P-04-206

Oskarshamn site investigation

Borehole: KAV04A

Determination of P-wave velocity, transverse borehole core

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Norwegian Geotechnical Institute

July 2004

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

Summary

The Norwegian Geotechnical Institute (NGI) has carried out P-wave measurements on drill cores from borehole KAV04A at Simpevarp in June 2004. Thirty three P-wave velocity measurements have been carried out from a total of 901 m of core.

The results from the P-wave velocity measurements over the whole length of the borehole show maximum velocities between 5,022–5,980 m/s and a variable anisotropy ratio of between 1.00 to 1.08. The maximum velocity appears to be constant with depth and lies between 5,432–5,980 m/s, with an outlying low value of 5,022 m/s at 796 m.

The foliation is not identifiable over most of the core and the orientation of the principal velocities could not be identified relative to the foliation.

Sammanfattning

Norges Geotekniska Institut (NGI) har under juni 2004 utfört P-vågsmätningar på borrkärnor från borrhål KAV04A i Simpevarp. Sammanlagt utfördes 33 st hastighetsbestämningar av P-vågen på kärnprover som utvalts från borrkärnor med en sammanlagd längd av 901 m.

Resultaten längs hela borrkärnan uppvisar en maximihastighet på mellan ca 5 020–5 980 m/s och en varierande anisotropikvot mellan 1.00 och 1.08. Den maximala hastigheten är relativt konstant och ligger mellan 5 440–5 980 m/s med ett undantag där hastigheten är 5 020 m/s vid borrkärnelängden 796 m. Någon tydlig identifierbar foliation längs kärnan har inte kunnat identifieras och därmed har inte hastigheterna orientering till foliation kunnat bestämmas.

Contents

1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on cores from borehole KAV04A at Simpevarp in Sweden in accordance with SKB Activitetsplan AP PS 400-04-054 (SKB internal controlling document).

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski during the period 14th–15th June 2004 in accordance with SKB's method description MD 190.002 version 1.0 (SKB internal controlling document).

2 Objective and scope

The purpose of the testing is to determine the P-wave velocity transverse to 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 Simpevarp.

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
KAV04	30	33

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 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 volts 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 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 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 borehole core.*

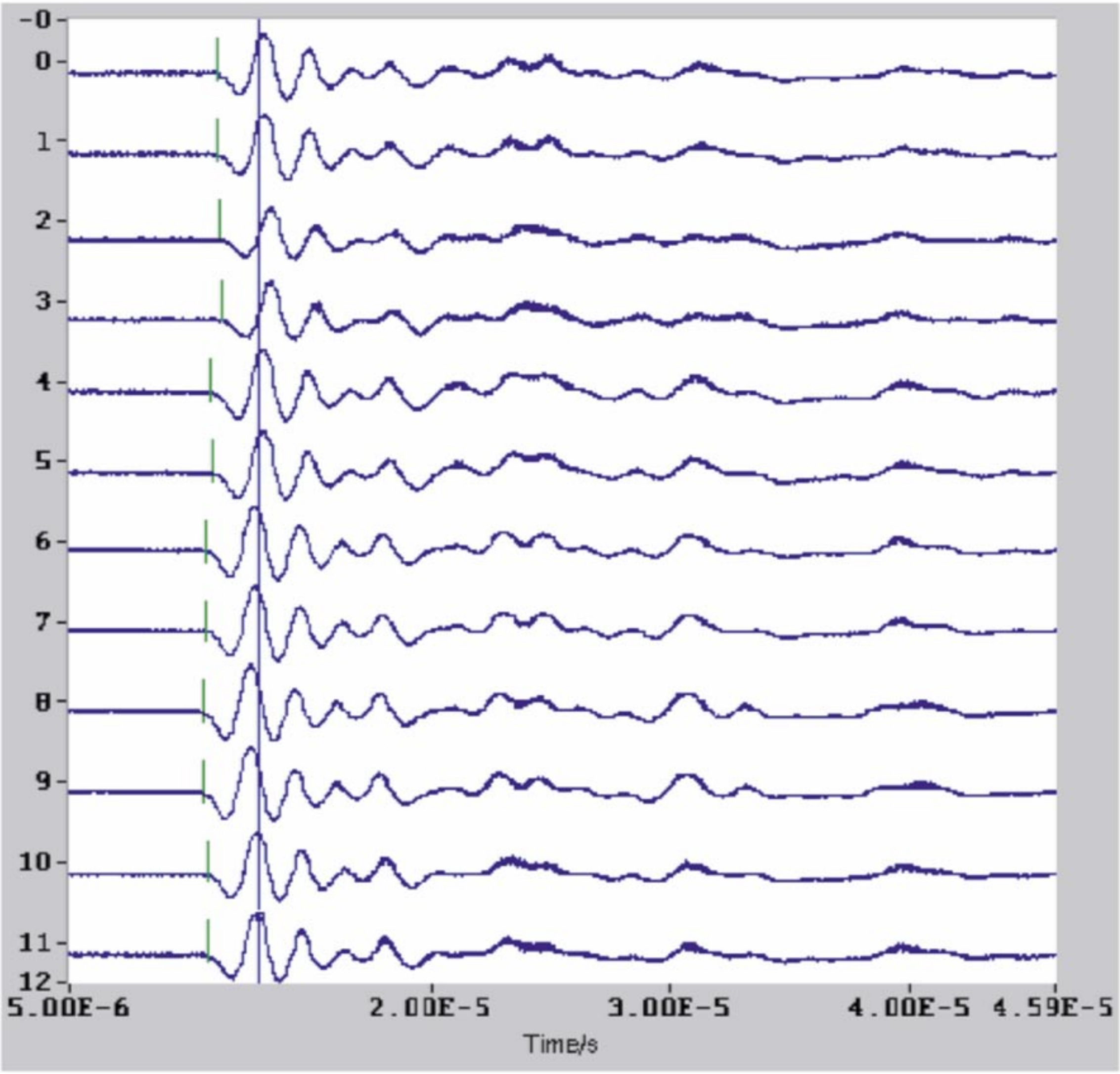

Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Thirty core specimens of length ca. 200–500 mm and diameter about 50 mm were selected from borehole KAV04A while the complete length of the borehole (depth 100 m–1,001.20 m) was displayed on the racks in the core shed at Simpevarp. The specimens were selected together by NGI and SKB.

These specimens represent the Ävrö granite found over most of the length of the borehole. Geological logging of core 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.

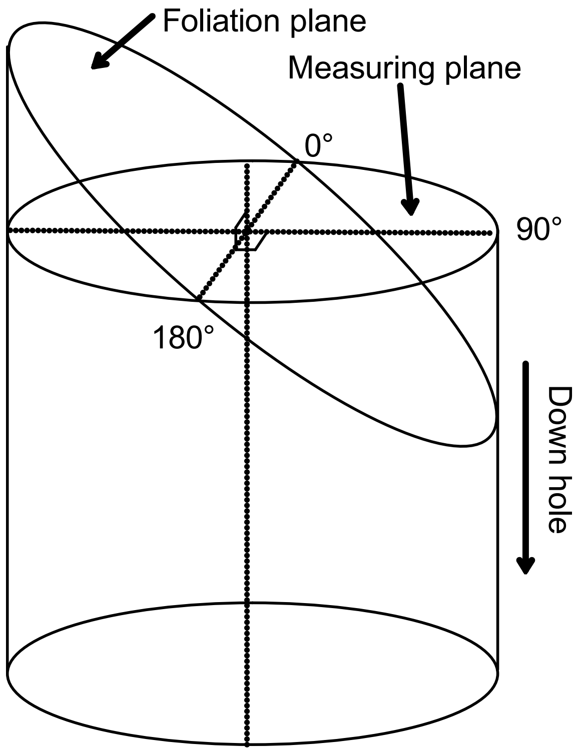

Figure 4-1. Orientation of measurements.

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 determined by dividing the diameter (in mm) by the travel time (in µs) and multiplying by 1,000 to obtain the velocity in m/s.

Analysis

Since the acoustic velocity is dependent on the elastic properties of the material, the results were analysed similarly to 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:

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

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.

The results of calculated principal velocities, and the anisotropy ratio are presented in Table 5-2, and shown diagrammatically versus borehole length in Figures 5-3 to 5-4. The foliation was not identifiable over most of the core and therefore the orientation of the maximum velocity could not be determined.

The results of calibration determinations for the system are shown in Appendix A. The results are also reported to SICADA (field note no Simpevarp 415).

5.2 Discussion

Accuracy and repeatability

Calibration tests on an aluminium cylinder indicated a variation of ±0.02 μs in determination of the time pick, equivalent to differences in velocity of about ±12 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 two locations, 331.15 m, 538.40 m and 735.80 m, after the first series of tests were completed. These tests were repeated to investigate and determine typical values for repeatability of velocity determinations.

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

At 331.15 m the difference in magnitude of the velocities is 5–90 m/s, the anisotropy ratio is the same and there about 10° difference in orientation. At 538.40 m the difference in magnitude of the velocities is 5–86 m/s, the anisotropy ratio is the same and there about 15° difference in orientation. At 735.80 m the difference in magnitude of the velocities is 43–233 m/s, the anisotropy ratio differs by 0.01 and there about 35° difference in orientation. The large difference in the orientation of the stresses is due to the significant differences between the two sets of measurements in this particular case and the low anisotropy which means that the calculation of the orientation angle is not well constrained.

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 331.15 m the maximum difference was 58 m/s, at 538.40 m the maximum difference was 40 m/s, and at 735.80 m the maximum difference was 39 m/s, see Figure 5.5.

Typically in the entire series of tests, the average deviation between the measured value and the model fit is about 0.44% (about 22 m/s), with a maximum error of 2.5% (about 125 m/s).

The deviation between the model fitted to the data and the measured data reported here is somewhat better or equal to that found in the previous work /Chryssanthakis and Tunbridge, 2003a, b, c, d, e, f/. The results are also consistent, except for the tests at 735.80 m depth where there was a significant discrepancy between the two sets of readings, which may have been due to not setting the wave guides in exactly the same positions. It is, however, concluded that the measurement errors are similar to those determined previously.

It is therefore concluded 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°;
- the 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.

Conclusions

The results from the P-wave velocity measurements over the whole length of the borehole show maximum velocities between 5,022–5,980 m/s and a variable anisotropy ratio of between 1.00 to 1.08. The maximum velocity appears to be constant with depth and lies between 5,432–5,980 m/s, with an outlying low value of 5,022 m/s at 796 m.

The foliation is not identifiable over most of the core and the orientation of the principal velocities could not be identified relative to the foliation.

**Table 5-1. Measurements of acoustic velocity, transverse core in borehole KAV04A, Simpevarp.
(orientation clockwise looking down hole, 0° is parallel with foliation if observed)**

Depth m	Diameter mm	Corrected time, mS Parallel foliation			Perpendicular foliation			Velocity m/S Parallel foliation			Perpendicular foliation			Anisotropy ratio
		0°	30°	60°	90°	120°	150°	0°	30°	60°	90°	120°	150°	
156.85	50.25	9.15	9.06	9.12	9.17	9.39	9.42	5491	5546	5509	5479	5351	5334	1.04
180.20	50.29	9.30	9.21	9.30	9.22	9.25	9.26	5407	5460	5407	5454	5436	5430	1.01
198.80	50.11	9.74	9.66	9.27	9.20	9.52	9.77	5144	5187	5405	5446	5263	5128	1.06
226.80	50.19	8.95	8.94	9.18	9.18	9.20	9.08	5607	5613	5467	5467	5455	5527	1.03
235.25	50.70	8.98	8.98	9.13	9.18	9.11	9.00	5645	5645	5552	5522	5565	5633	1.02
249.60	50.17	8.72	9.03	9.00	8.56	8.69	8.76	5753	5555	5574	5860	5772	5726	1.05
266.30	50.23	8.61	8.61	8.41	8.56	8.68	8.68	5833	5833	5972	5867	5786	5786	1.03
275.00	50.13	9.06	9.16	9.25	9.15	8.82	8.89	5532	5472	5419	5478	5683	5638	1.05
286.60	50.18	8.74	8.74	8.74	8.44	8.59	8.57	5741	5741	5741	5945	5841	5854	1.04
331.15	50.11	9.11	8.78	8.85	9.13	9.30	9.21	5500	5706	5661	5488	5387	5440	1.06
352.25	50.08	8.81	8.51	8.46	8.51	8.54	8.92	5684	5884	5919	5884	5863	5614	1.05
376.20	50.13	9.15	8.98	8.85	8.69	8.78	9.05	5478	5582	5664	5768	5709	5538	1.05
429.40	50.09	9.38	9.43	9.21	9.08	9.16	9.29	5339	5311	5438	5516	5468	5391	1.04
440.90	50.09	9.84	9.88	9.48	9.29	9.23	9.54	5090	5069	5283	5391	5426	5250	1.07
458.15	50.07	8.68	8.64	8.54	8.45	8.53	8.61	5768	5794	5862	5925	5869	5814	1.03
480.50	50.16	8.87	8.90	9.18	9.28	9.24	8.98	5654	5635	5463	5404	5428	5585	1.05
520.30	50.20	9.08	9.11	9.44	9.45	9.32	9.24	5528	5510	5317	5311	5386	5432	1.04
538.40	50.30	9.26	9.30	9.20	9.08	8.93	9.02	5431	5408	5467	5539	5632	5576	1.04
560.80	50.33	9.16	9.16	9.32	9.28	9.12	9.22	5494	5494	5399	5423	5518	5458	1.02
580.22	50.25	8.81	9.00	9.23	9.08	8.89	8.98	5703	5583	5443	5533	5652	5595	1.05
602.20	50.20	8.73	8.64	8.69	8.69	8.62	8.64	5749	5809	5776	5776	5823	5809	1.01
643.50	49.90	8.47	8.29	8.54	8.61	8.64	8.56	5890	6018	5842	5795	5775	5829	1.04
649.62	50.09	9.14	9.29	9.16	9.08	9.10	9.18	5480	5391	5468	5516	5504	5456	1.02
667.80	50.10	8.85	8.82	8.85	8.96	8.96	8.89	5660	5679	5660	5591	5591	5635	1.02
683.52	50.29	8.53	8.41	8.55	8.88	8.93	8.70	5895	5979	5881	5662	5631	5780	1.06
735.80	50.17	9.21	9.02	9.00	8.99	9.16	9.24	5447	5561	5574	5580	5476	5429	1.03
747.90	50.23	9.34	8.87	8.97	9.42	9.15	9.21	5377	5662	5599	5332	5489	5453	1.06
772.00	50.20	9.17	9.22	9.24	9.23	9.20	9.24	5474	5444	5432	5438	5456	5432	1.01
796.10	50.34	10.13	10.28	10.19	10.07	10.03	10.09	4969	4896	4940	4998	5018	4988	1.02
822.70	49.85	8.95	8.75	8.77	8.83	9.00	8.97	5569	5696	5683	5645	5538	5557	1.03
331.15	50.10	9.02	8.77	8.89	9.28	9.27	9.12	5554	5712	5635	5398	5404	5493	1.06
538.40	50.29	9.30	9.20	9.16	8.94	8.92	9.11	5407	5466	5489	5624	5637	5520	1.04
735.80	50.17	8.98	8.95	8.89	8.78	8.90	8.86	5586	5605	5643	5713	5636	5662	1.02

Table 5-2. Determinations of principal velocity and orientation, transverse core in borehole KAV04A, Simpevarp.
(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	
156.85	5559	45°	5344	135°	1.04	n	
180.20	5440	90°	5424	0°	1.00	n	
198.80	5432	80°	5093	170°	1.07	n	
226.80	5610	10°	5434	100°	1.03	n	
235.25	5661	0°	5526	90°	1.02	n	
249.60	5823	125°	5590	35°	1.04	n	
266.30	5922	60°	5771	150°	1.03	n	
275.00	5663	140°	5411	50°	1.05	n	
286.60	5900	110°	5720	20°	1.03	n	
331.15	5688	40°	5373	130°	1.06	n	
352.25	5956	70°	5660	160°	1.05	n	
376.20	5762	90°	5484	0°	1.05	n	
429.40	5508	100°	5312	10°	1.04	n	
440.90	5442	105°	5061	15°	1.08	n	
458.15	5912	95°	5766	5°	1.03	n	
480.50	5669	5°	5388	95°	1.05	n	
520.30	5526	0°	5302	90°	1.04	n	
538.40	5619	120°	5398	30°	1.04	n	
560.80	5502	160°	5426	70°	1.01	n	
580.22	5680	160°	5490	70°	1.03	n	
602.20	5805	125°	5776	35°	1.01	n	
643.50	5960	25°	5756	115°	1.04	n	
649.62	5513	110°	5425	20°	1.02	n	
667.80	5683	20°	5589	110°	1.02	n	
683.52	5980	25°	5629	115°	1.06	n	
735.80	5597	65°	5425	155°	1.03	w	
747.90	5580	40°	5391	130°	1.03	n	
772.00	5456	170°	5435	80°	1.00	n	
796.10	5022	125°	4914	35°	1.02	n	
822.70	5699	50°	5530	140°	1.03	n	
331.15	5685	30°	5380	120°	1.06	n	Repeat
538.40	5636	105°	5411	15°	1.04	n	Repeat
735.80	5688	100°	5594	10°	1.02	w	Repeat

f = foliation (clearly identifiable)
n = no identifiable foliation
w = weak foliation (not good)
s = strong foliation (good)

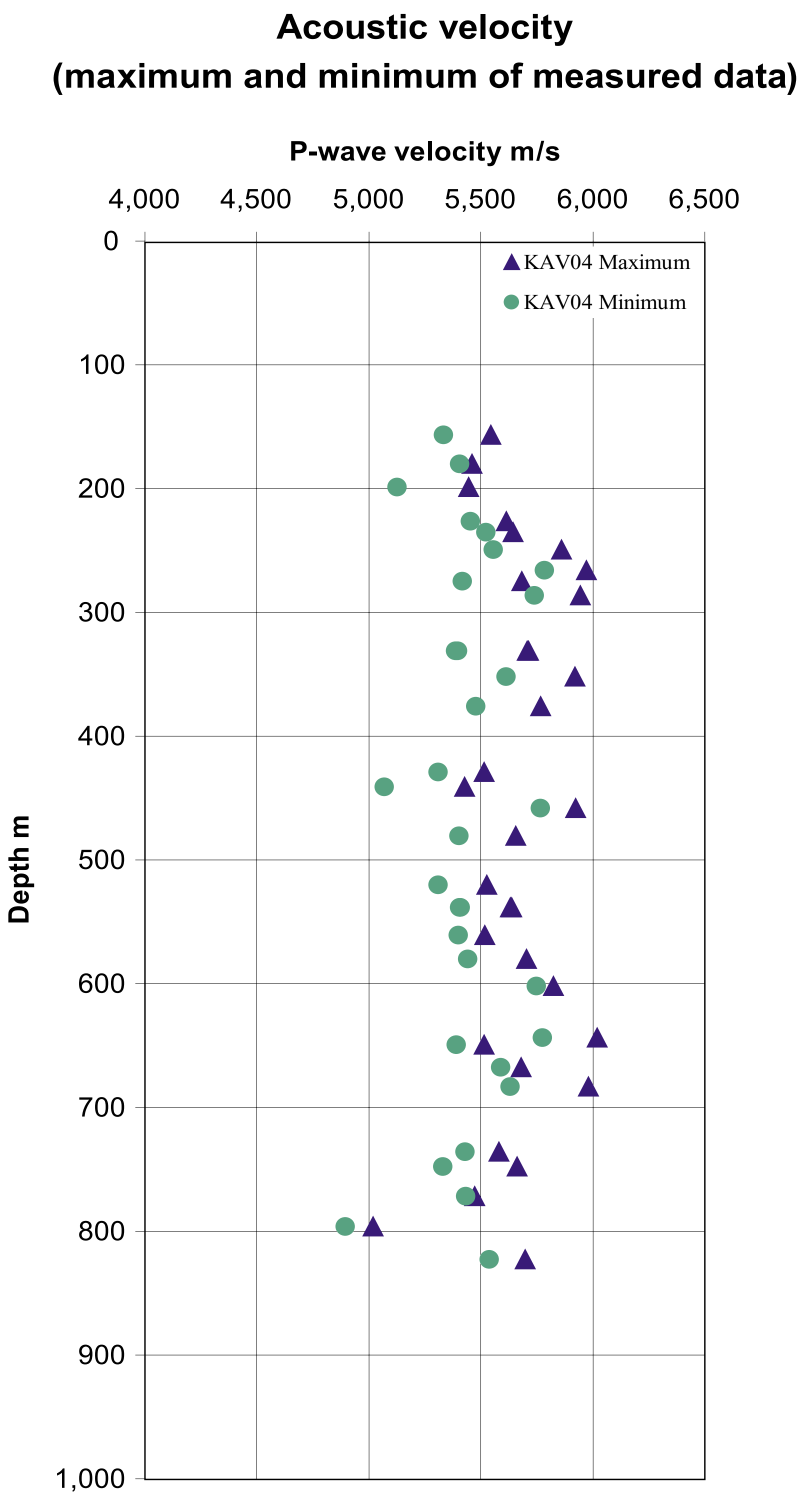

Figure 5-1. Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KAV04A.

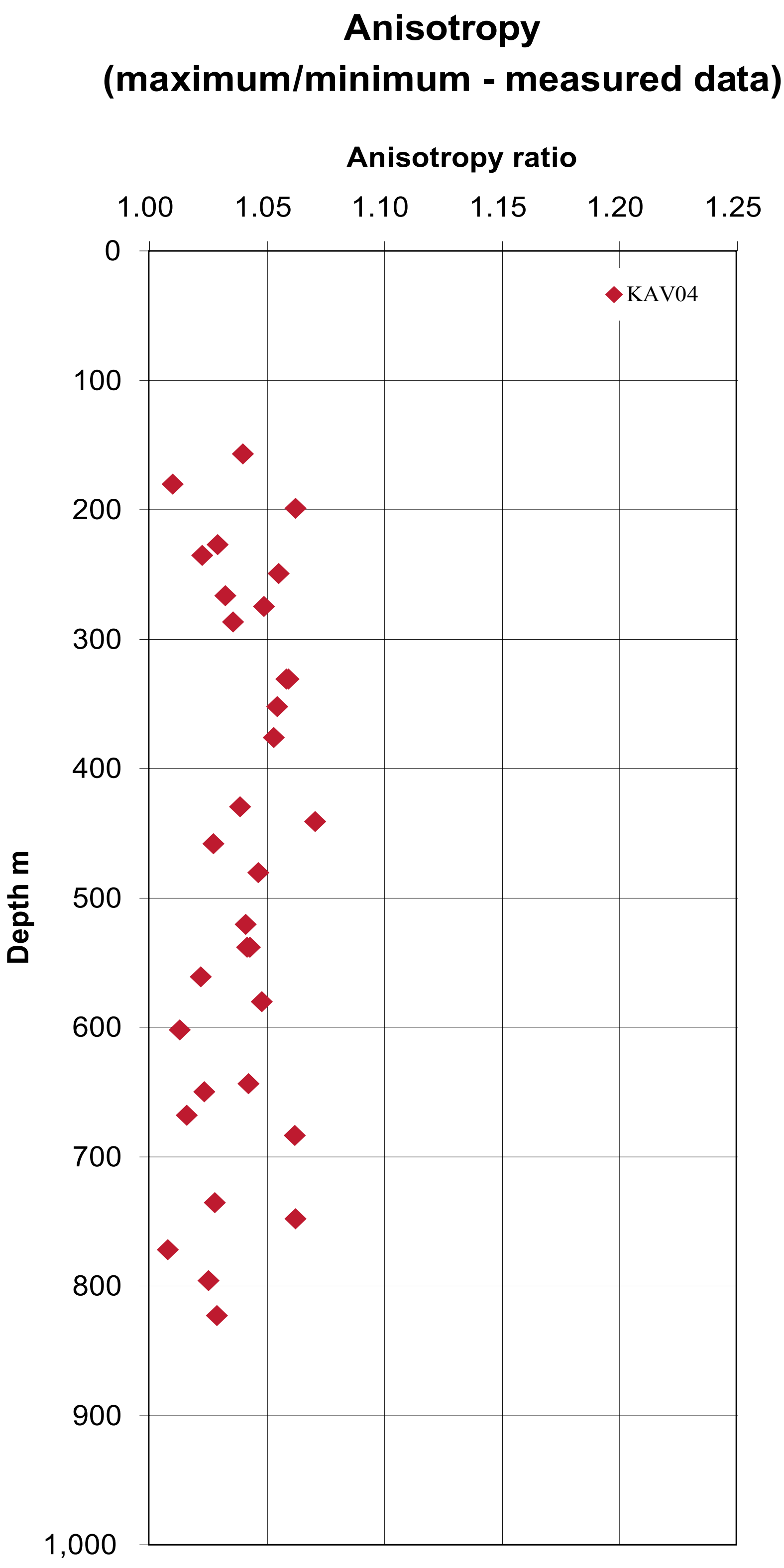

Figure 5-2. *Measured values of acoustic velocities anisotropy plotted versus borehole length in KAV04A.*

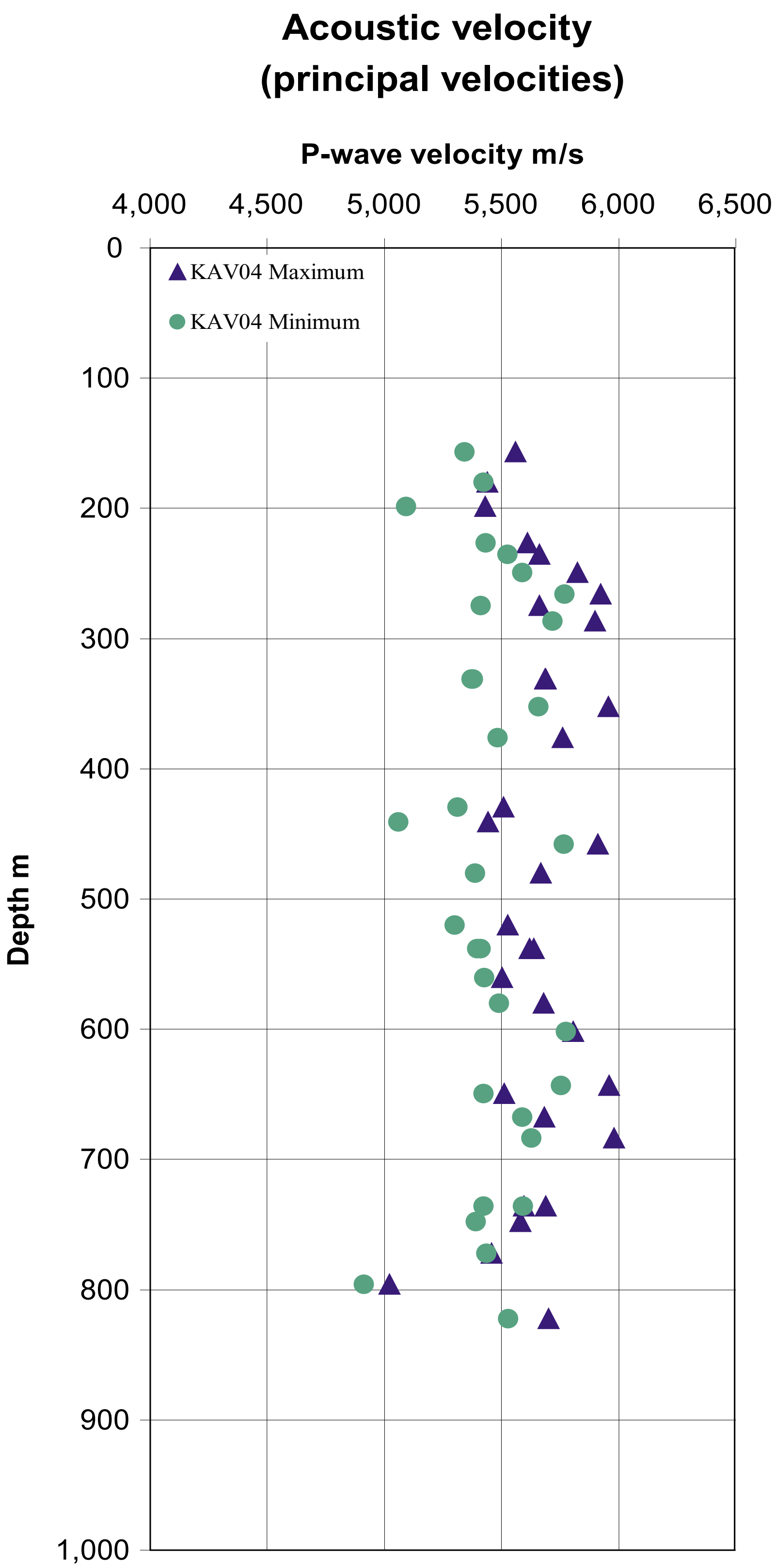

Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KAV04A.*

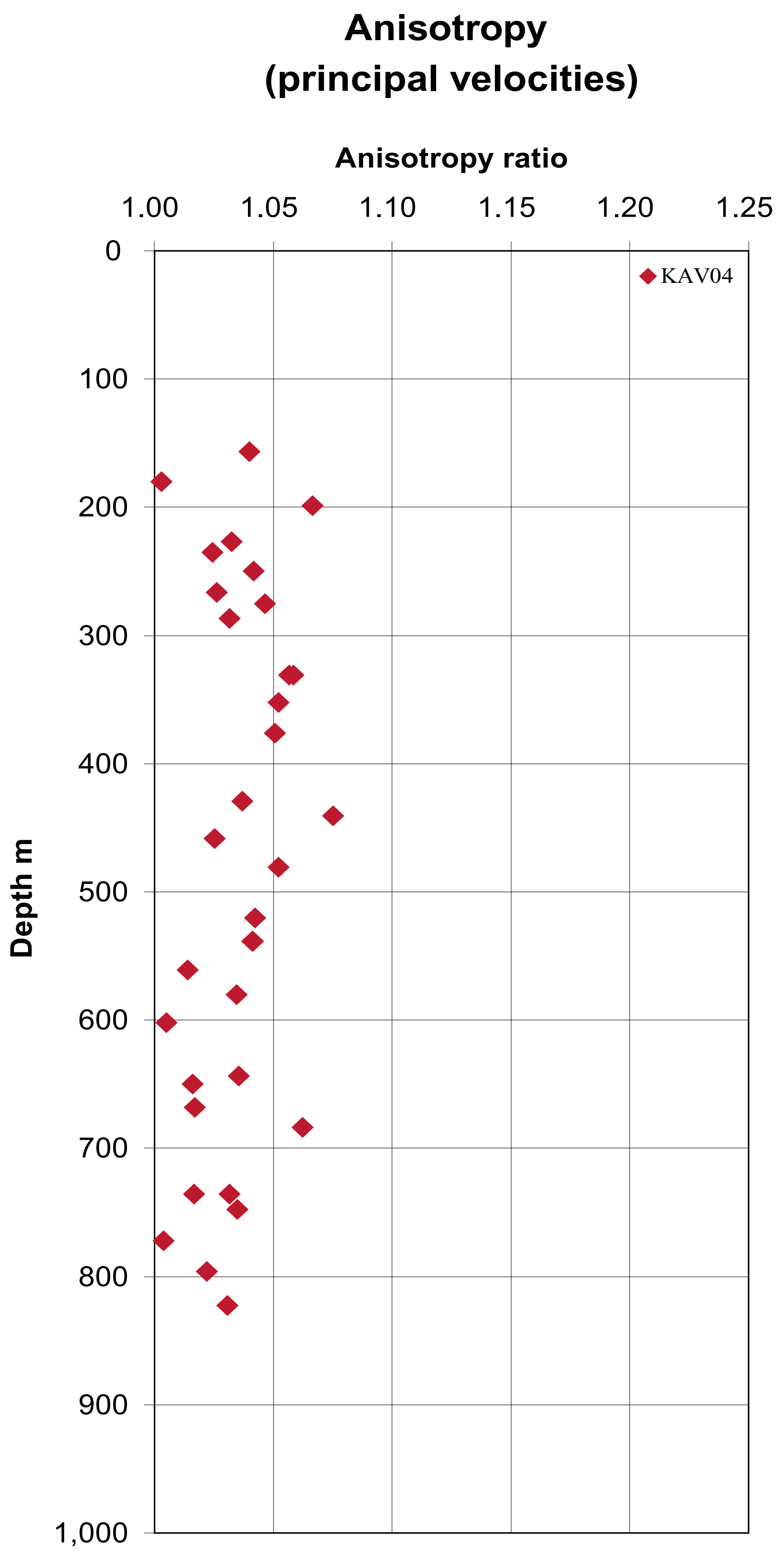

Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KAV04A.*

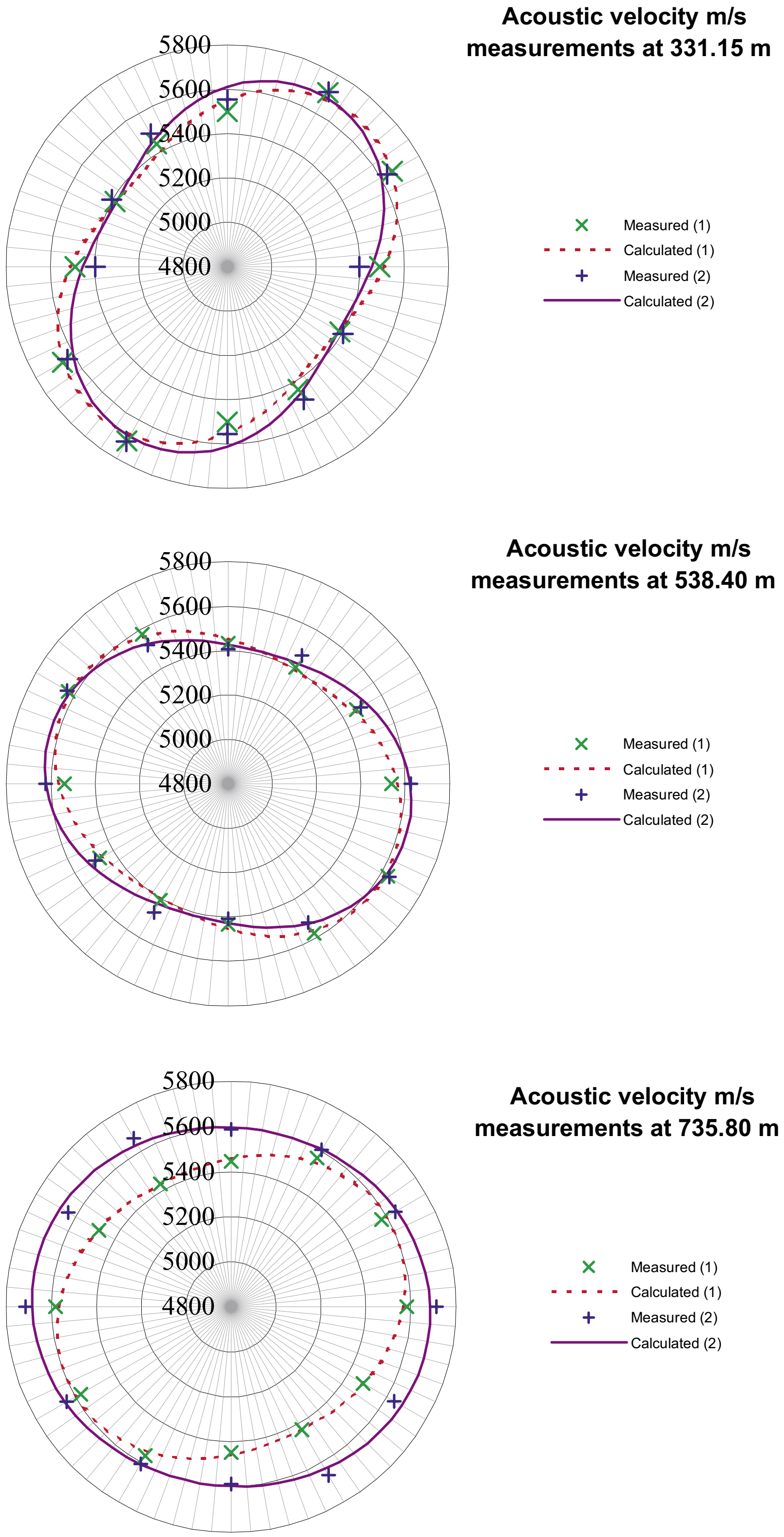

Figure 5-5. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at three different depths in borehole KAV04.*

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Appendix A

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

Date and time	Known velocity m/S	Diameter mm	Time Measured μS	Calculated μS	Correction μS
2004-06-14 15.30 hrs	6.320	50.90	9.17	8.05	1.12
2004-06-15 08.45 hrs	6.320	50.90	9.16	8.05	1.11
2004-06-15 13.00 hrs	6.320	50.90	9.14	8.05	1.09
2004-06-15 15.00 hrs	6.320	50.90	9.18	8.05	1.13
Average			9.163		1.109