P-06-33

Oskarshamn site investigation

Borehole KLX10

Determination of P-wave velocity, transverse borehole core

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Norwegian Geotechnical Institute, Oslo

October 2006

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Keywords: AP PS 400-05-109, Rock mechanics, P-wave velocity, Anisotropy.

Abstract

The Norwegian Geotechnical Institute has carried out P-wave measurements on drill cores from borehole KLX10 at Oskarshamn in January 2006. Thirty three P-wave velocity measurements have been carried out from a total of 900 m of core.

The results from the P-wave velocity measurements over the entire length of the borehole show that the maximum principal velocity, V_1, at the tested locations lies between 5,053–5,778 m/s with an anisotropy ratio of between 1.01 to 1.17. There was no readily apparent trend with depth. The average value of the maximum velocity V_1 is 5,591 m/s.

The anisotropy ratio of the principal velocities, V_1/V_3, is quite variable between 1.01 to 1.12, with an outlying value of 1.17 at 574.95 m, and an average value of 1.05. There was no readily apparent trend with depth.

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 and is therefore random and unknown.

Sammanfattning

Norges Geotekniske Institutt (NGI) har under Januar 2006 utfört P-vågsmätningar på borrkärnor från borrhål KLX10 i Oskarshamn. Sammanlagt är det utfört 33 stycken hastighetsbestämningar av P-vågor på kärnprover från ett ca 900 m lång kärnborrhål.

Resultaten från P-vågsmätningarna visade för hela borhålets längd, en maximalhastighet, V_1, som varierade mellan 5 053–5 778 m/s och en anisitropikvot som varierade mellan 1,01 till 1,17. Mätningarna visade inte någon speciell tendens mot djupet. Beräknat medelvärdet på maximalhastighet, V_1, är 5 591 m/s.

Anisotropikvoten, V_1/V_3, varierande mellan 1,01–1,12, med undantag av ett värde kring 1,17 på 574,95 m djup, och har ett medelvärde kring 1,05. Mätningarna visade ingen speciell tendens mot djupet.

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

Contents

1 Introduction

This document reports the data gained by the P-wave velocity measurements on cores from borehole KLX10, which is one of the activities performed within the site investigation at Oskarshamn. The work was carried out in accordance with activity plan AP PS-400-05-109. The controlling documents for performing this activity are listed in Table 1-1. Both activity plan and method descriptions are SKB's internal controlling documents.

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski of the Norwegian Geotechnical Institute (NGI) during the period 10th–12th of January 2006.

The original results are stored in the SICADA data base and are traceable by the activity plan number.

The location of borehole KLX10 is shown on Figure 1-1.

Table 1-1. Controlling documents for the performance of the activity.

Activity plan	Number	Version
KLX10 – Bergmekaniska Parameterbestämningar	AP PS 400-05-109	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för bestämning av P-vågens hastighet	SKB MD 190.002	1.0

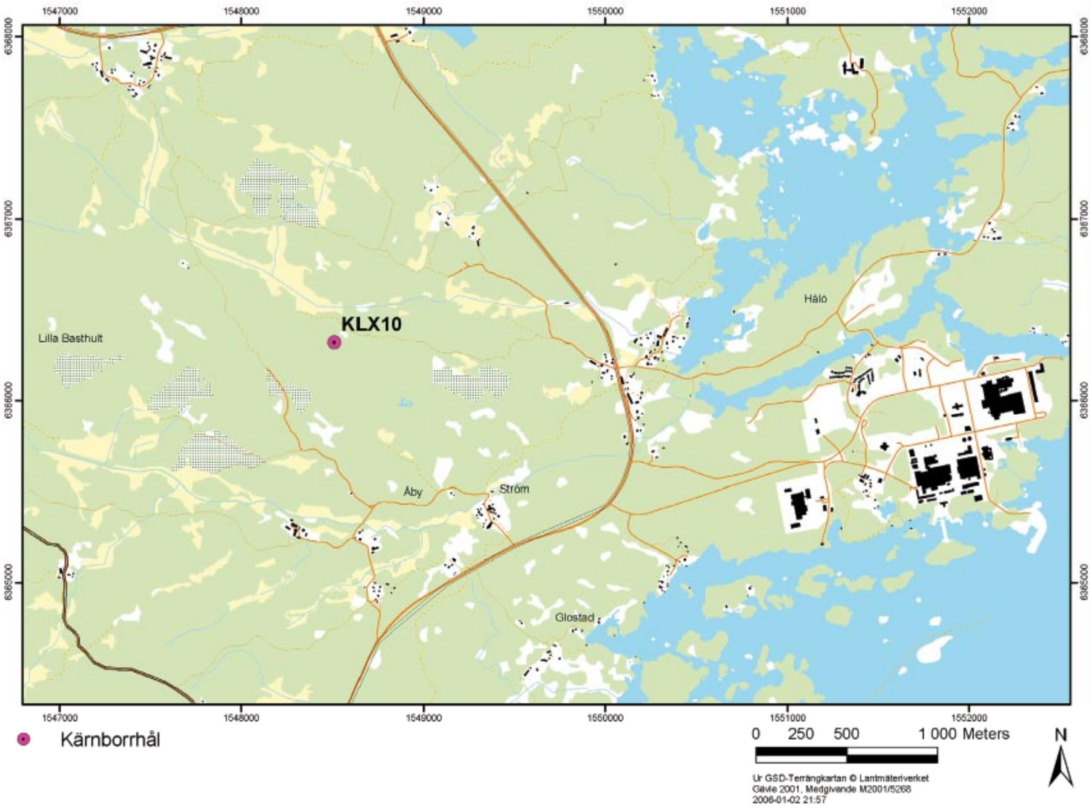

Figure 1-1. General overview over Oskarshamn site investigation area with borehole KLX10.

2 Objective and scope

The purpose of the testing is to determine the orientation and magnitude of the principal P-wave velocities (maximum and minimum) transverse to the axis of borehole rock cores. This is done by measuring the P-wave velocity across the core in different orientations and fitting these measurements to a numerical model to determine the principal velocities and their orientation.

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 Oskarshamn.

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
KLX10	30	33

3 Equipment

3.1 Description of equipment/interpretation tools

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 information provided by SKB /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 on 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 borehole core.

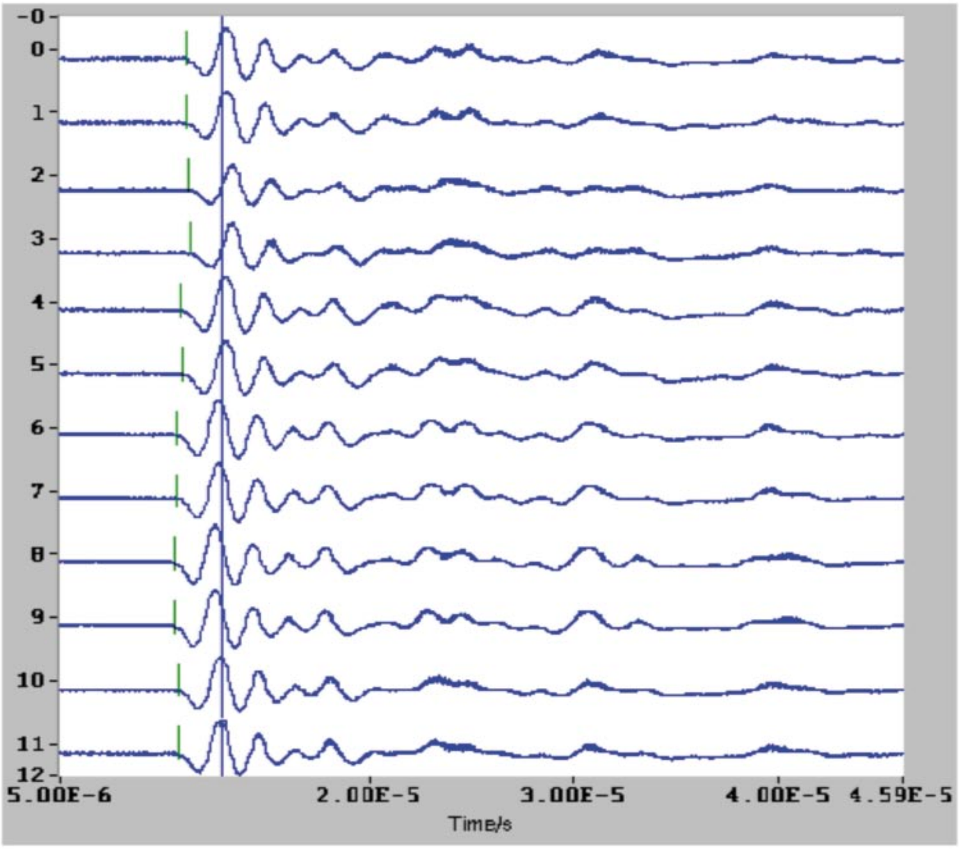

__Figure 3-3.__ Example traces from 12 measurements of P-wave travel time transverse borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.

4 Execution

4.1 General

Execution of the tests was in accordance with SKB Method Description number SKB MD 190.002 – Metodbeskrivning för bestämning av P-vågens hastighet (SKB internal document).

4.2 Preparations

Thirty core specimens of length ca 200–500 mm and diameter about 50 mm were selected from borehole KLX10 while the complete length of the borehole (depth 101.13 m–1,001.20 m) was displayed on the racks in the core shed at Oskarshamn. The specimens were selected together by NGI and Björn Ljunggren representing SKB.

These specimens represent the Ävrö granite, with some veins of diorite-gabbro, fine grained granite, fine grained diorite-gabbro and fine grained dioritoid 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.

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 therefore 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.

4.3 Execution of field work

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 length 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.

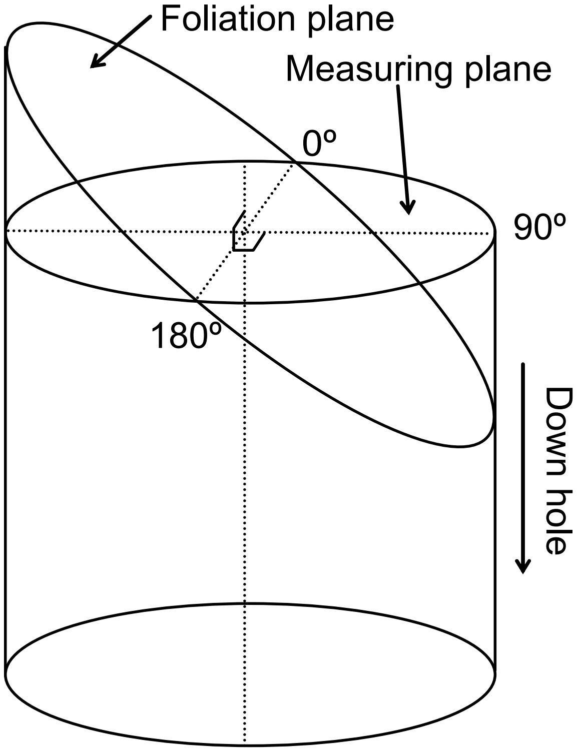

Figure 4-1. *Orientation of measurements.*

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.

4.4 Data handling/post processing

The traces and time picks (see Figure 3-3) on the oscilloscope were saved as a datafile for each specimen for quality control purposes only. The raw time pick data was read off, the average taken and entered manually on a paper form and in a spreadsheet where the calibration correction was applied. The corrected data was copied to another spreadsheet where the measurement raw data was processed to determine the magnitude and the orientation of the principal velocities and diagrams of the velocities, anisotropy and orientation against depth were drawn.

Tests on specimens from three depths were repeated in order to determine the repeatability of the results. The data was processed in the same spreadsheet and diagrams to show the comparison were drawn.

The processed data of magnitude and orientation of the principal velocities was copied to a third spreadsheet for reporting to the SICADA database.

4.5 Analyses and interpretations

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:

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

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, V_1, V_3, θ_{V1} and θ_{V3}. were determined from the Eigen values and vectors of the 2D tensor matrix:

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

The results are reported as the maximum principal velocity, V_1, the minimum principal velocity, V_3, the anisotropy ratio, V_1/V_3, and the orientations of the principal velocities with respect to the foliation direction in the plane perpendicular to the core sample, θ_{V1} and θ_{V3}.

In cases where the foliation could not be identified the orientation is random and unknown. If the core is later oriented the orientation of the principal velocities could be determined from the marks on the core.

4.6 Nonconformities

Tests were made at 30° intervals around the core instead of 45° intervals, which were suggested in the Method Description. This provides more data for the regression analysis, and thereby a more accurate determination of the magnitudes and orientations of the principal velocities and the errors. This was the only nonconformity to the controlling documents.

5 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 ratio are shown diagrammatically versus borehole length in Figures 5-1 and 5-2.

Table 5-1. Measurements of acoustic velocity, transverse core in borehole KLX10, Oskarshamn. (Orientation clockwise looking down hole, 0° is parallel with foliation where identified.)

Depth m	Diameter mm	Corrected time, m/S						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°	
198.70	47.61	8.71	8.66	8.88	8.99	8.61	8.55	5,466	5,497	5,361	5,295	5,529	5,568	1.05
221.20	50.21	9.09	8.79	8.83	8.88	8.94	9.35	5,523	5,712	5,686	5,654	5,616	5,370	1.06
276.80	50.29	8.76	8.80	8.93	9.13	9.07	8.91	5,740	5,714	5,631	5,508	5,544	5,644	1.04
293.25	50.32	9.13	9.08	9.04	9.05	8.95	9.27	5,511	5,541	5,566	5,560	5,622	5,428	1.04
317.54	50.22	8.96	8.91	8.90	8.83	8.71	8.85	5,604	5,636	5,642	5,687	5,765	5,674	1.03
356.75	49.98	8.91	8.75	8.80	8.73	8.61	8.92	5,609	5,711	5,679	5,725	5,804	5,603	1.04
381.15	49.89	8.82	9.21	9.08	8.88	8.69	8.76	5,656	5,416	5,494	5,618	5,741	5,695	1.06
410.70	49.96	9.34	9.48	9.43	9.54	9.45	9.53	5,349	5,270	5,298	5,236	5,286	5,242	1.02
442.20	50.11	9.29	9.30	9.25	9.54	9.35	9.39	5,394	5,388	5,417	5,252	5,359	5,336	1.03
469.10	50.21	9.26	9.17	9.24	9.28	9.27	9.19	5,422	5,475	5,434	5,410	5,416	5,463	1.01
500.15	50.07	10.57	10.15	9.99	10.14	10.84	11.21	4,737	4,933	5,012	4,937	4,619	4,466	1.12
521.55	50.01	8.92	9.13	9.49	9.91	9.56	9.14	5,606	5,477	5,269	5,046	5,231	5,471	1.11
530.55	49.74	9.05	8.97	8.93	8.95	9.09	9.24	5,496	5,545	5,569	5,557	5,471	5,383	1.03
544.70	49.84	9.46	9.08	9.20	9.30	9.32	9.46	5,268	5,489	5,417	5,359	5,347	5,268	1.04
560.50	49.85	9.51	9.74	9.56	9.07	9.15	9.20	5,241	5,118	5,214	5,496	5,448	5,418	1.07
574.95	49.96	10.45	11.13	10.63	9.91	9.53	9.57	4,780	4,488	4,700	5,041	5,242	5,220	1.17
591.90	50.07	9.38	9.52	9.39	9.31	9.13	9.17	5,337	5,259	5,332	5,378	5,484	5,460	1.04
604.85	50.09	9.15	8.97	9.07	9.54	9.80	9.29	5,474	5,584	5,522	5,250	5,111	5,391	1.09
620.55	49.92	9.02	8.90	9.30	9.50	9.50	9.11	5,534	5,608	5,367	5,254	5,254	5,479	1.07
636.60	49.98	8.62	8.76	9.26	9.31	9.22	8.90	5,798	5,705	5,397	5,368	5,420	5,615	1.08
650.35	49.99	9.15	8.93	8.66	8.78	8.81	9.09	5,463	5,597	5,772	5,693	5,674	5,499	1.06
665.95	50.13	8.73	8.92	9.01	9.20	9.04	8.88	5,742	5,619	5,563	5,448	5,545	5,645	1.05
679.95	50.13	9.33	9.02	8.88	8.80	8.73	9.00	5,373	5,557	5,645	5,696	5,742	5,570	1.07
695.23	50.11	9.09	9.24	9.15	9.10	9.02	8.78	5,512	5,423	5,476	5,506	5,555	5,707	1.05
710.28	50.12	8.88	8.79	8.78	8.89	8.90	8.95	5,644	5,701	5,708	5,637	5,631	5,600	1.02
726.10	50.18	8.84	9.00	8.90	8.87	8.92	8.88	5,676	5,575	5,638	5,657	5,625	5,650	1.02
739.75	50.24	8.78	8.99	9.00	9.10	9.11	9.24	5,722	5,588	5,582	5,520	5,514	5,437	1.05
755.35	50.28	9.03	9.10	9.16	9.41	9.14	8.97	5,568	5,525	5,489	5,343	5,501	5,605	1.05
772.88	50.31	9.01	9.12	9.20	9.40	9.28	8.94	5,583	5,516	5,468	5,352	5,421	5,627	1.05
785.20	50.31	9.85	10.16	9.79	9.27	9.36	9.54	5,107	4,951	5,138	5,427	5,375	5,273	1.10
276.80	50.29	8.82	8.93	8.95	9.07	9.10	9.02	5,701	5,631	5,618	5,544	5,526	5,575	1.03
560.50	49.86	9.39	9.57	9.46	8.97	8.96	9.04	5,309	5,210	5,270	5,558	5,564	5,515	1.07
772.88	50.29	9.01	9.06	9.19	9.43	9.17	8.82	5,581	5,550	5,472	5,333	5,484	5,701	1.07

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 generally not identified and the orientation of the tests is therefore random and unknown and the orientation of the maximum velocity is therefore not reported.

The results of calibration determinations for the system are shown in Appendix 1.

The results are also reported to SICADA.

Table 5-2. Determinations of principal velocity and orientation, transverse core in borehole KLX10, Oskarshamn. (Orientation clockwise looking down hole, 0° is parallel with foliation where identified.)

Depth m	Maximum velocity V_1 m/s	Orientation θ_{V1}	Minimum velocity V_3 m/s	Orientation θ_{V3}	Anisotropy	Foliation
198.70	5,563	160°	5,343	70°	1.04	n
221.20	5,737	60°	5,450	150°	1.05	n
276.80	5,747	10°	5,513	100°	1.04	n
293.25	5,593	80°	5,483	170°	1.02	n
317.54	5,732	115°	5,604	25°	1.02	n
356.75	5,755	90°	5,622	0°	1.02	n
381.15	5,755	135°	5,452	45°	1.06	n
410.70	5,308	10°	5,252	100°	1.01	n
442.20	5,407	20°	5,308	110°	1.02	n
469.10	5,457	10°	5,416	100°	1.01	n
500.15	5,053	55°	4,514	145°	1.12	n
521.55	5,612	0°	5,088	90°	1.10	n
530.55	5,588	60°	5,419	150°	1.03	n
544.70	5,447	55°	5,268	145°	1.03	n
560.50	5,509	120°	5,135	30°	1.07	n
574.95	5,301	125°	4,523	35°	1.17	n
591.90	5,481	125°	5,269	35°	1.04	n
604.85	5,607	25°	5,170	115°	1.08	n
620.55	5,601	10°	5,232	100°	1.07	n
636.60	5,778	0°	5,323	90°	1.09	n
650.35	5,763	80°	5,470	170°	1.05	n
665.95	5,718	0°	5,470	90°	1.05	n
679.95	5,751	95°	5,443	5°	1.06	n
695.23	5,636	140°	5,423	50°	1.04	n
710.28	5,705	45°	5,602	135°	1.02	n
726.10	5,655	135°	5,619	45°	1.01	n
739.75	5,644	25°	5,477	115°	1.03	n
755.35	5,607	170°	5,403	80°	1.04	n
772.88	5,615	175°	5,373	85°	1.05	f
785.20	5,435	115°	4,989	25°	1.09	n
276.80	5,675	15°	5,523	105°	1.03	n Repeat
560.50	5,605	120°	5,204	30°	1.08	n Repeat
772.88	5,660	170°	5,380	80°	1.05	n Repeat

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

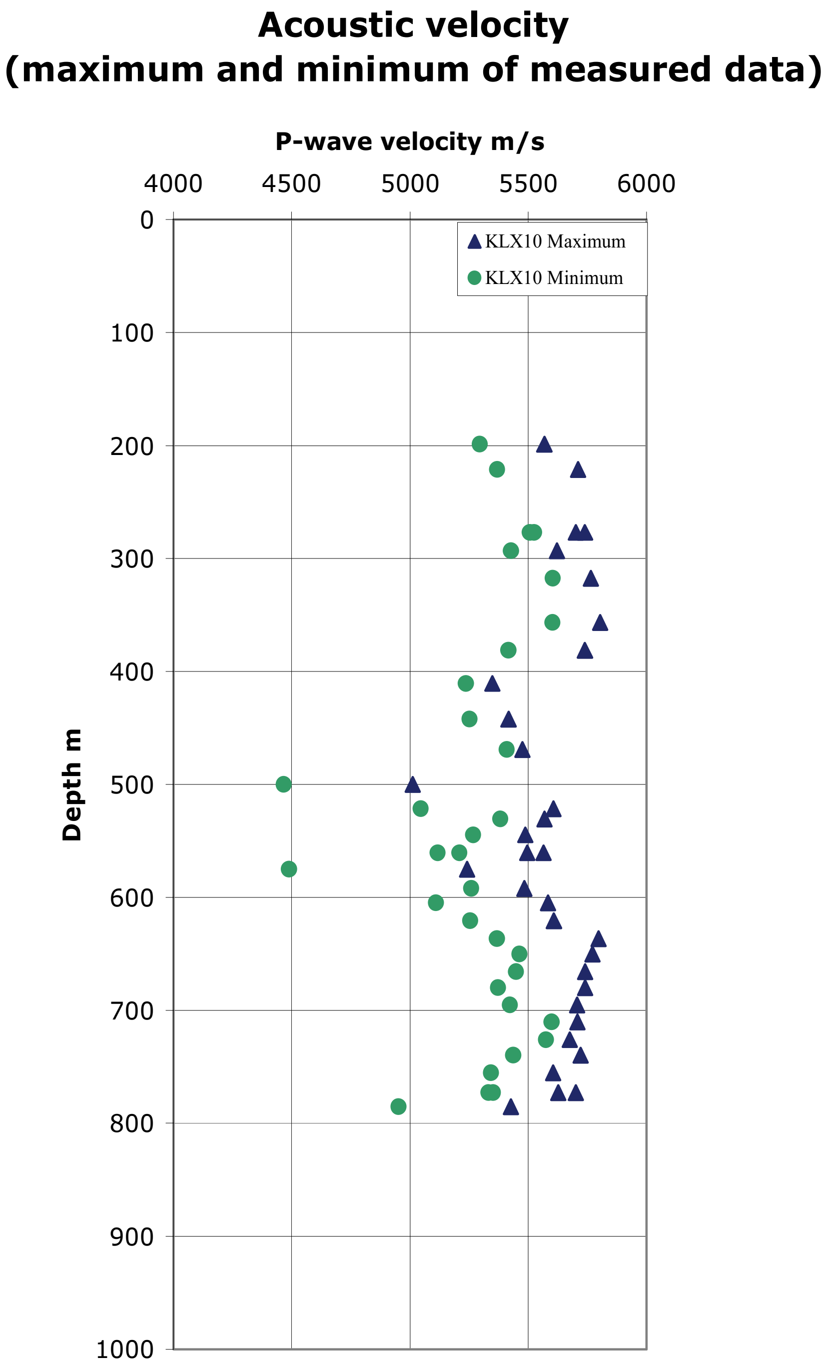

Figure 5-1. *Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KLX10.*

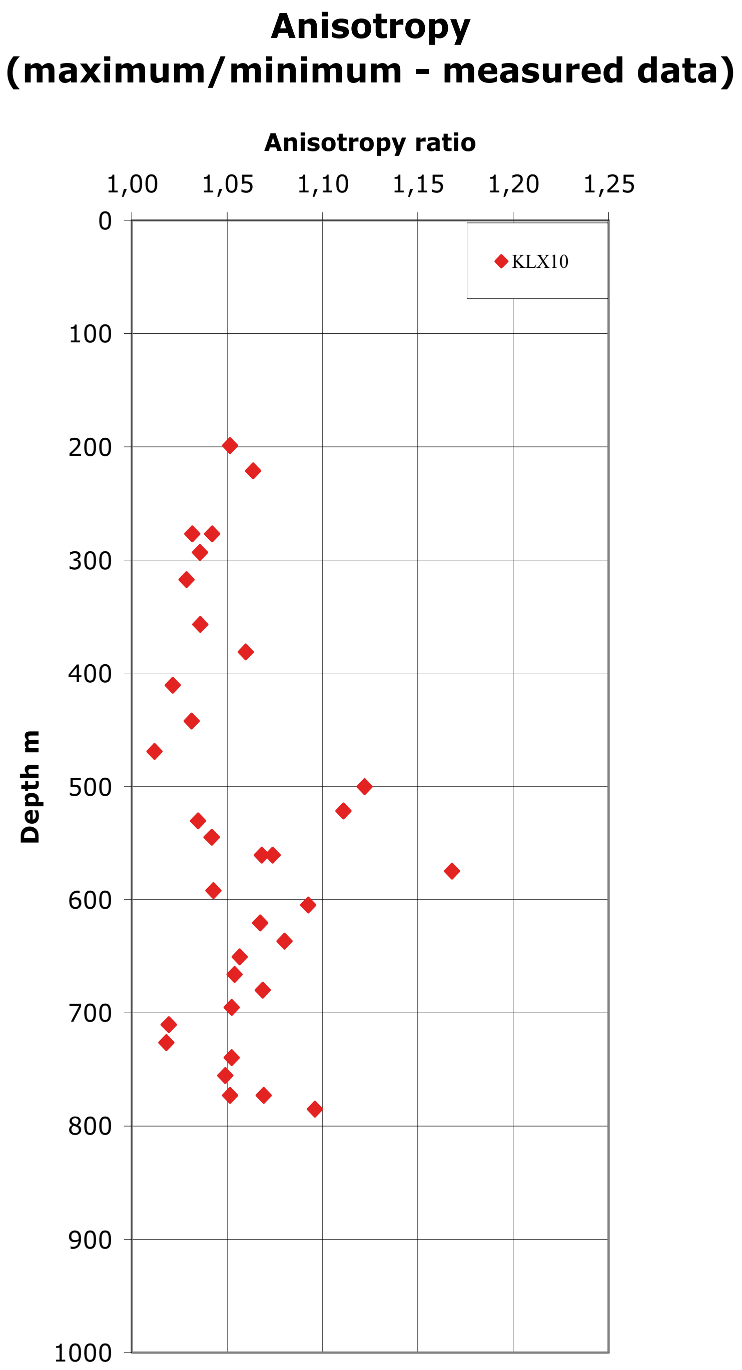

Figure 5-2. *Measured values of acoustic velocities anisotropy plotted versus borehole length in KLX10.*

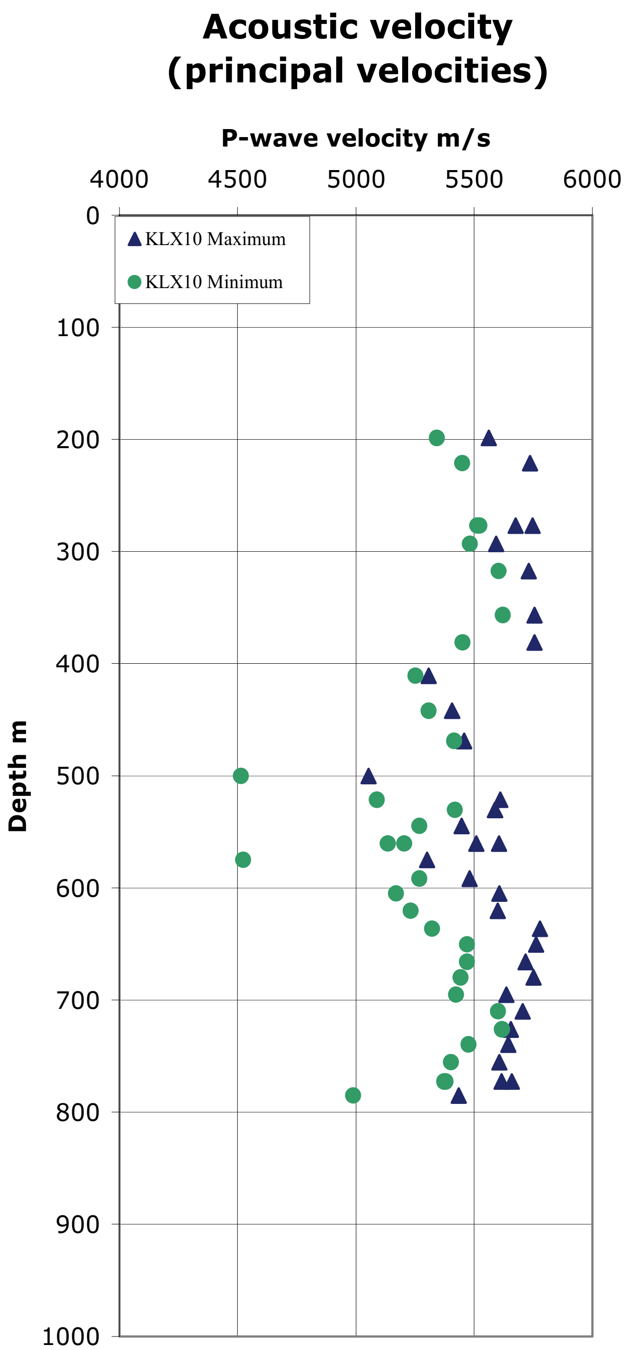

***Figure 5-3.** Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KLX10.*

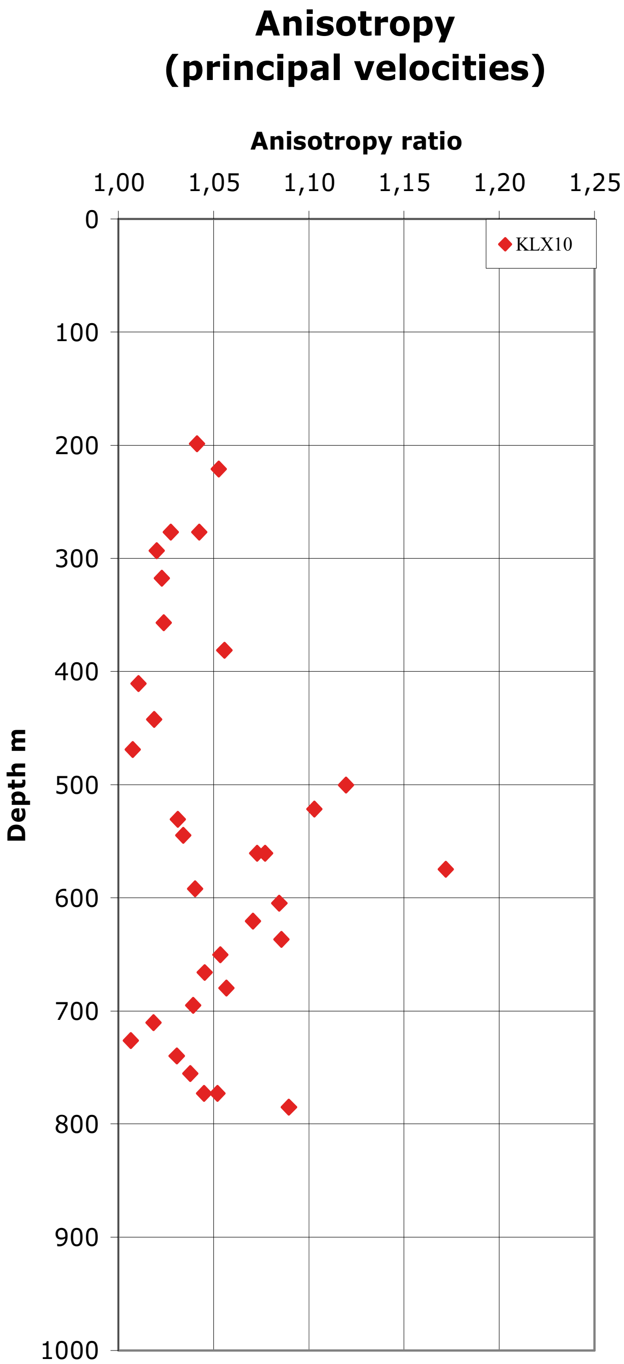

Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KLX10.*

6 Summary and discussions

6.1 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 three locations, 276.80 m, 560.50 m and 772.88 m, after the first eries 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 ± 0.01 mm which gives an error of about ± 1 m/s.

The differences between the two sets of measurements are summarised in Table 6-1.

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 276.80 m the maximum difference was 39 m/s, at 560.50 m the maximum difference was 68 m/s, and at 772.88 m the maximum difference was 74 m/s, see Figure 6-1.

Typically in the entire series of tests, the average deviation between the measured value and the model fit is about 0.58% (about 33 m/s), with a maximum error of 1.85% (about 104 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 2003abcdefgh, 2004ab, 2005abcde, 2006/. 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.

Table 6-1. Differences between two sets of velocity measurements at the same depth.

Depth m	Maximum difference in measured velocity m/s	Difference in anisotropy ratio of principal velocities	Difference in orientation of the maximum principal velocity
276.80	83	0.02	7°
560.50	117	0.00	2°
772.88	74	0.01	6°

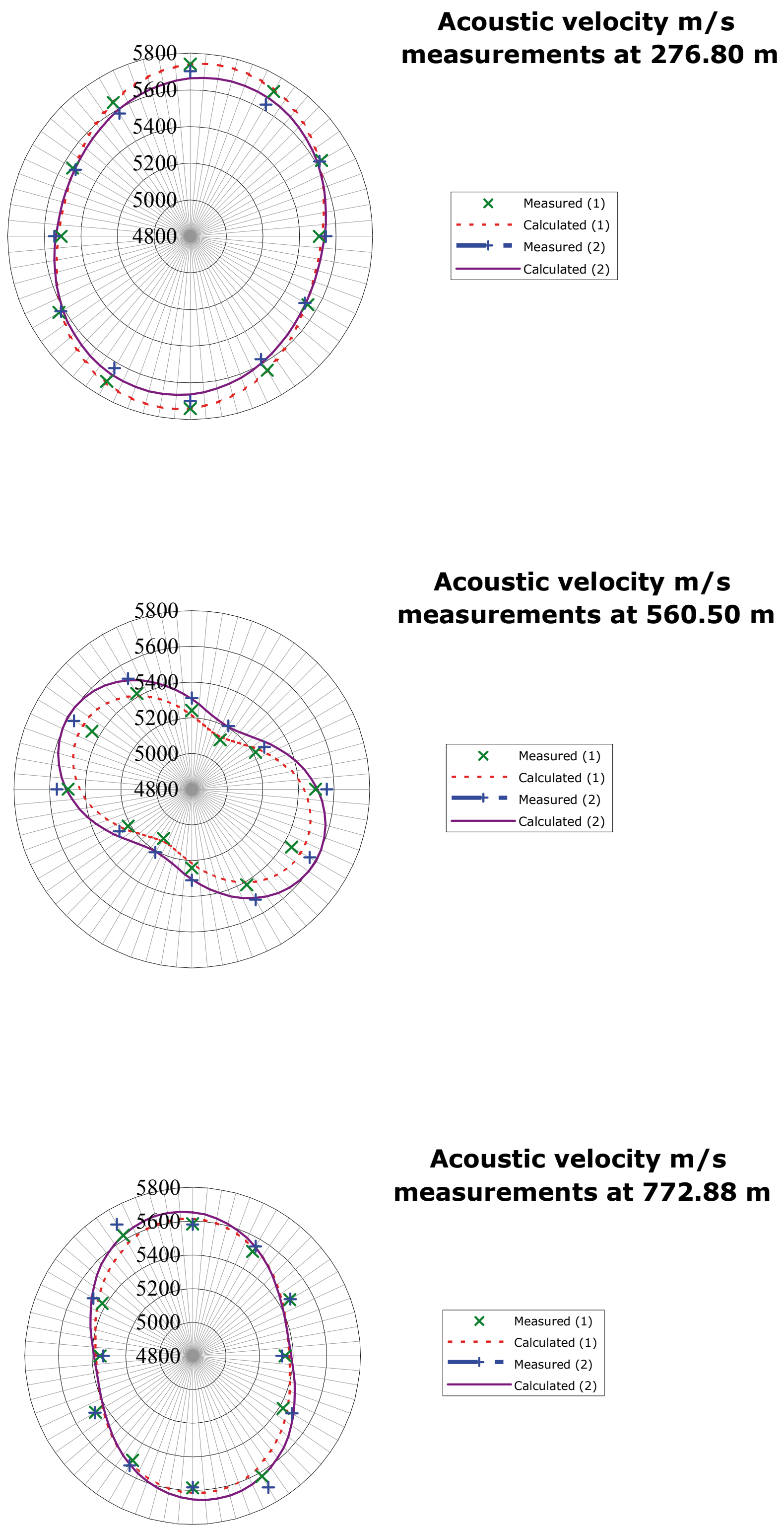

Figure 6-1. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at three different depths in borehole KLX10.*

6.2 Conclusions

The results from the P-wave velocity measurements over the entire length of the borehole show that the maximum principal velocity, V_1, at the tested locations lies between 5,053–5,778 m/s with an anisotropy ratio of between 1.01 to 1.17. There was no readily apparent trend with depth. The average value of the maximum velocity V_1 is 5,591 m/s.

The anisotropy ratio of the principal velocities, V_1/V_3, is quite variable between 1.01 to 1.12, with an outlying value of 1.17 at 574.95 m, and an average value of 1.05. There was no readily apparent trend with depth.

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 and is therefore random and unknown.

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Appendix 1

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	Time calculated µs	Time correction µs
20060110 – 1700 hrs	6,320	50.90	9.21	8.05	1.15
20060111 – 0900 hrs	6,320	50.90	9.24	8.05	1.18
20060111 – 1330 hrs	6,320	50.90	9.23	8.05	1.17
20060111 – 1700 hrs	6,320	50.90	9.24	8.05	1.19
20060112 – 0900 hrs	6,320	50.90	9.21	8.05	1.16
Average			**9.223**		**1.169**