P-06-273

Oskarshamn site investigation

Borehole KLX13A

Determination of P-wave velocity, transverse borehole core

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Norwegian Geotechnical Institute, Oslo

December 2006

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Keywords: AP PS 400-06-100, Rock mechanics, P-wave velocity, Anisotropy.

Abstract

The Norwegian Geotechnical Institute has carried out P-wave measurements on drill core samples from borehole KLX13A at Oskarshamn, Sweden, in September 2006. KLX13A has a total length of 593.64 m. Twenty-eight P-wave velocity measurements were carried out on 25 drill core samples from KLX13A.

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 5,416–6,097 m/s with an anisotropy ratio of between 1.00 and 1.05.

The maximum principal velocity, $V_{1,}$ lies between 5,811–5,938 m/s at 201–215 m. From 233–335 m there is a regular increasing trend between 5,582–6,075 m/s. Below 335 m there is a regular decreasing trend between 6,075–5,649 m/s, with an outlying value of 5,416 at 472 m.

The anisotropy ratio lies between 1.00 to 1.05, and with an average of 1.02. The ratio is quite variable, between 1.01–1.05 down to 398 m. Below this the ratio is quite consistent and generally between 1.01–1.02, with an outlying value of 1.05 at 587 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 utfört P-vågsmätningar på borrkärnor från borrhål KLX13A i Oskarshamn i September 2006. KLX13A har en total längd på ca 593,64 m. Sammanlagt har 28 stycken hastighetsbestämningar av P-vågor utförts på 25 kärnprover.

Resultaten från P-vågsmätningarna utförda längs hela borrkärnans längd visar att maximum hastigheten, V_1, varierar mellan 5 416–6 097 m/s och med en anisotropi som varierar mellan 1,00 och 1,05.

Den maximala huvudhastigheten, V_1, varierar mellan 5 811–5 938 m/s, från 201 till 215 m djup. Mellan 233–335 m djup är det en jämnt ökande trend, från 5 582 till 6 075 m/s. Under 335 m djup är det en jämnt minskande trend från 6 075 till 5 649 m/s, men med en avvikande hastighet på 5 416 m/s på 472 m djup

Anisotropiförhållandet varierar mellan 1,00 till 1,05, med ett medelvärde på 1,02. Ned till 398 m djup är anisotropiförhållandet relativt varierande, mellan 1,01 till 1,05 medan under 398 m djup är förhållandet relativt konstant, mellan 1,01 till 1,02, men med ett avvikande anisotropiförhållande på 1,05 på 587 m djup

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

Contents

1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on drill core samples from borehole KLX13A at Oskarshamn, Sweden. KLX13A is a conventional core drilled borehole with a total length of 593.64 m and a nominal diameter of 50 mm. The drill core diameter is about 50.5 mm. The samples selected for P-wave measurements were collected within the interval 100.36–593.64 m borehole length. All deep boreholes drilled in Oskarshamn up to September 2006 are shown in Figure 1-1. The work was carried out in accordance with activity plan AP PS 400-06-100. The SKB internal controlling documents for performance of this activity are presented in Table 1-1.

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski during the period September 26–27, 2006.

The original results for borehole KLX13A are stored in the primary data base (SICADA) and that they are traceable by the AP PS 400-06-100.

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

Activity Plan	Number	Version
KLX13A – Bergmekaniska parameterbestämningar	AP PS 400-06-100	1.0
Method descriptions	**Number**	**Version**
Bestämning av P-vågens hastighet	SKB MD 190.002.	2.0

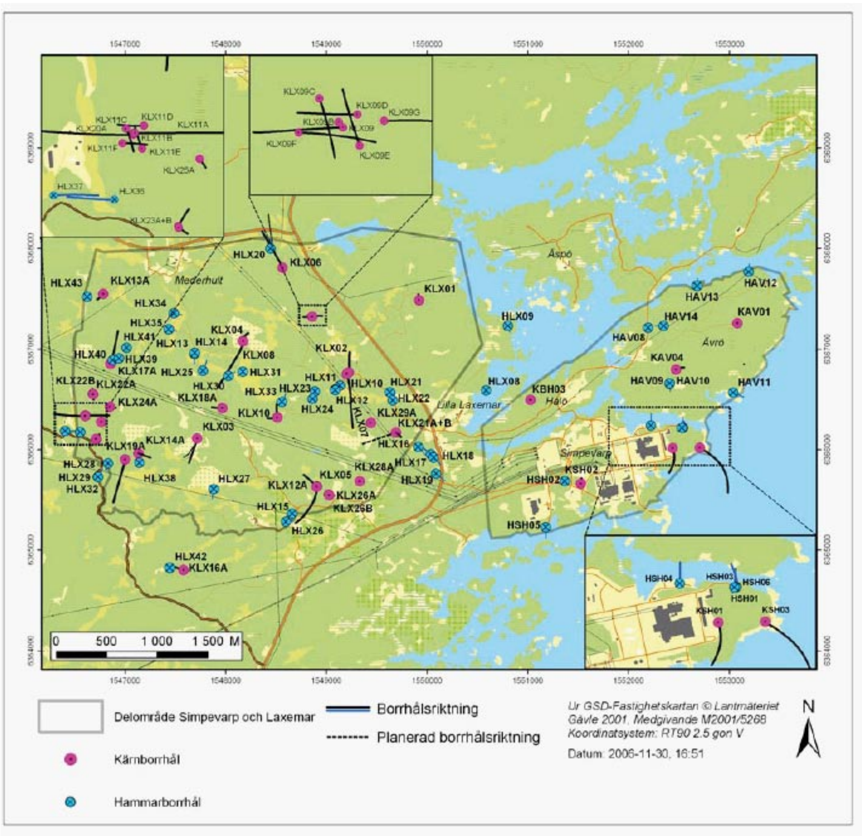

Figure 1-1. Location of all deep boreholes, including borehole KLX13A, drilled up to November 2006 at the Oskarshamn site.

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 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
KLX13A	25	28

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 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 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 a foliated drill core. The aluminium cylinder for calibration of the device is on the right.*

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

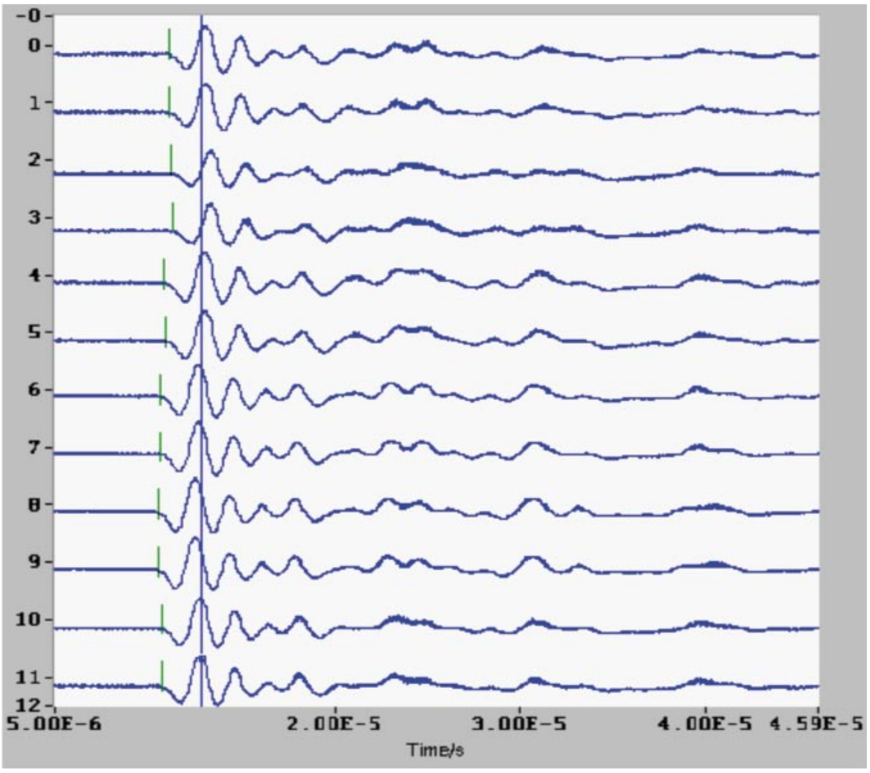

Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse a borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 General

Execution of the tests was in accordance with SKB Method Description number SKB MD 190.002 version 1.0 – *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 KLX13A while the complete length of the borehole (depth 100.36 m–593.64 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 Ävrö granite with veins of fine grained diorite-gabbro, and zones of diorite-gabbro encountered by 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.

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.

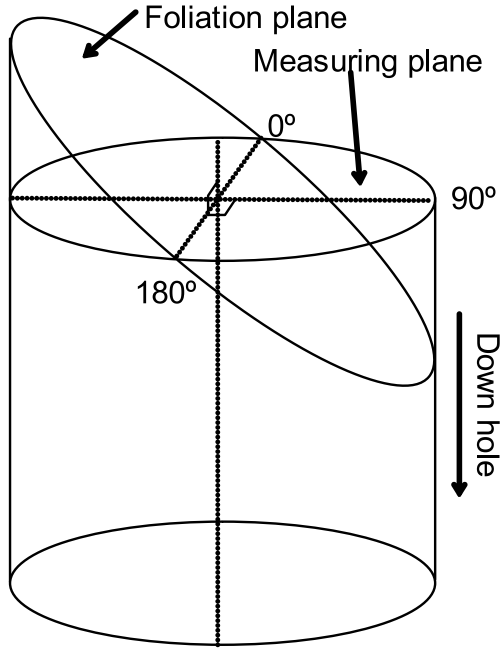

Figure 4-1. *Orientation of measurements.*

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

None.

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.

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. It may be seen from Table 5-2 that the calculated maximum principal velocity at depth 366.55 m is 6,063 m/s. This value is somewhat lower than the repeat value of 6,102 m/s at the same depth. The repeat values are basically to check the true measurements and in this case the difference in values is relatively small.

Table 5-1. Measurements of acoustic velocity transverse the drill core in borehole KLX13A, Oskarshamn. (Orientation clockwise looking down hole, 0° is parallel with foliation.)

Depth m	Diameter mm	Corrected time, µS Parallel foliation			Perpendicular foliation			Velocity m/S Parallel foliation			Perpendicular foliation			Anisot-ropy ratio	
		0°	30°	60°	90°	120°	150°	0°	30°	60°	90°	120°	150°		
201.20	50.02	8.56	8.69	8.69	8.57	8.63	8.66	5,843	5,756	5,756	5,837	5,796	5,776	1.02	
215.20	49.99	8.50	8.44	8.53	8.56	8.47	8.38	5,881	5,923	5,860	5,840	5,902	5,965	1.02	
233.10	50.01	8.76	8.97	9.08	9.01	8.95	8.90	5,709	5,575	5,508	5,550	5,588	5,619	1.04	
245.20	50.08	8.76	8.95	9.28	9.14	9.15	8.99	5,717	5,596	5,397	5,479	5,473	5,571	1.06	
260.20	50.14	9.05	8.99	8.97	9.03	9.05	8.90	5,540	5,577	5,590	5,553	5,540	5,634	1.02	
274.65	50.17	8.88	9.00	8.91	9.11	8.88	8.78	5,650	5,574	5,631	5,507	5,650	5,714	1.04	
290.35	50.20	8.79	8.77	8.74	8.71	8.60	8.62	5,711	5,724	5,744	5,763	5,837	5,824	1.02	
306.80	50.25	8.37	8.78	8.85	8.94	8.93	8.95	6,004	5,723	5,678	5,621	5,627	5,614	1.07	
319.20	50.28	8.76	8.93	8.80	8.58	8.65	8.52	5,740	5,630	5,714	5,860	5,813	5,901	1.05	
334.75	50.29	8.51	8.59	8.58	8.38	8.26	8.36	5,909	5,854	5,861	6,001	6,088	6,016	1.04	
352.80	50.12	8.43	8.43	8.35	8.47	8.48	8.37	5,945	5,945	6,002	5,917	5,910	5,988	1.02	
366.55	50.08	8.38	8.28	8.24	8.31	8.36	8.34	5,976	6,048	6,078	6,026	5,990	6,005	1.02	
379.35	50.15	8.37	8.35	8.49	8.38	8.43	8.40	5,992	6,006	5,907	5,984	5,949	5,970	1.02	
398.35	49.88	8.44	8.43	8.63	8.66	8.58	8.46	5,910	5,917	5,780	5,760	5,813	5,896	1.03	
411.70	49.80	8.29	8.19	8.14	8.38	8.38	8.37	6,007	6,081	6,118	5,943	5,943	5,950	1.03	
424.60	49.84	8.55	8.59	8.64	8.57	8.50	8.48	5,829	5,802	5,768	5,816	5,863	5,877	1.02	
441.40	49.94	8.65	8.55	8.48	8.49	8.35	8.59	5,773	5,841	5,889	5,882	5,981	5,814	1.04	
455.70	50.02	8.71	8.66	8.69	8.76	8.81	8.76	5,743	5,776	5,756	5,710	5,678	5,710	1.02	
471.75	50.00	9.23	9.27	9.35	9.40	9.51	9.34	5,417	5,394	5,348	5,319	5,258	5,353	1.03	
488.75	50.16	8.63	8.67	8.57	8.54	8.64	8.65	5,812	5,785	5,853	5,874	5,806	5,799	1.02	
511.30	49.75	8.49	8.43	8.38	8.45	8.42	8.43	5,860	5,902	5,937	5,888	5,909	5,902	1.01	
526.00	49.93	8.61	8.59	8.44	8.68	8.65	8.61	5,799	5,813	5,916	5,752	5,772	5,799	1.03	
534.25	49.85	8.59	8.50	8.56	8.74	8.39	8.65	5,803	5,865	5,824	5,704	5,942	5,763	1.04	
553.85	49.90	8.82	8.89	8.86	8.91	8.96	8.84	5,658	5,613	5,632	5,600	5,569	5,645	1.02	
586.90	50.01	8.84	8.82	8.65	8.61	9.09	8.99	5,657	5,670	5,781	5,808	5,502	5,563	1.06	
245.20	50.08	8.70	8.85	9.16	9.20	9.02	9.17	5,756	5,659	5,467	5,443	5,552	5,461	1.06	Repeat
366.55	50.09	8.25	8.26	8.20	8.19	8.29	8.24	6,071	6,064	6,109	6,116	6,042	6,079	1.01	Repeat
488.75	50.16	8.66	8.68	8.53	8.51	8.58	8.75	5,792	5,779	5,880	5,894	5,846	5,733	1.02	Repeat

Table 5-2. Determinations of principal velocity and orientation transverse the drill core in borehole KLX13A, 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 ratio	Foliation	
201.20	5,811	135°	5,777	45°	1.01	n	
215.20	5,938	165°	5,853	75°	1.01	n	
233.10	5,669	165°	5,514	75°	1.03	n	
245.20	5,668	175°	5,409	85°	1.05	n	
260.20	5,582	175°	5,563	85°	1.00	n	
274.65	5,688	160°	5,554	70°	1.02	n	
290.35	5,827	125°	5,707	35°	1.02	n	
306.80	5,852	10°	5,570	100°	1.05	n	
319.20	5,890	125°	5,663	35°	1.04	n	
334.75	6,075	125°	5,835	35°	1.04	n	
352.80	5,971	25°	5,932	115°	1.01	n	
366.55	6,063	60°	5,978	150°	1.01	n	
379.35	5,991	0°	5,946	90°	1.01	n	
398.35	5,933	0°	5,759	90°	1.03	n	
411.70	6,097	40°	5,917	130°	1.03	n	
424.60	5,877	140°	5,775	50°	1.02	n	
441.40	5,938	95°	5,789	5°	1.03	n	
455.70	5,775	30°	5,683	120°	1.02	n	
471.75	5,416	15°	5,280	105°	1.03	n	
488.75	5,856	80°	5,787	170°	1.01	n	
511.30	5,917	75°	5,881	165°	1.01	n	
526.00	5,854	45°	5,763	135°	1.02	n	
534.25	5,828	170°	5,805	80°	1.00	n	
553.85	5,649	10°	5,590	100°	1.01	n	
586.90	5,790	60°	5,537	150°	1.05	n	
245,20	5,682	10°	5,431	100°	1.05	n	Repeat
366,55	6,102	70°	6,058	160°	1.01	n	Repeat
488,75	5,894	80°	5,747	170°	1.03	n	Repeat

f=foliation (clearly identifiable)

n=no identifiable foliation

w=weak foliation (not good)

s=strong foliation (good)

x=disturbed sample

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, where they are traceable by the Activity Plan number AP PS 400-06-100.

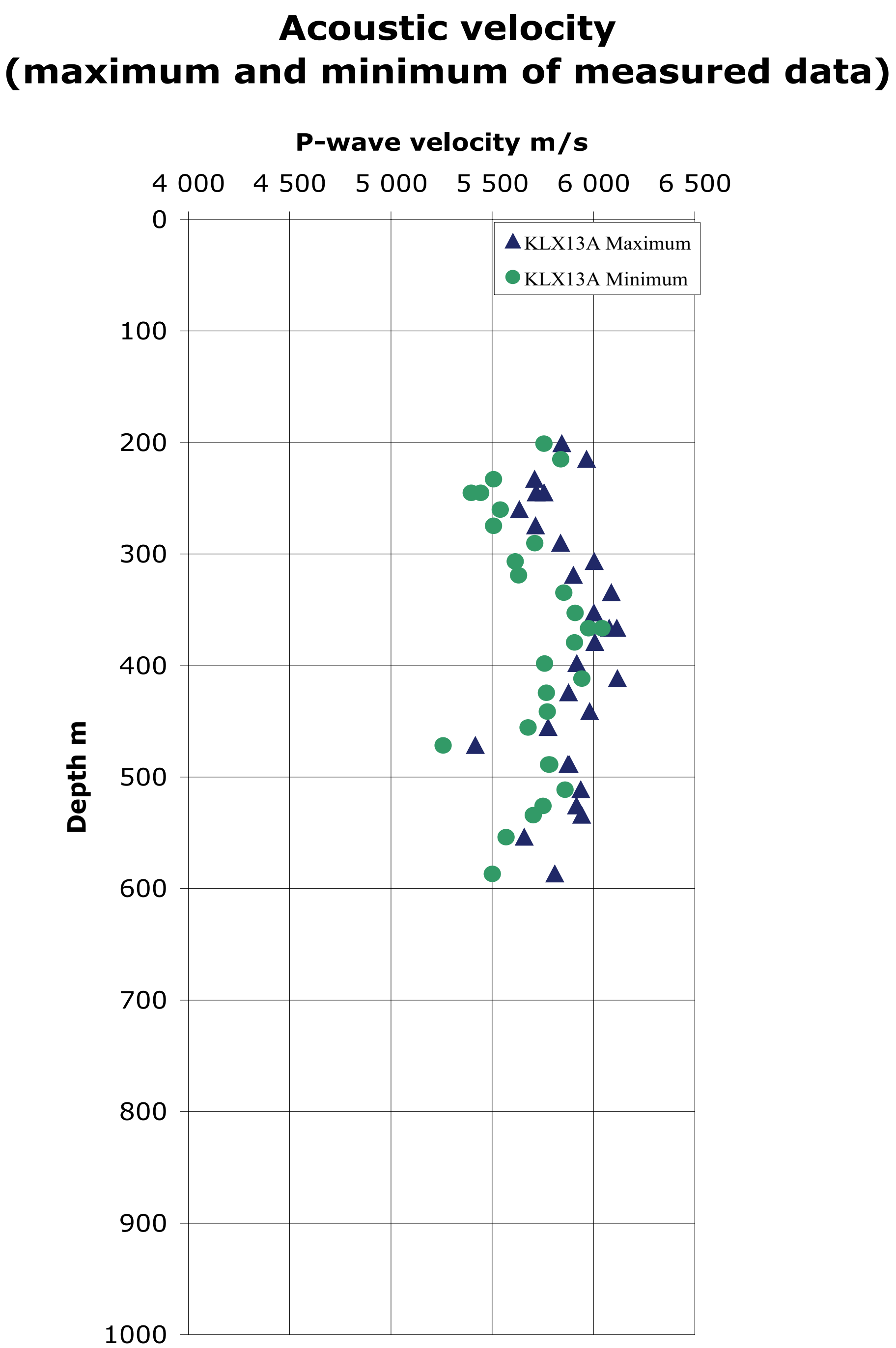

Figure 5-1. Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KLX13A.

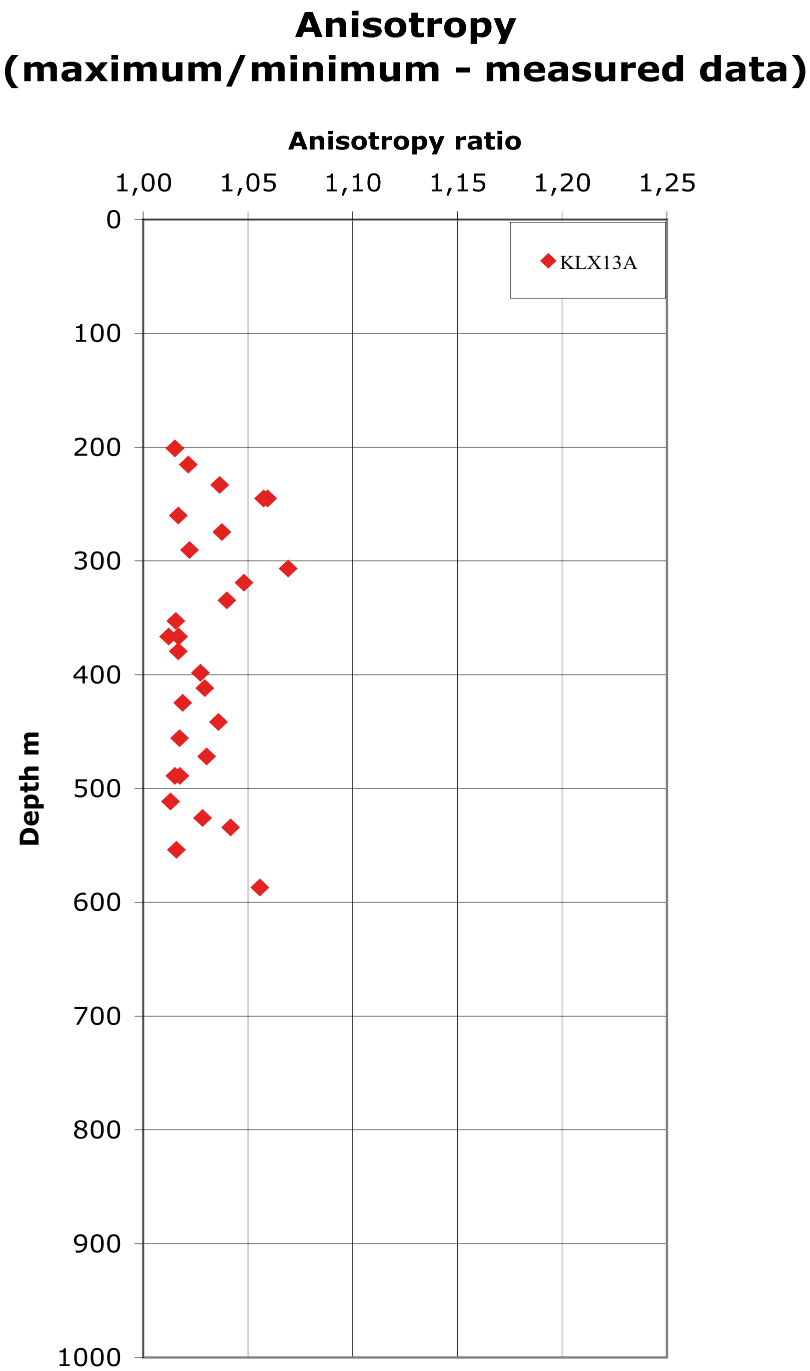

Figure 5-2. *Measured values of acoustic velocity anisotropy plotted versus borehole length in KLX13A.*

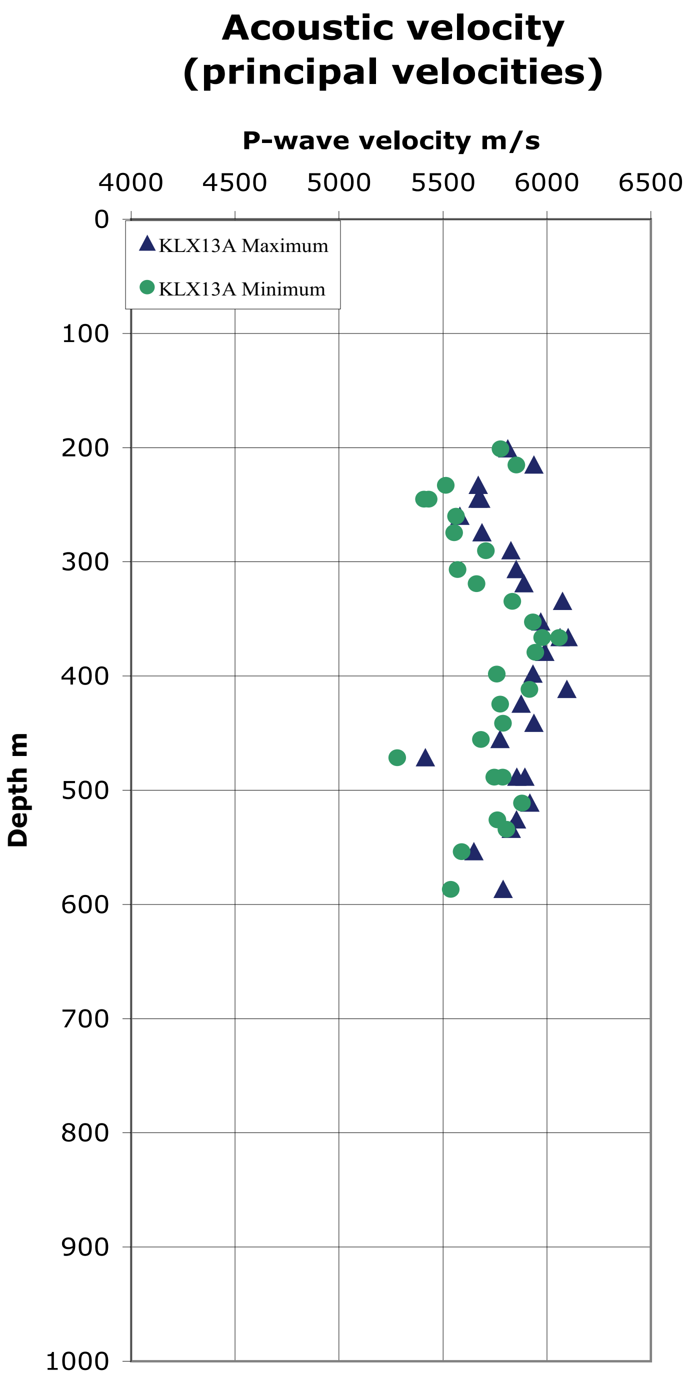

Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KLX13A.*

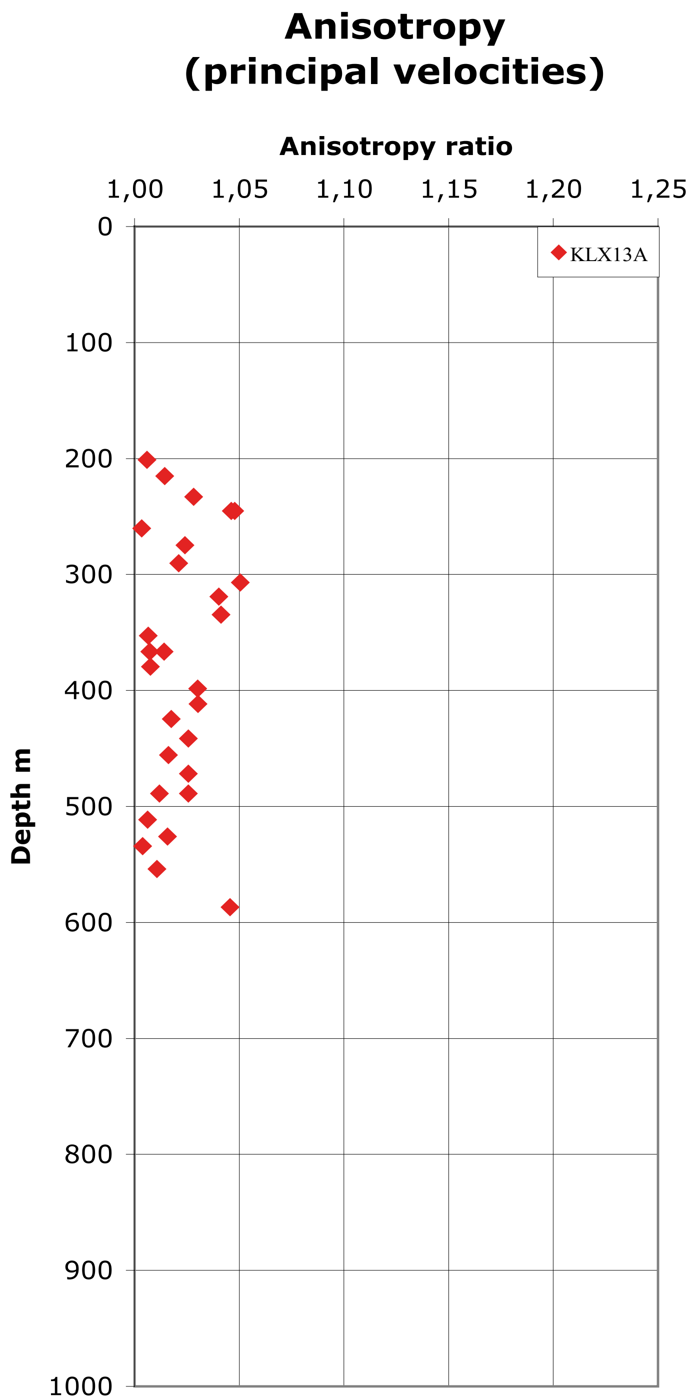

Figure 5-4. Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KLX13A.

6 Summary and discussions

6.1 Accuracy and repeatability

Calibration tests on an aluminium cylinder indicated a noise factor of ±0.02 µs in determination of the time pick, equivalent to differences in velocity of about ±12 m/s. Some of this noise may be explained by temperature variations, thickness of the 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, 245.20 m, 366.55 m and 488.75 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.

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 245.20 m the maximum difference was 128 m/s, 33 m/s at 366.55 m, and finally 41 m/s at 488.75 m, see Figure 6-1.

Typically in the entire series of tests, the average deviation between the measured value and the model fit is about 0.50% (about 30 m/s), with a maximum error of 2.7% (about 155 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, 2006abc/. 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 larger 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 location.

Depth (borehole length)	Maximum difference in measured velocity	Difference in anisotropy ratio of principal velocities	Difference in orientation of the maximum principal velocity
245.20 m	109 m/s	0.00	11°
366.55 m	95 m/s	0.01	10°
488.75 m	66 m/s	0.01	1°

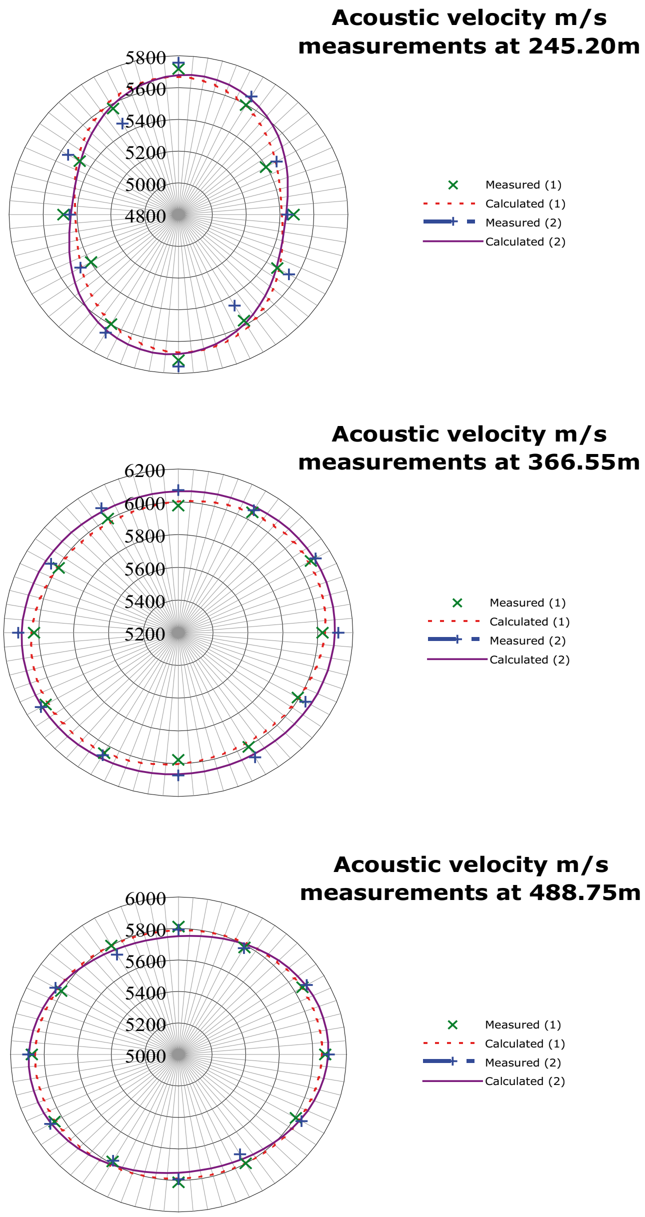

Figure 6-1. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at three different depths in borehole KLX13A.*

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 5,416–6,097 m/s with an anisotropy ratio of between 1.00 and 1.05.

The maximum principal velocity, $V_{1,}$ lies between 5,811–5,938 m/s at 201–215 m. From 233–335 m there is a regular increasing trend between 5,582–6,075 m/s. Below 335 m there is a regular decreasing trend between 6,075–5,649 m/s, with an outlying value of 5,416 at 472 m.

The anisotropy ratio lies between 1.00 to 1.05, and with an average of 1.02. The ratio is quite variable, between 1.01–1.05 down to 398 m. Below this the ratio is quite consistent and generally between 1.01–1.02, with an outlying value of 1.05 at 587 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.

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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**	**Calculated µs**	**Correction µs**
2006.09.26 13:30 hrs	6,320	50.90	9.21	8.05	1.16
2006.09.26 17:30 hrs	6,320	50.90	9.18	8.05	1.13
2006.09.27 09:00 hrs	6,320	50.90	9.19	8.05	1.13
2006.09.27 12:00 hrs	6,320	50.90	9.20	8.05	1.15
		Average	9.180		1.126