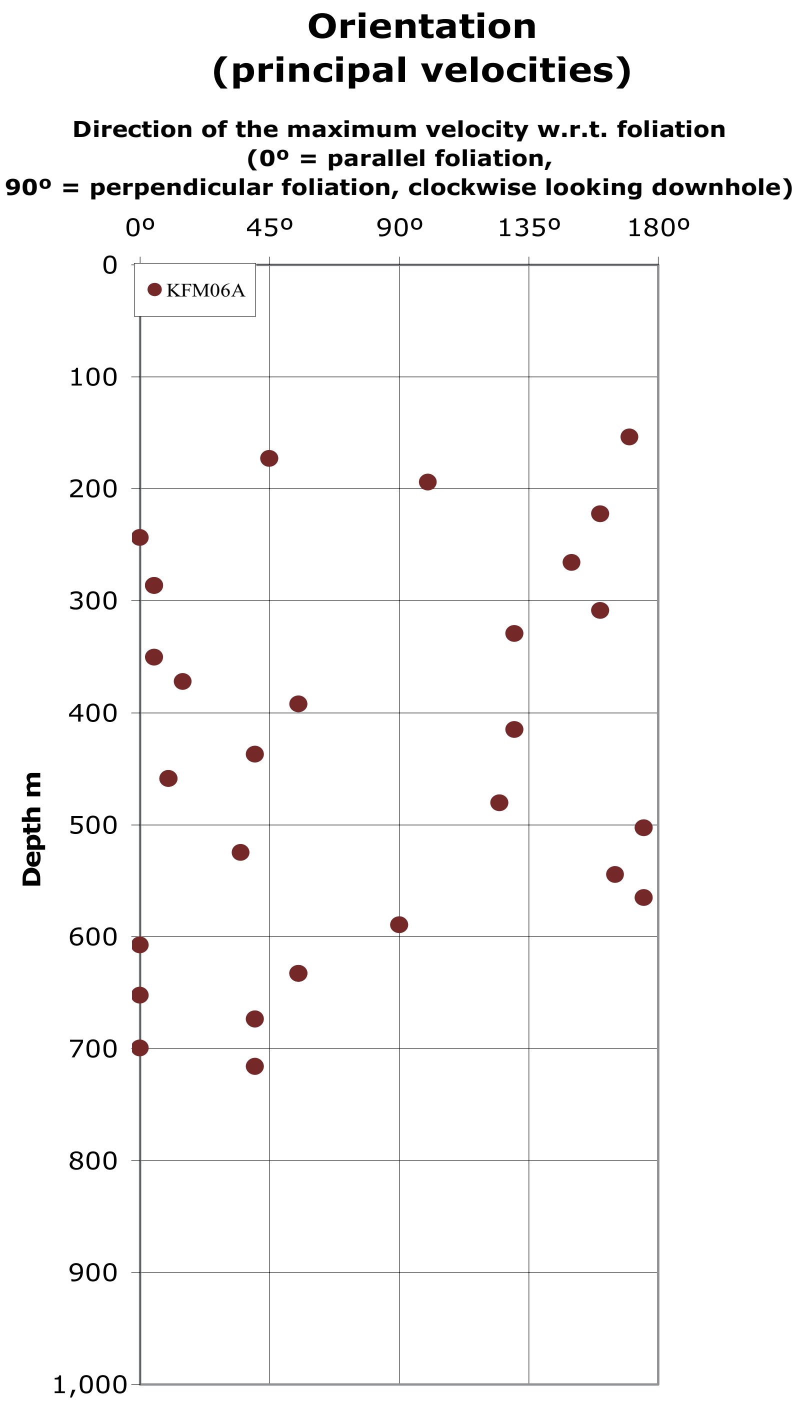


Figure 5-5. *Calculated orientation of the maximum principal acoustic velocity plotted versus borehole length in KFM06A.*

5.2 Discussion

Accuracy and Repeatability

Calibration tests on an aluminium cylinder indicated a variation of ± 0.015 μs in determination of the time pick, equivalent to differences in velocity of about ± 10 m/s. Some of this variation may be explained by temperature variations, thickness of coupling medium and seating of the shoes. Similar variations may be expected from the measurements on the cores.

Tests on cores were repeated at three locations, 286.55 m, 458.90 m and 633.15 m borehole length, after the first series of tests were completed. These tests were repeated to investigate length and determine typical values for repeatability of velocity determinations.

The repeatability of the diameter measurements was about ± 0.01 mm which gives an error of about ± 1 m/s.

At 286.55 m the difference in magnitude of the velocities is up to 176 m/s, the anisotropy ratio differs by 0.02 and there is no difference in orientation. At 458.90 m the difference in magnitude of the velocities is up to 80 m/s, the anisotropy ratio differs by 0.01 and there is no difference in orientation. Finally, at 633.15 m the difference in magnitude off finelly velocities is 65 m/s, the anisotropy ratio differs by 0.01 and there is no difference in orientation.

The differences in the measured velocities on the calibration cylinder and rock cores are presumably due to temperature changes, the problems in seating the transducers and obtaining good signal contact with the material, and due to the interpretation of the time pick.

Generally, there is a good fit between the measurements and the best fit line (model fit) which suggests that random type errors are relatively small. At 286.55 m the maximum difference was 171 m/s, at 458.90 m it was 62 m/s, and at 633.15 m it amounted to 48 m/s, see Figure 5-6.

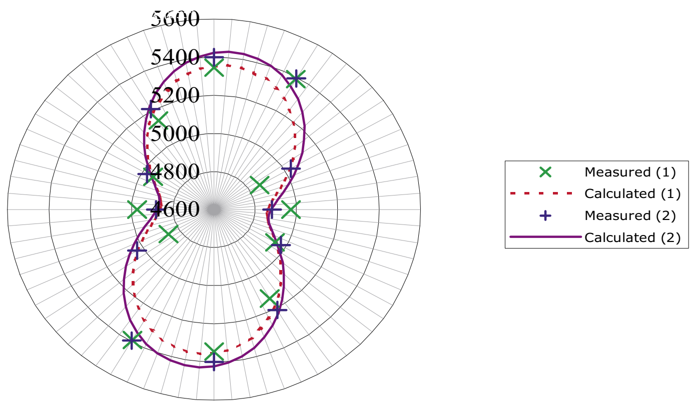
Typically in the entire series of tests, the average deviation between the measured value and the model fit is about 0.37% (about 20 m/s), with a maximum error of 3.5% (about 190 m/s).

The deviation between the model fitted to the data and the measured data reported here is similar to the previous work /Chryssanthakis and Tunbridge, 2003a,b,c,d,e,f/. The results are also very consistent. It is therefore concluded that the measurement errors are similar to those determined previously.

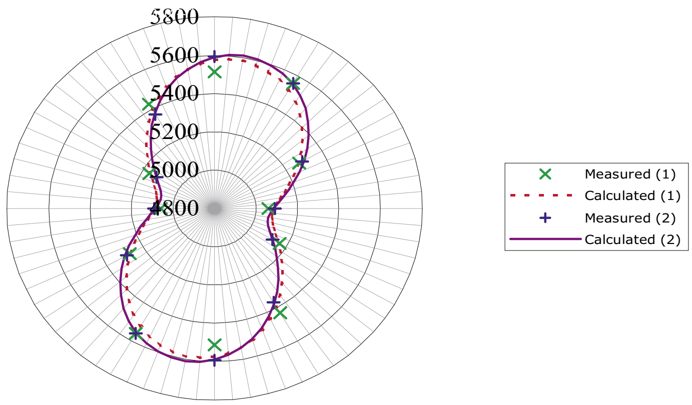
It is therefore inferred that:

- the repeatability of the reported results for velocities is generally better than ± 100 m/s,
- the error in the orientation of the principal velocities is generally better than ± 10° where the anisotropy ratio exceeds 1.10 with larger errors below this limit (with an anisotropy ratio of less than about 1.03 the determination of the orientation is poorly constrained and has little significance in practice),
- errors in determining the anisotropy ratio and orientation are partly mitigated by the redundant data and regression analysis and it is considered that the error in the anisotropy ratio is generally better than ± 0.02.

Acoustic velocity m/s
measurements at 286.55m



Acoustic velocity m/s
measurements at 548.90m



Acoustic velocity m/s
measurements at 633.15m

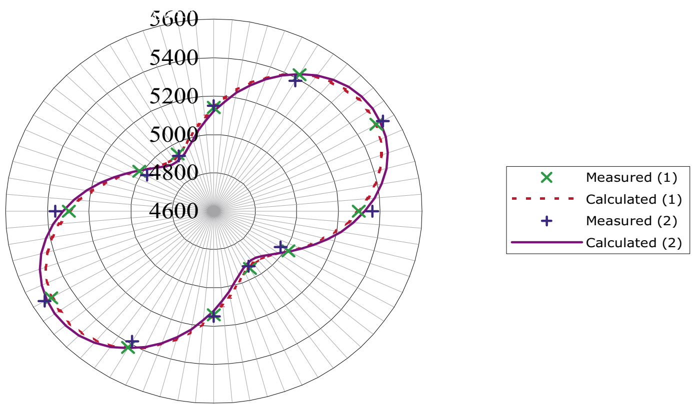


Figure 5-6. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at three different depths in borehole KFM06A.*

Conclusions

The results from the P-wave velocity measurements over the entire length of the borehole core show maximum velocities between 5,358–5,893 m/s and an anisotropy ratio between 1.03 and 1.16. There is little variation in the maximum velocity, lying between 5,772–5,840 m/s, down to 266 m. From 266 m to 415 m the maximum velocity is more variable, between 5,358–5,893 m/s. Below 415 m there is again only a minor variation in the maximum velocity, which amounts to between 5,508–5,704 m/s with an outlying low value of 5,365 m/s at 525 m depth.

The anisotropy ratio is quite variable, but there appears to be a trend of slightly increasing anisotropy ratio with depth lying between 1.03 to 1.10 at the upper end lying and 1.07–1.16 at the lower end of the drill core.

The orientation of the maximum velocity is quite variable relative to the foliation direction, with no consistent or preferred orientation, although there are very few values oriented between 55° and 130°. It is neihter parallel nor perpendicular to the foliation as might have been expected.

References

Chryssanthakis P, Tunbridge L, 2003a. Site investigation, Forsmark. Borehole KFM01A. Determination of P-wave velocity, transverse borehole core, SKB P-03-38. Svensk Kärnbränslehantering AB.

Chryssanthakis P, Tunbridge L, 2003b. Simpevarp Site investigation. Borehole KSH01A. Determination of P-wave velocity, transverse borehole core, SKB P-03-106. Svensk Kärnbränslehantering AB.

Chryssanthakis P, Tunbridge L, 2003c. Oskarshamn site investigation. Borehole KSH02A. Determination of P-wave velocity, transverse borehole core, SKB P-04-11. Svensk Kärnbränslehantering AB.

Chryssanthakis P, Tunbridge L, 2003d. Forsmark Site investigation. Borehole KFM02A. Determination of P-wave velocity, transverse borehole core, SKB P-04-09. Svensk Kärnbränslehantering AB.

Chryssanthakis P, Tunbridge L, 2003e. Simpevarp Site investigation. Borehole KAV01. Determination of P-wave velocity, transverse borehole core, SKB P-04-43. Svensk Kärnbränslehantering AB.

Chryssanthakis P, Tunbridge L, 2003f. Simpevarp Site investigation. Borehole KLX02. Determination of P-wave velocity, transverse borehole core, SKB P-04-45. Svensk Kärnbränslehantering AB.

Eitzenberger A, 2002. Detection of Anisotropy by Diametral Measurements of Longitudinal Wave Velocities on Rock Cores, SKB IPR-03-17. Svensk Kärnbränslehantering AB.

Appendix A

Calibration measurements on aluminium cylinder with diameter 50.90 mm and with known velocity 6,320 m/s.

Date and time	Known velocity m/S	Diameter mm	Time Measured µS	Calculated µS	Correction µS
20041130–09.30 hrs	6,320	50.90	9.16	8.05	1.11
20041130–13.30 hrs	6,320	50.90	9.18	8.05	1.13
20041130–17.00 hrs	6,320	50.90	9.19	8.05	1.14
20041201–09.30 hrs	6,320	50.90	9.18	8.05	1.12
20041201–12.00 hrs	6,320	50.90	9.19	8.05	1.13
Average			9.178		1.124