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Oskarshamn site investigation

Borehole KLX04A

Determination of P-wave velocity, transverse borehole core

Panayiotis Chryssanthakis, Lloyd Tunbridge
Norwegian Geotechnical Institute

October 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 KLX04A at Simpevarp in October 2004. Thirty seven P-wave velocity measurements have been carried out from a total of 600 m of core.

The results from the P-wave velocity measurements over the whole length of the borehole show maximum velocities between 5,365–6,101 m/s and a variable anisotropy ratio between 1.01 to 1.17. The maximum velocity appears to be constant with depth and range between 5,365–5,929 m/s, with an outlying high value of 6,101 m/s at 497.30 m depth.

The anisotropy ratio appears to be constant with depth and lies between 1.01 to 1.06 with outlying high values of 1.17 at 335.60 m, 1.12 at 364.50 m and 1.09 at 372.35 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 oktober 2004 utfört P-vågsmätningar på borrkärnor från borrhål KLX04A i Simpevarp. Sammanlagt utfördes 37 st hastighetsbestämningar av P-vågen på kärnprover som utvalts från borrkärnor med en sammanlagd längd av 600 m.

Resultaten längs hela borrkärnelängden uppvisar en maxhastighet på mellan ca 5 365–6 101 m/s och en varierande anisotropikvot mellan 1.01 och 1.17. Den maximala hastigheten är relativt konstant mellan 5 365–5 929 m/s, med ett undantag där hastigheten är 6 101 m/s vid 497.30 m.

Den anisotropikvot är relativt konstant mellan 1,01 och 1,06, med undantag där anisotropikvot är 1,17 vid 335,60 m, 1,12 vid 364,50 m och 1,09 vid 372,35 m.

Någon tydlig identifierbar foliation längs kärnan har inte kunnat identifieras och därmed har inte hastigheterna orientering till foliation kunnat bestämmas.

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1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on cores from borehole KLX04A at Simpevarp, see Figure 1-1, in accordance with SKB's activity plan AP PS 400-04-078, version 1.0 (SKBs internal controlling document).

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski in October 2004 in accordance with SKB's method description MD 190.002 version 1.0 (SKB internal controlling document).

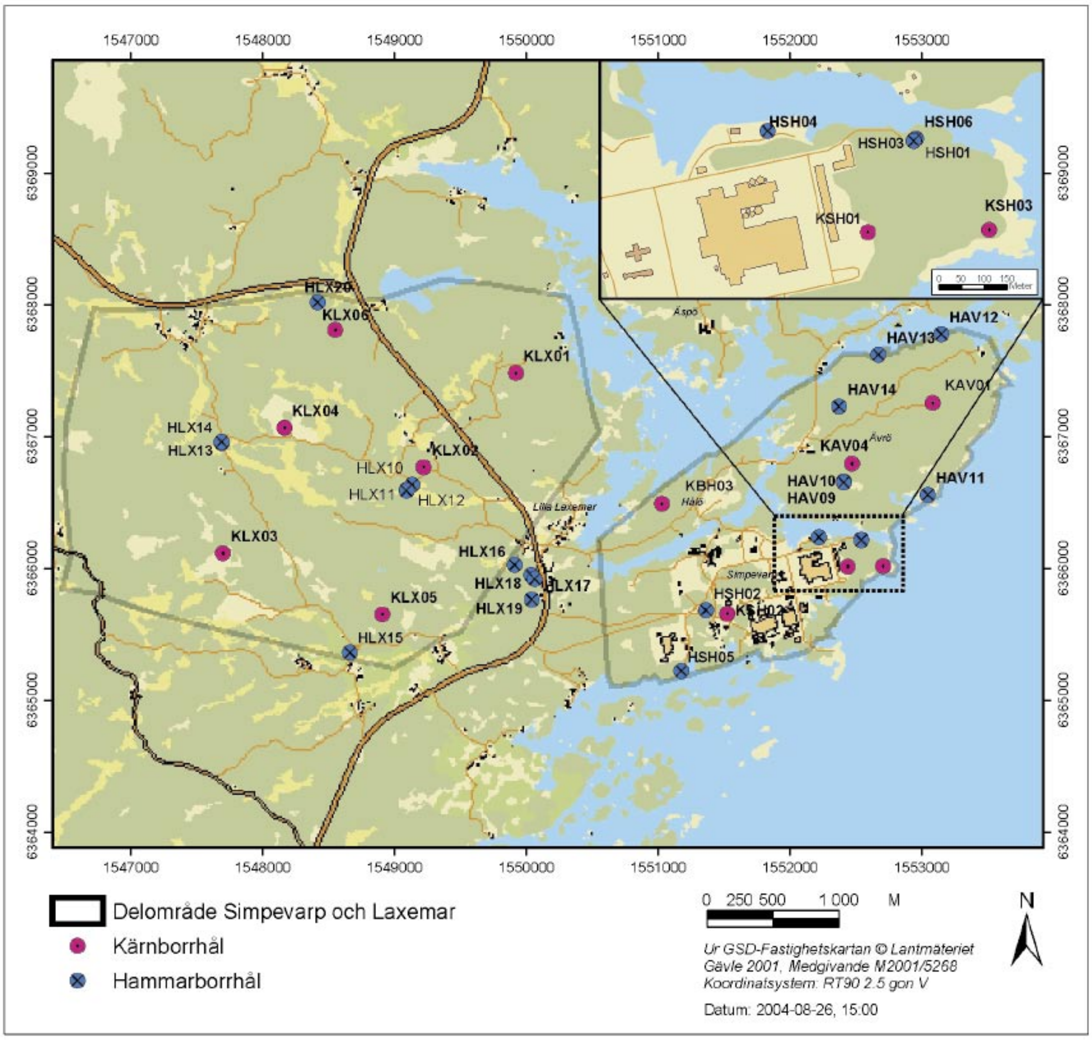

Figure 1-1. Simpevarp investigation area.

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
KLX04A	34	37

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.*

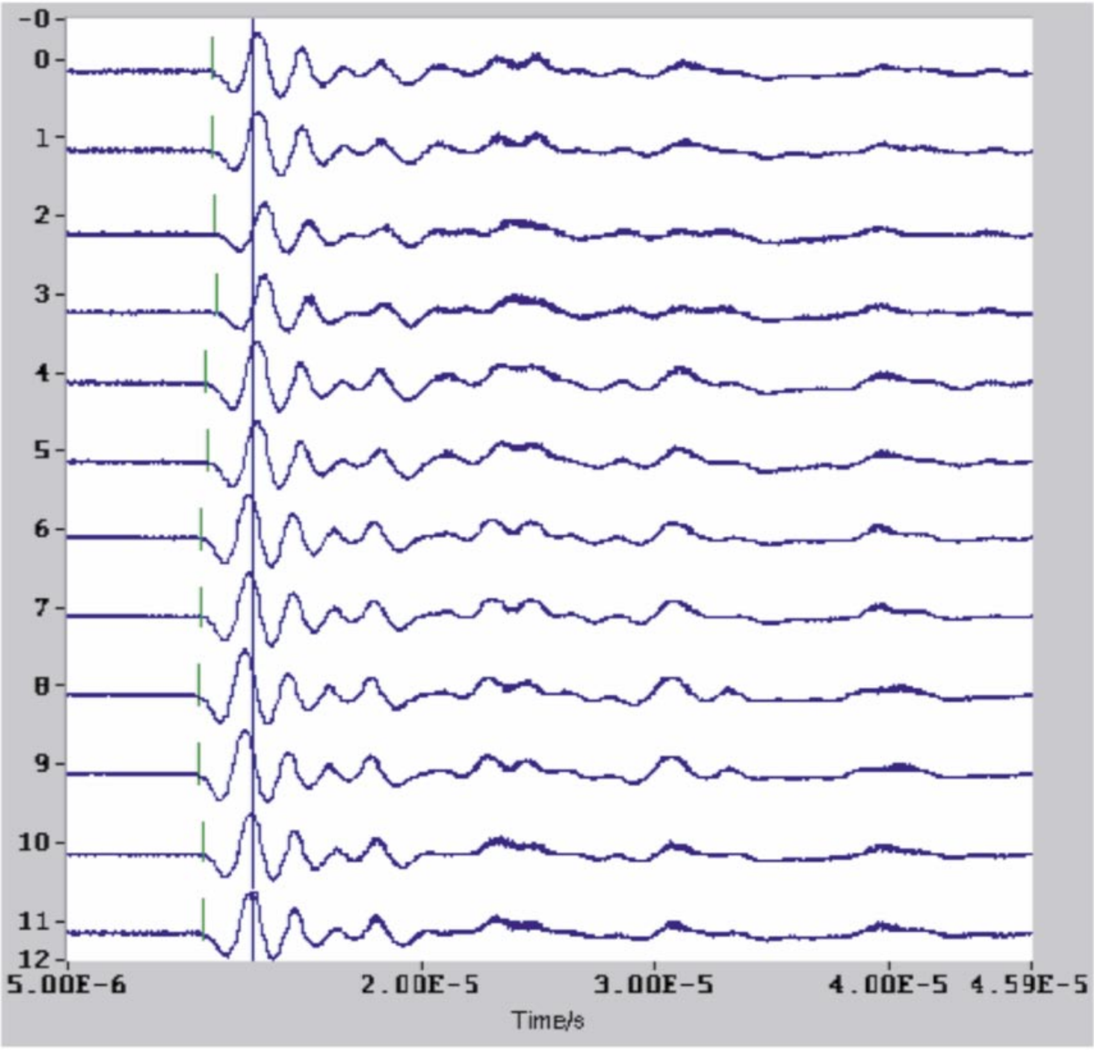

Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Thirty four core specimens of length app. 200 – 500 mm and diameter about 50 mm were selected from borehole KLX04A while the complete length of the borehole (depth 100.35 m – 993,49 m) was displayed on the racks in the core shed at Simpevarp. The specimens were selected together by NGI and Thomas Jansson representing SKB.

These specimens represent the Ävrö granite, with some veins of quartz monzonite and fine grained granitoid, 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.

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.

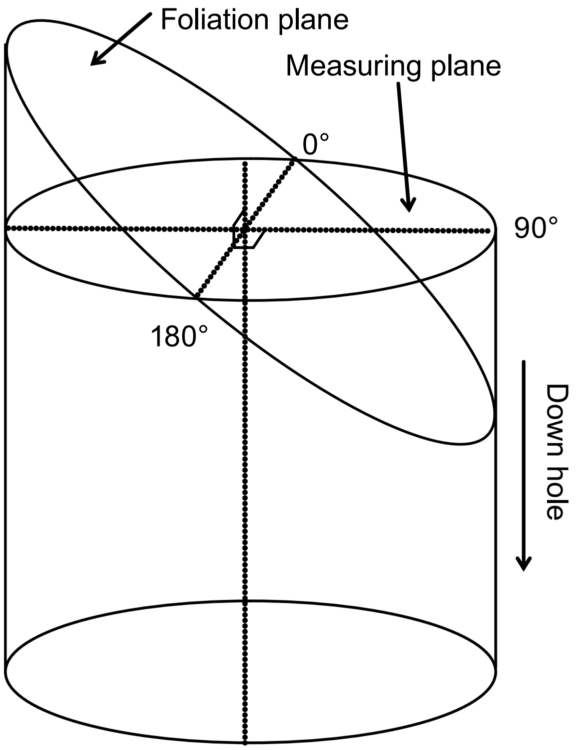

Figure 4-1. *Orientation of measurements.*

Analysis

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

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

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 the 45° intervals 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 (FN507).

5.2 Discussion

Accuracy and repeatability

Calibration tests on an aluminium cylinder indicated a variation of ± 0.020 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, 299.30 m, 446.90 m and 620.25 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 299.30 m the maximum difference in magnitude of the velocities is 73 m/s, the anisotropy ratio differ by 0.02 and there is no difference in orientation. At 446.90 m the maximum difference in magnitude of the velocities is 74 m/s, the anisotropy ratio differ by 0.02 and there is about 6° difference in orientation. At 620.25 m the maximum difference in magnitude of the velocities is 66 m/s, the anisotropy ratio differ by 0.01 and there is about 10° 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 299.30 m the maximum difference was 65 m/s, at 446.90 m the maximum difference was 49 m/s, and at 625.20 m the maximum difference was 62 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 0.5% (about 25 m/s), with a maximum error of 2.43% (about 130 m/s).

The deviation between the model fitted to the data and the measured data reported here is in agreement to the previous work /Chryssanthakis and Tunbridge, 2003a,b,c,d,e,f,g/. The results are also very consistent. It is therefore 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° where the anisotropy ratio is greater than 1.10 with greater 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.

Conclusions

Exceptionally low values of velocity were measured at 446.90m and 452.00 m, adjacent to an area of overcoring between 245.28 m and 250.48 m. It is considered that the core may have been disturbed and damaged and the results are therefore not representative. These results are therefore not reported on Figures 5.3 and 5.4.

Ignoring the disturbed results indicates that the P-wave velocity measurements over the whole length of the borehole show maximum velocities between 5,365–6,101 m/s and a variable anisotropy ratio between 1.01 to 1.17. The maximum velocity appears to be constant with depth and lies between 5,365–5,929 m/s, with an outlying high value of 6,101 m/s at 497.30 m depth. The anisotropy ratio appears to be constant with depth and lies between 1.01 to 1.06 with outlying high values of 1.17 at 335.60 m, 1.12 at 364.50 m and 1.09 at 372.35 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 KLX04A, Simpevarp (orientation clockwise looking down hole, 0° is parallel with foliation).

Depth m	Diameter mm	Corrected time, mS						Velocity m/S						Anisotropy ratio
		Parallel foliation			Perpendicular foliation			Parallel foliation			Perpendicular foliation			
		0°	30°	60°	90°	120°	150°	0°	30°	60°	90°	120°	150°	
200.30	50.17	8.97	8.85	8.96	9.24	9.24	9.27	5,591	5,666	5,597	5,427	5,427	5,410	1.05
220.55	50.20	9.27	9.29	9.18	9.08	9.08	9.21	5,413	5,401	5,466	5,526	5,526	5,448	1.02
235.85	50.10	8.89	8.89	9.07	9.02	8.98	8.99	5,633	5,633	5,521	5,552	5,577	5,571	1.02
241.80	50.17	8.95	8.89	8.90	8.74	8.64	8.79	5,603	5,641	5,635	5,738	5,804	5,705	1.04
259.34	50.14	8.84	8.87	9.20	9.43	9.11	8.92	5,670	5,650	5,448	5,315	5,502	5,619	1.07
271.12	50.19	8.80	9.17	9.29	9.12	9.11	9.02	5,701	5,471	5,400	5,501	5,507	5,562	1.06
284.20	50.24	9.17	9.61	9.55	9.27	9.18	8.99	5,476	5,226	5,259	5,417	5,471	5,586	1.07
299.30	50.25	9.55	9.50	9.31	9.19	9.00	9.20	5,260	5,287	5,395	5,466	5,581	5,460	1.06
319.60	50.18	8.91	8.86	8.61	8.69	9.05	9.13	5,629	5,661	5,826	5,772	5,542	5,494	1.06

Depth m	Diameter mm	Corrected time, mS						Velocity m/S						Anisotropy ratio
		Parallel foliation			Perpendicular foliation			Parallel foliation			Perpendicular foliation			
		0°	30°	60°	90°	120°	150°	0°	30°	60°	90°	120°	150°	
335.60	50.22	10.14	9.82	9.04	8.80	9.35	10.13	4,951	5,112	5,553	5,704	5,369	4,956	1.15
352.25	50.20	9.22	9.31	9.30	9.10	9.06	8.97	5,442	5,390	5,396	5,514	5,539	5,594	1.04
364.50	50.24	9.68	9.20	9.18	9.36	10.20	10.02	5,188	5,459	5,471	5,365	4,924	5,012	1.11
372.35	50.25	9.55	9.79	9.46	9.10	8.93	9.21	5,260	5,131	5,310	5,520	5,625	5,454	1.10
382.05	50.20	9.04	9.15	9.47	9.28	9.27	9.03	5,551	5,484	5,299	5,407	5,413	5,557	1.05
394.80	50.19	9.07	9.19	9.16	8.92	8.80	8.84	5,531	5,459	5,477	5,624	5,701	5,675	1.04
410.90	50.09	8.71	8.68	8.73	8.82	8.85	8.85	5,748	5,768	5,735	5,677	5,657	5,657	1.02
430.15	50.17	8.79	9.06	9.07	9.03	8.70	8.64	5,705	5,535	5,529	5,554	5,764	5,804	1.05
446.90	50.11	11.16	11.55	11.80	11.20	10.90	10.92	4,489	4,337	4,245	4,473	4,596	4,587	1.08
452.00	50.12	11.14	11.33	11.35	11.15	10.94	11.17	4,498	4,422	4,414	4,494	4,580	4,485	1.04
454.00	50.10	9.26	9.38	9.63	9.56	9.91	9.52	5,408	5,339	5,200	5,239	5,054	5,261	1.07
461.00	50.09	9.02	8.81	9.19	9.18	9.36	9.14	5,551	5,683	5,448	5,454	5,349	5,478	1.06
478.00	50.11	9.49	9.52	9.42	9.34	9.35	9.45	5,278	5,262	5,317	5,363	5,357	5,301	1.02
497.30	50.10	8.36	8.51	8.51	8.29	8.26	8.23	5,990	5,885	5,885	6,041	6,063	6,085	1.03
530.75	50.06	8.80	8.89	8.83	8.74	8.72	8.64	5,686	5,629	5,667	5,725	5,738	5,791	1.03
556.95	50.06	8.77	8.92	9.05	9.25	9.16	8.90	5,706	5,610	5,529	5,410	5,463	5,622	1.05
577.60	50.03	8.74	8.81	9.00	9.22	9.06	8.78	5,722	5,676	5,557	5,424	5,520	5,696	1.05
601.60	50.08	8.98	8.75	8.62	8.86	9.02	9.00	5,574	5,721	5,807	5,650	5,550	5,562	1.05
620.25	50.19	9.06	9.18	9.06	8.97	8.92	9.17	5,537	5,465	5,537	5,593	5,624	5,471	1.03
642.70	50.18	9.16	9.17	9.18	9.06	8.78	9.33	5,476	5,470	5,464	5,536	5,713	5,376	1.06
668.00	50.12	8.58	8.65	8.66	8.69	8.54	8.44	5,839	5,792	5,785	5,765	5,866	5,936	1.03
693.50	50.10	8.58	8.45	8.47	8.47	8.52	8.57	5,837	5,926	5,912	5,912	5,878	5,843	1.02
730.20	50.21	9.11	8.97	8.98	8.91	8.75	8.98	5,509	5,595	5,589	5,633	5,736	5,589	1.04
759.90	50.09	8.82	8.71	8.87	9.01	9.01	8.96	5,677	5,748	5,645	5,557	5,557	5,588	1.03
791.10	49.95	8.93	8.98	9.00	8.85	8.65	8.84	5,591	5,560	5,548	5,642	5,772	5,648	1.04
299.30	50.25	9.43	9.37	9.29	9.21	8.98	9.26	5,327	5,361	5,407	5,454	5,593	5,424	1.05
446.90	50.12	11.35	11.66	11.70	11.14	10.86	10.79	4,414	4,297	4,282	4,498	4,613	4,643	1.08
620.25	50.19	9.06	9.07	9.08	9.01	8.91	9.08	5,537	5,531	5,525	5,568	5,631	5,525	1.02

Table 5-2. Determinations of principal velocity and orientation , transverse core in borehole KLX04A, 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
200.30	5,658	30°	5,382	120°	1.05	n
220.55	5,532	105°	5,395	15°	1.03	n
235.85	5,626	0°	5,536	90°	1.02	n
241.80	5,778	115°	5,597	25°	1.03	n
259.34	5,705	0°	5,362	90°	1.06	n
271.12	5,628	165°	5,419	75°	1.04	n
284.20	5,574	140°	5,237	50°	1.06	n
299.30	5,557	110°	5,259	20°	1.06	n
319.60	5,808	60°	5,500	150°	1.06	n
335.60	5,680	85°	4,869	175°	1.17	n
352.25	5,581	130°	5,378	40°	1.04	n
364.50	5,527	50°	4,946	140°	1.12	n

Depth m	Maximum velocity m/s	Orientation	Minimum velocity m/s	Orientation	Anisotropy ratio	Foliation	
372.35	5,617	115°	5,149	25°	1.09	n	
382.05	5,568	165°	5,336	75°	1.04	n	
394.80	5,711	125°	5,445	35°	1.05	n	
410.90	5,769	30°	5,645	120°	1.02	n	
430.15	5,805	145°	5,492	55°	1.06	n	
446.90	4,629	140°	4,280	50°	1.08	x	
452.00	4,549	130°	4,415	40°	1.03	x	
454.00	5,381	15°	5,119	105°	1.05	n	
461.00	5,622	20°	5,366	110°	1.05	n	
478.00	5,365	105°	5,261	15°	1.02	n	
497.30	6,101	130°	5,881	40°	1.04	n	
530.75	5,775	130°	5,638	40°	1.02	n	
556.95	5,696	5°	5,417	95°	1.05	n	
577.60	5,748	0°	5,450	90°	1.05	n	
601.60	5,770	55°	5,518	145°	1.05	n	
620.25	5,600	105°	5,476	15°	1.02	n	
642.70	5,593	105°	5,418	15°	1.03	n	
668.00	5,905	150°	5,755	60°	1.03	n	
693.50	5,929	65°	5,840	155°	1.02	n	
730.20	5,685	105°	5,532	15°	1.03	n	
759.90	5,724	25°	5,534	115°	1.03	n	
791.10	5,724	125°	5,530	35°	1.04	n	
299.30	5,534	110°	5,321	20°	1.04	n	Repeat
446.90	4,655	130°	4,261	40°	1.09	x	Repeat
620.25	5,592	115°	5,514	25°	1.01	n	Repeat

F = foliation (clearly identifiable), n = no identifiable foliation, w = weak foliation (not good), s = strong foliation (good), x = disturbed sample.

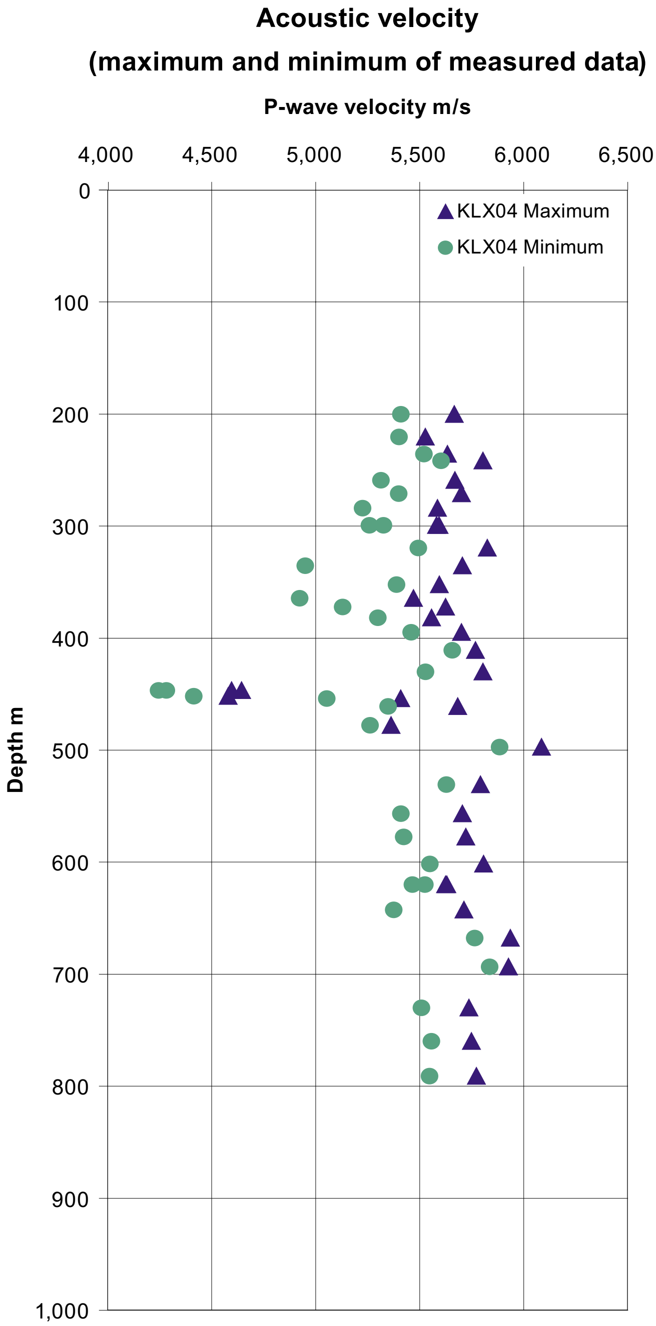

Figure 5-1. *Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KLX04A.*

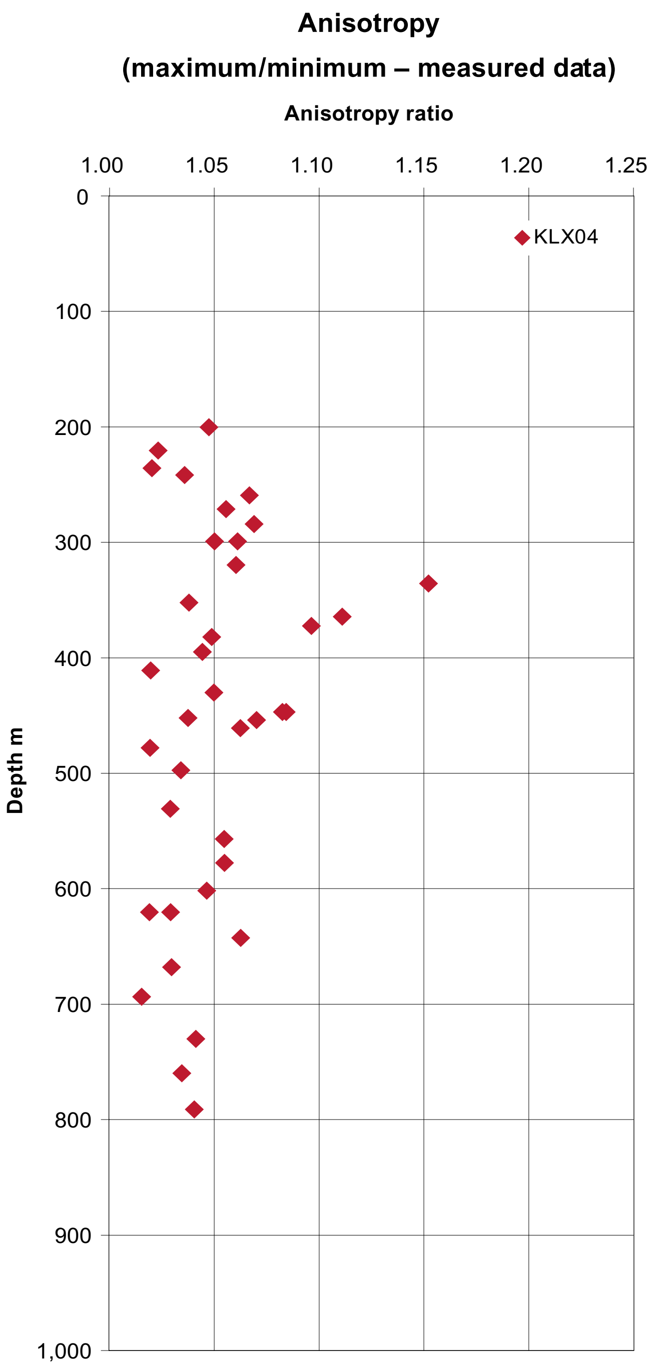

Figure 5-2. *Measured values of acoustic velocities anisotropy plotted versus borehole length in KLX04A.*

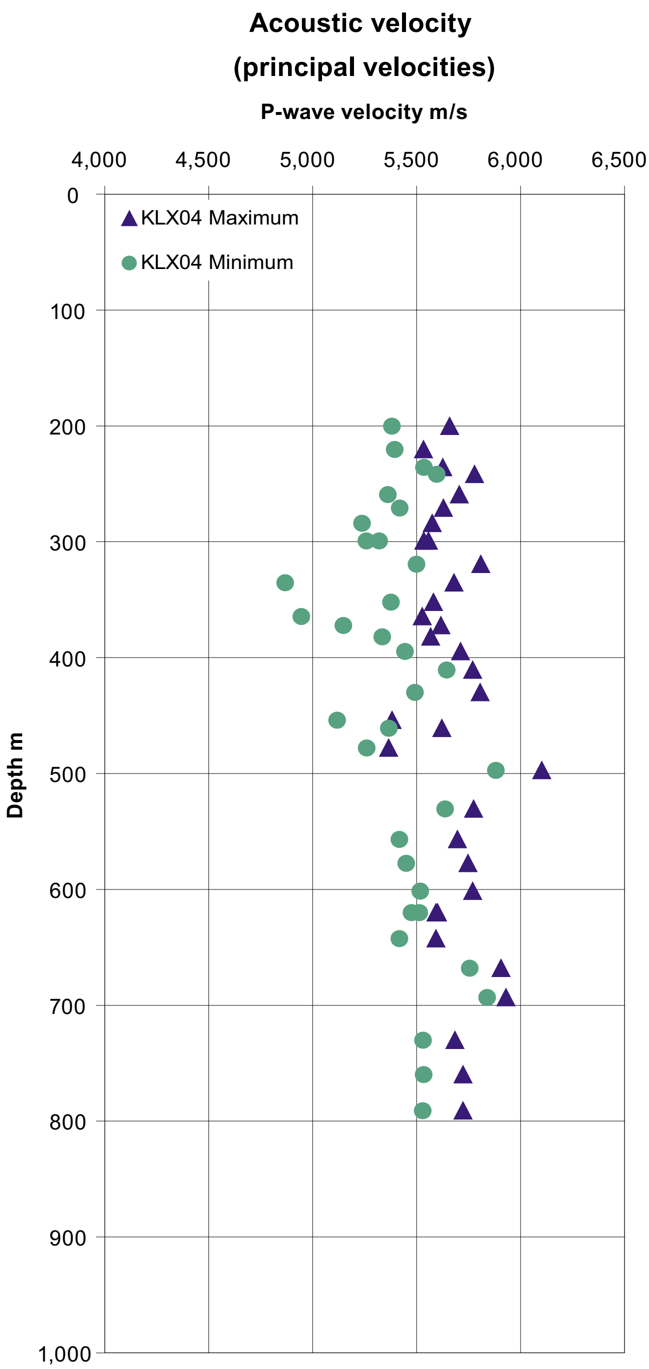

Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KLX04A.*

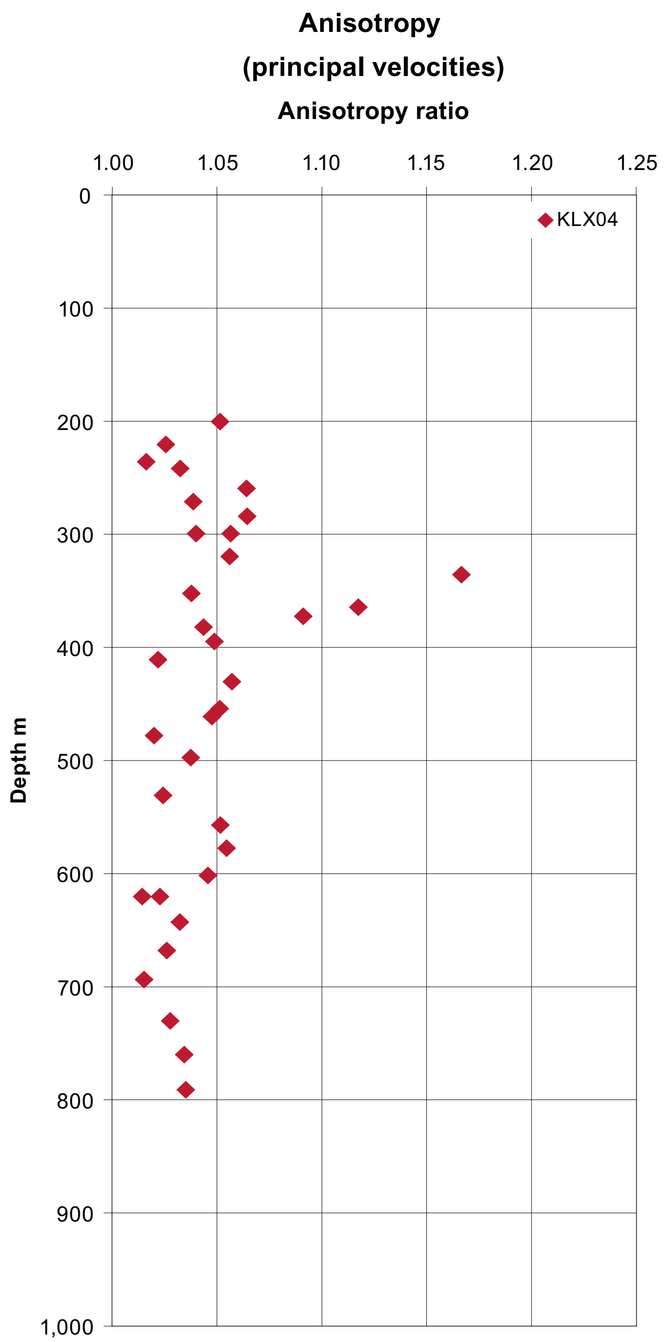

Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KLX04A.*

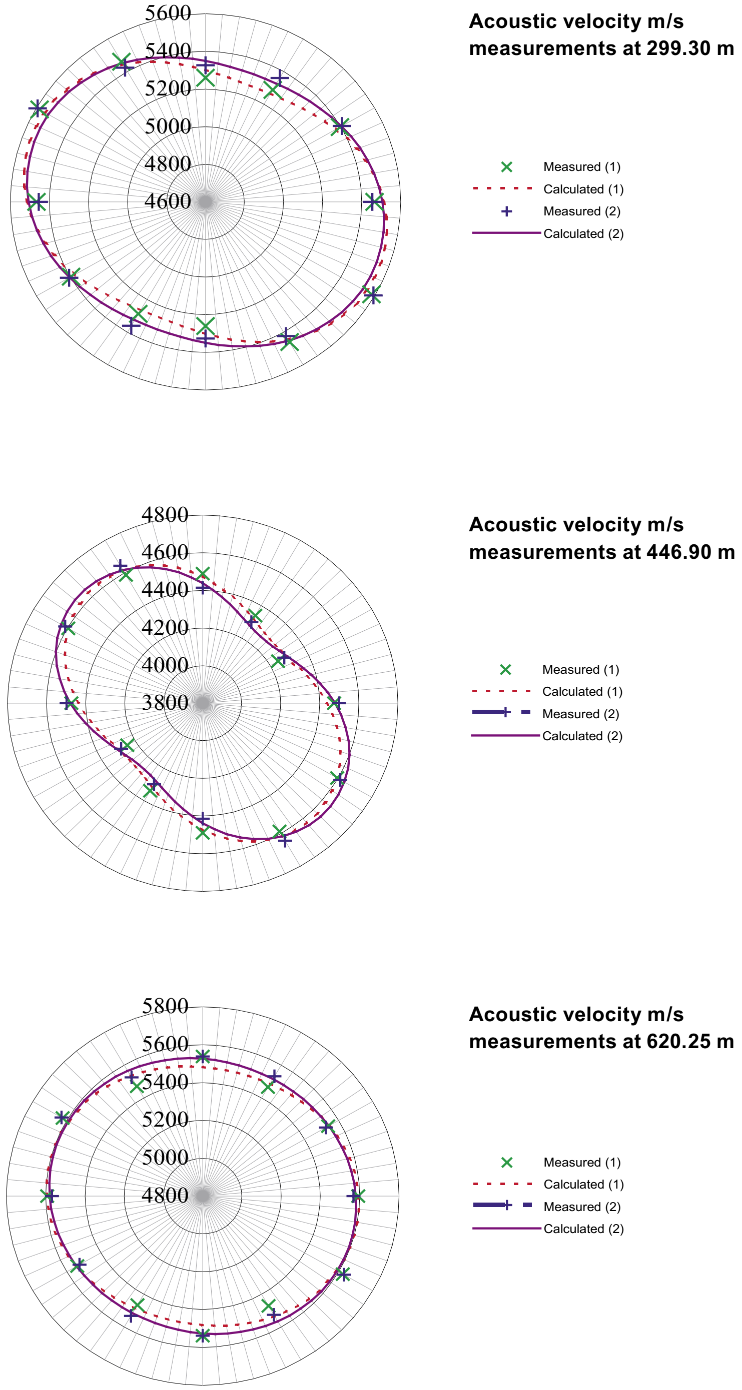

Figure 5-5. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at three different depths in borehole KLX04A.*

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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
20041006–0900 hrs	6,320	50.90	9.180	8.054	1.126
20041006–1300 hrs	6,320	50.90	9.175	8.054	1.121
20041006–1800 hrs	6,320	50.90	9.195	8.054	1.141
20041007–0900 hrs	6,320	50.90	9.170	8.054	1.116
20041007–1400 hrs	6,320	50.90	9.180	8.054	1.126
Average			9.180		1.126