Assessing sample disturbance in low plasticity sensitive clays using shear wave velocity

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ABSTRACT: The aim of this study was to explore the use of shear wave velocity measurements as a rapid cost-effective approach for the assesment of sample quality. High quality data from four Norwegian low plasticty, high sensitivity clay sites were studied. The basis of the study was an existing set of quality criteria which were developed for materials significantly diffferent from those under study here, i.e. they had high plasticity and low sensitivity. These criteria were re-assessed for Singapore clay which has very similar properties to those used in the original study and found to work well. However the criteria seem to be too strict for the Norwegian soils under study and classified the samples as poor even though inspection of the resulting stress – strain and stress path curves showed that the samples were of very good quality. It is thought that the main reason for the finding is the contrasting nature of the materials in the orignal work and those under study here. Some new criteria which could be applied to low plasticity highly sensitive clays are suggested.

Keywords: soft clay; sampling; sample quality; shear wave velocity

1. Introduction

Several methods exist for the assessment of sample disturbance effects in soft clays. Perhaps the most widely used is that of [2] which involves measuring the change in void ratio relative to the initial void ratio ($\Delta e/e_0$) when consolidating a sample back to its in situ stress in the lab. Although this method is widely accepted and has been referred to as the "gold star" method [3] it involves a time consuming laboratory test and sample destructuration.

Researchers have been seeking quicker techniques for assessing sample disturbance to act as a rapid screening tool for assessing sample disturbance prior to advanced laboratory testing. This is of particular concern in offshore site investigations given the cost of these investigations and the need to maximise data quality.

Perhaps the most widely used techniques involve the measurement of suction (or initial effective stress) or shear wave velocity (V_s) on the recovered samples. Suction measurements have proven to be difficult in low plasticity clays and silts and the measured values are sensitive to various factors such as the time between sampling and testing. As a result the use of V_s measurements has become more widespread. Landon et al. [4] developed a series of criteria for assessing sample disturbance based on the ratio of the shear weave velocity measured on the sample (in unconfined conditions) to that of the in situ shear wave velocity (e.g. from seismic piezocone, SCPTU). However these criteria were based on tests on low sensitivity, relative high water content and high plasticity clays. The purpose of this paper is to reassess the criteria of [4] for high sensitivity, low plasticity clays such as those commonly found in Norway. The work is based on tests on high quality block samples (i.e. Sherbrooke with a diameter of 250 mm or mini-block samples with a diameter of 160 mm).

2. Previous studies

Comparisons between in situ and laboratory measured shear wave velocity have been used by many researchers for the purposes of assessing sample disturbance or destructuration or even densification sandy soils [5,6,7,8,9,10,11].

To the knowledge of the authors, only two studies, i.e. those of [4] and [12] have given specific guidelines and criteria for assessing sample disturbance using shear wave velocity measurements. The work by [12] was on residual soil derived from Porto granite in Portugal. These authors proposed a series of sample quality designation indices (SQD) which are summarised on Table 1.

Table 1. Sample quality assessment criteria of [12]

SQD	Vs*lab / Vs*insitu	Sample quality (SQ)
A	≥ 0.85	Excellent
B	0.85 – 0.7	Very good
C	0.7 – 0.6	Good
D	0.6 – 0.5	Fair
E	< 0.5	Poor

Note these authors used the normalised shear wave velocity:

$$V_s^* = \frac{V_s}{\sqrt{F(e)}} \quad (1)$$

where F(e) = void ratio function, rather than the actual shear wave velocity in their assessment procedure.

Landon et al. [4] worked on soft clays from Onsøy, Norway, Newbury, USA and Burswood, Australia and suggested the assessment criteria summarised on Table 2.

Table 2. Sample quality designation (SQD) of [4] in comparison to that of [2]

SQD	Landon et al. [4] $V_{s\text{-}lab}$ / $V_{s\text{-}insitu}$	Lunne et al. [2] with OCR 1-2 $\Delta e/e_0$	Lunne et al. [2] with OCR 2-4 $\Delta e/e_0$	Sample quality (SQ)
SQ1	≥ 0.6	< 0.04	< 0.03	Very good / excellent
SQ2	≥ 0.6	0.04-0.07	0.03-0.05	Good to fair
SQ3	0.35– 0.6	0.07-0.14	0.05-0.10	Poor
SQ4	< 0.35	> 0.14	> 0.10	Very poor

Ferriera et al. [12] considered their criteria to be more restrictive than those of [4] but it is difficult to make a clear comparison given the different materials involved and the use of the normalised shear wave velocity in the Portuguese study.

An alternative criteria based on shear wave velocity and suction measurements was developed by researchers at University College Dublin using data for Irish and Norwegian clays [13,14,15]. However in addition to suction measurements these criteria require knowledge of the V_s of remoulded clay samples which is not available for the sites under study here.

Tan et al. [1] report on some V_s data measured on Singapore lower marine clay. Their data is shown on Figure 1 and comprises tests on unconfined samples (which were used for unconfined compressive strength testing) and tests on samples which had been consolidated in the triaxial cell to the best estimate of the in situ stress. High quality samples were obtained using the Japanese fixed piston sampler and poorer quality samples were recovered using the Shelby tube. (Note that the data reported in [1] was for small strain stiffness G_{max} and was converted to V_s assuming the unit weight of the clay was 17 kN/m^3 after [16]). Seismic piezocone data were also available.

Table 3. Basic site properties for other sites

Parameter	BBC	Onsøy	Burs-wood	Singa-pore
γ (kN/m^3)	17.2-18.1	15.7-16.6	13.8-16.1	17
w (%)	40-54	53-74	63-105	55 - 63
c_{ur} (kPa)	1.2-25	2-7.2	3.1-8.7	n/a
S_t	2-30	4-9	3-14	3 - 6
I_p (%)	19-21	22-38	28-54	40 - 57
CC (%)	55-64	48-79	46-54	60-70

Data for the Singapore clay is summarised on Table 3. where γ is the unit weight, w the water content, c_{ur} the remoulded shear strength, S_t the sensitivity, I_p the plasticity index and CC the clay content. It can be seen from Figure 1 that the criteria of [4] works well for this clay and correctly characterises the Japanese fixed piston samples as generally "very good / excellent" and the Shelby tube samples as "poor". This work on Singapore clay reinforces the usefulness of the [4] criteria for lightly overconsolidated, high plasticity, high water content and low sensitivity clays.

3. Description of test sites

Data from four well characterised Norwegian sites are presented here. The sites are located at Tiller – Flotten, Skatval and Koa near to Trondheim in Mid-Norway and at Rakkestad about 50 km northeast of Oslo, see Figure 2. The work at Tiller-Flotten was carried out as part of the Norwegain Geo-Test Site (NGTS) project [17,18]. The Tiller-Flotten site is the NGTS quick clay site.

Investigations at the Skatval, Koa and Rakkestad sites were undertaken as part of the strategic research project SP8 GEODiP funded by The Research Council of Norway. The work at Rakkestad was also in conjunction with the E16 Nybakk to Slomarka highway development.

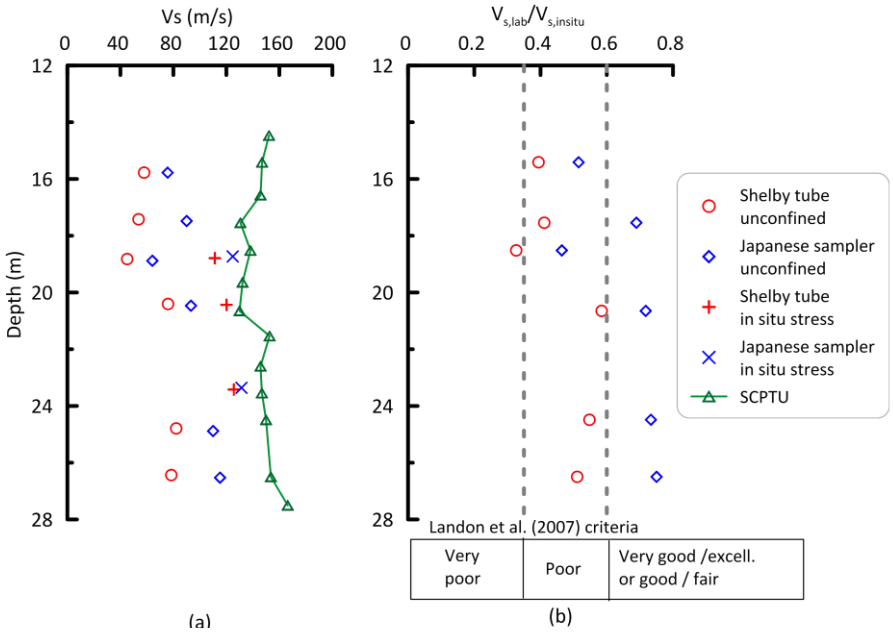

Figure 2. (a) Measured shear wave velocity values and (b) $V_{s,lab}$ / $V_{s,insitu}$ for Singapore marine clay after [1]

Figure 2. Site locations

Basic engineering properties of the soils at the four sites are summarised on Table 4 and on Figures 3a and b to 6a and b. Further details of the geotechnical properties of each site can be found in [19] for Tiller – Flotten, in [20] for Skatval, Koa and Rakkestad and also in [21] for Rakkestad.

Table 4. Basic site properties for sites under study here (in depth range under study)

Parameter	Tiller-Flotten	Skatval	Koa	Rakkestad
γ (kN/m^3)	16.8-19	19.4	19.5	18.5
w (%)	32-55	32	30	35
c_{ur} (kPa)	0.1-0.4	0.4-7	0.4-2	0.3-4.5
S_t	6-350	5-50	13-63	5-150
I_p (%)	8-23	11-17	8-25	8-17
CC (%)	45-70	35-43	50-53	40-47
Overconsol. ratio, OCR	1.5-2.5	2-4	3-4	2-6

The four sites have the same marine depositional environment. The basic engineering properties are relatively simlar for the sites and can be summarised as being of low water content, low plasticity, moderately overconsolidated and sensitive clay.

The properties contrast strongly with those of the sites studied by [4] and with the Singapore clay all of which have higher water content and plasticity, lower OCR and lower sensitivity.

The contrast between the two sets of sites can be seen clearly in the plasticity data as presented on the "A-Line" chaart on Figure 7. Much of the data under study here is classified as a clay of either low or intermediate plasticity in contrast to those of [4] which are generally classified as high plasticity.

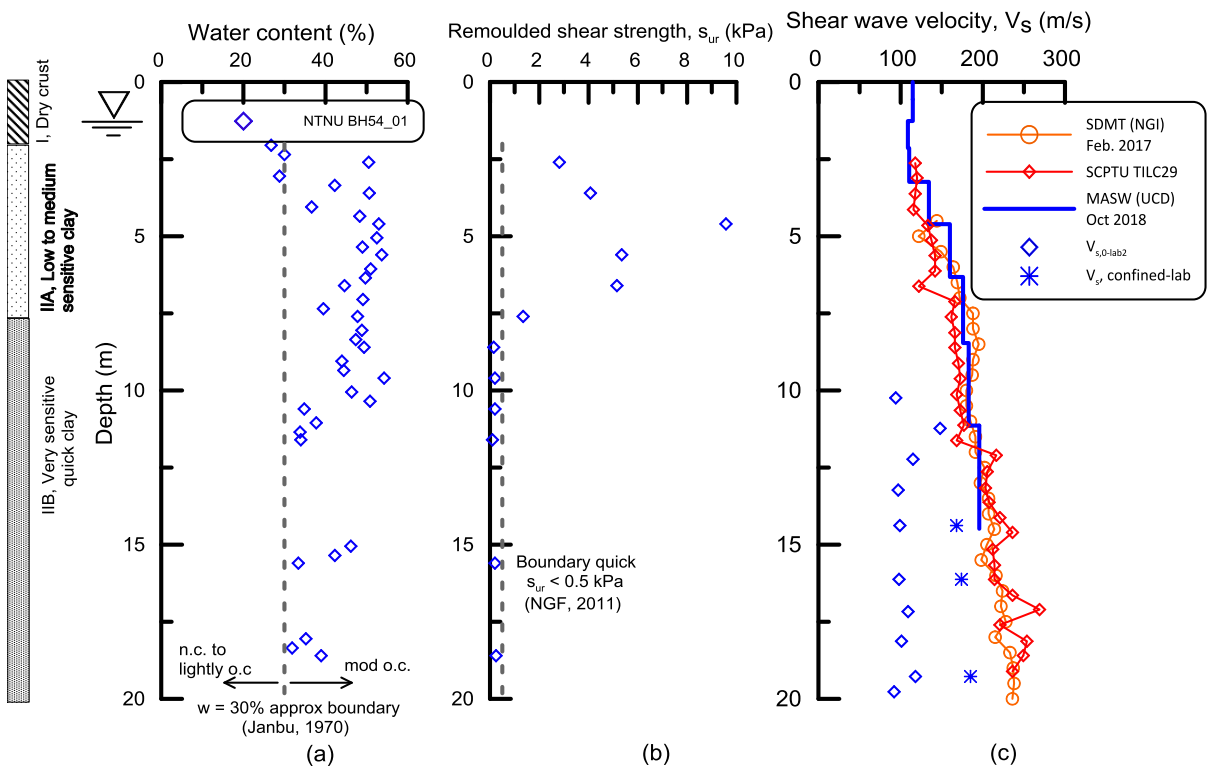

Figure 3. Tiller Flotten (a) water content, (b) c_{ur} and (c) V_s

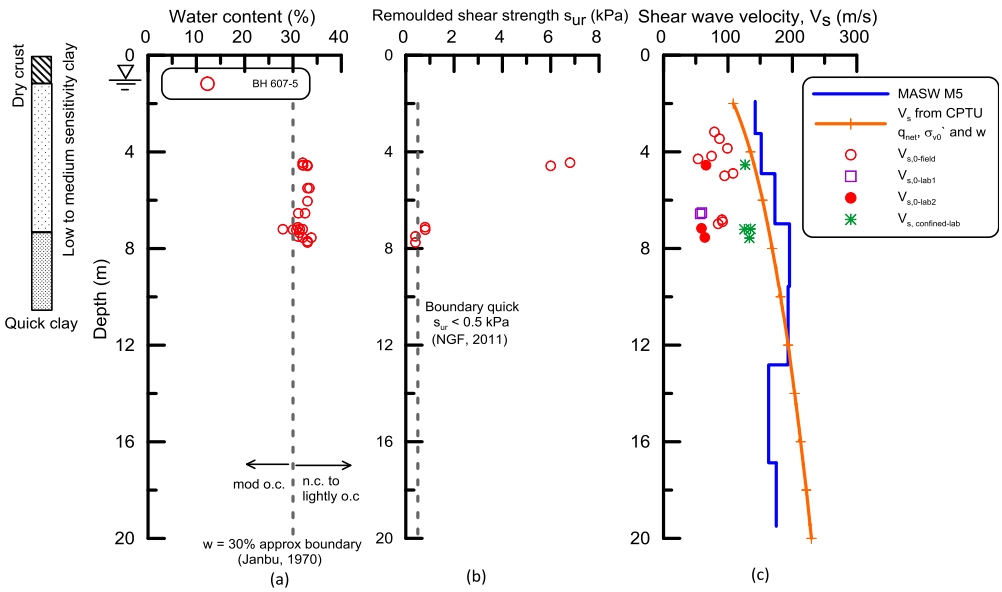

Figure 4. Skatval (a) water content, (b) c_{ur} and (c) V_s

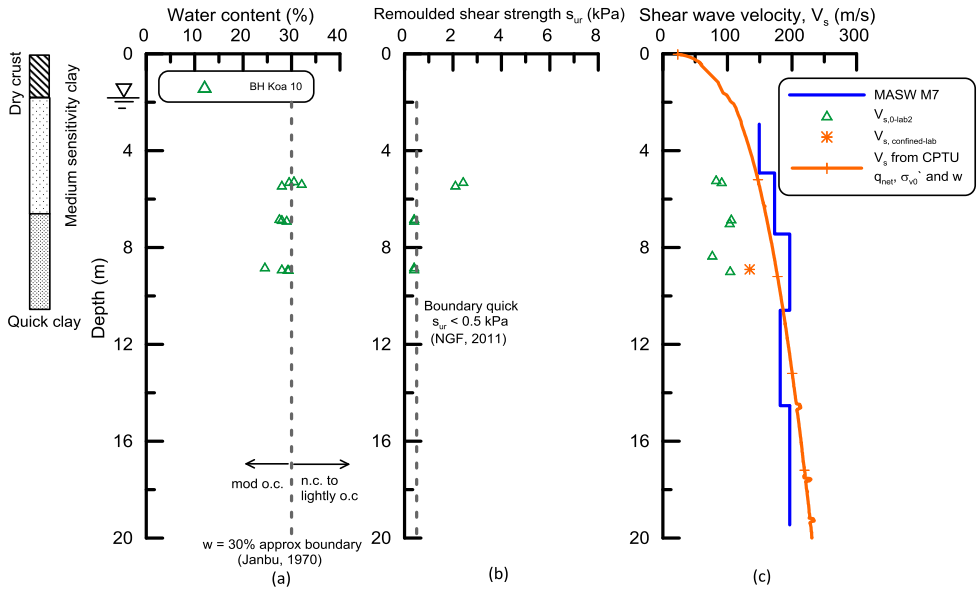

Figure 5. Koa (a) water content, (b) c_{ur} and (c) V_s

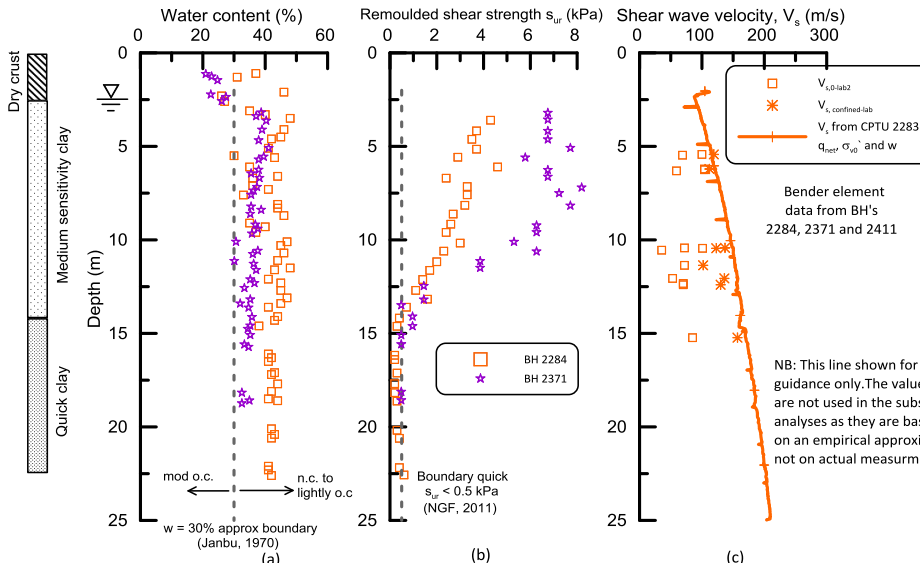

Figure 6. Rakkestad (a) water content, (b) c_{ur} and (c) V_s

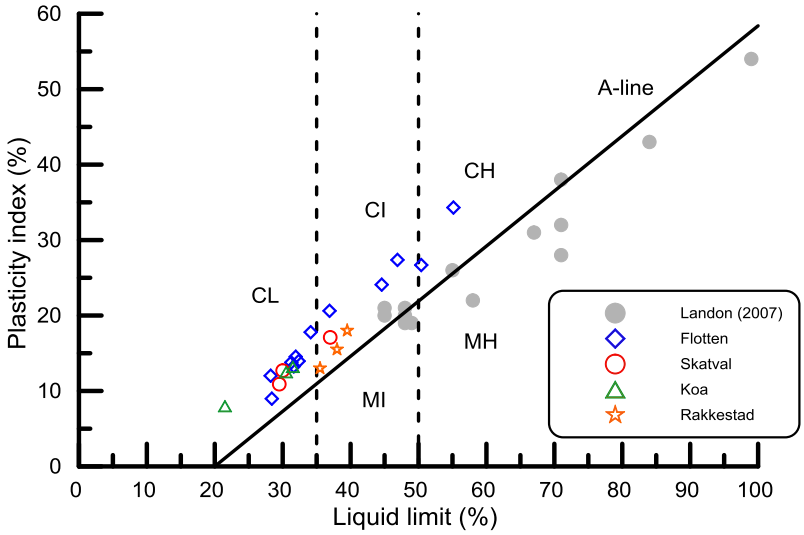

Figure 7. "A-line" plasticity chart

4. Methodology

4.1. Soil sampling

All the soil samples, for which data is presented here, were taken by high quality Sherbrooke type block samplers. These were either with the original 250 mm diameter sampler [22] or the 160 mm diameter mini-block sampler which is essentially a reduced version of the original sampler with some improvements in the mechanical operation [23]. It has been shown that these samplers yield samples of more or less identical quality.

4.2. In situ shear wave velocity profiling

In situ shear wave velocity profiles were obtained either from the seismic dilatometer (SDMT), the seismic CPTU (SCPTU) or the multichannel analysis of surface wave technique (MASW). Full details of these methods can be found in [24]. It is also possible to estimate V_s from the CPTU profile. Various methods exist for this purpose. L'Heureux and Long [24] found the best fit between the measured and predicted data was obtained using the following formula:

$$V_s = 71.7 \cdot (q_{net})^{0.09} \cdot \left(\frac{\sigma'_{v0}}{w}\right)^{0.33} \quad (2)$$

where q_{net} is the net cone resistance, σ'_{v0} is the in situ vertical effective stress and w is the water content

4.3. Shear wave velocity measurements on soil samples

Unconfined measurements of shear wave velocity ($V_{s,0}$) were collected on site ($V_{s,0\text{-field}}$) and in the laboratory ($V_{s,0\text{-lab}}$) using the bender element device described by [4]. For this, samples were carefully trimmed from block sample size to a cube about 70 mm x 70 mm x 70 mm size due to restrictions in the equipment size.

Two different laboratories were used for the Skatval samples. Lab 1 is located in Trondheim and Lab 2 in Oslo. All of the tests for Tiller – Flotten, Koa and Rakkestad were carried out in Lab 2.

Additional tests were carried out during triaxial (CAUC and CAUE) or direct simple shear (DSS) tests where the V_s was measured after the samples had been consolidated to the best estimate of the in situ stress. These values are termed $V_{s,\text{confined-lab}}$ and were carried out in Lab 2.

Shear wave travel time (i.e. arrival time), for all tests, was calculated as the difference between two peaks of the transmitted signal minus the system calibration time. The frequencies used varied between 2 kHz and 6 kHz depending on the quality of the signal observed on the screen aparatus. The measurement equipment used in the field is shown on Figure 8. A summary of the V_s measurements on soil samples is given on Table 5.

Figure 8. Test set up for shear wave velocity measurements on unconfined samples in the field (Photo Priscilla Paniagua)

Table 5. Summary of V_s measurements on soil samples

Site	$V_{s,0\text{-field}}$	$V_{s,0\text{-lab}}$	$V_{s,\text{confined-lab}}$	Full in situ V_s profile
Tiller-Flotten	No	Yes	Yes	SCPTU/SDMT And MASW
Skatval	Yes	Yes (at 2 labs)	Yes	MASW
Koa	No	Yes	Yes	MASW
Rakkestad	No	Yes	Yes	No derived from CPTU correlations using Eq. 1

5. Results

5.1. In situ shear wave velocity profiling

From Figure 3c it can be seen that for all practical purposes the individual shear wave velocity profiles obtained for the Tiller – Flotten site by SDMT, SCPTU and MASW are more or less identical.

For Skatval and Koa only MASW data is available but these measurements are consistent with the profile obtained by correlation from the CPTU data by using Equation 1.

For Rakkestad no direct measurements are available but the correlation with CPTU is shown for guidance purposes.

5.2. Shear wave velocity measurements on samples

The laboratory or in situ shear wave velocity measurements on the soil samples are shown on Figures 3c to 6c. Based on the data for all the sites, the following observations can be made:

- The Skatval data shows that unconfined mesurements of V_{s-0} on site are lower than the in situ values and transport resulted in a reduction in V_{s-0} between field and laboratory measurements (see in particular results for Skatval between 6.5 and 7.5 m)
- There was good agreement on results for the tests at the two laboratories despite the difference in transportation distance. Hence it is thought that greater travel distance does not play a significant role in V_{s-0} reduction.
- There is some scatter in field V_{s-0} values at Skatval between 4.0 m and 5.0 m. These might be due to disturbance while sampling cutting, since a big stone was encountered by the Sherbrooke block sampler between these depths.
- Reconsolidation to in situ stresses prior to testing seems to counteract sampling disturbance and gives the highest measured V_s values in the laboratory. These values are close to but consistently less than the in situ V_s measurments.
- The Rakkestad lab values seem a little high compared to the V_s profile predicted by CPTU. This suggests that the CPTU prediction is perhaps a little low.

6. Assessment of sample quality from V_s

A significant quantity of anisotropically consolidated undrained triaxial compression and extension tests (CAUC or CAUE) and constant rate of strain tests (CRS) were carried out on the block samples under study here.

Inspection of the stress – strain curves and stress paths confirmed that all of the samples tested as part of this study were of high quality. The reader is referred to the publications listed above for further details.

In order to test out the sample disturbance assessment criteria of [4] and [2] the data are plotted in the the form of $V_{s,0}/V_{s,insitu}$ against $\Delta e/e_0$ obtained from CAUC or CAUE tests or CRS tests on Figures 9 and 10 respectively. Note the colour green, orange and red are used to denote data in sample quality zones SQ1, SQ2 and SQ3 respctively usong the measured OCR values and the criteira listed on Table 2. The parallel data from [4] are also shown for comparative purposes.

For both plots it can be seen that although the data under study here is classiifed as either SQ1 or SQ2 by the criteria of [2], consistent with the observations of the stress – strain and stress path plots, it falls well below that of the data of [4] and would be classifed as "poor" according to the latter criteria.

In Norway the technique of [25] is also often used to assess sample quality. These criteria are based on the determination of the ratio between the constrained modulus at in situ stress (M_0) and that at the preconsolidation stress (M_L) in CRS oedoemeter tests. The criteria are summarised on Table 6.

Table 6. Sample disturbance assessment criteria of [25]

SQD	M_0 / M_L	Description
SQ1	≥ 2	Very good / excellent
SQ2	1.5-2	Good to fair
SQ3	1-1.5	Poor
SQ4	< 1	Very poor

Data measured here are compared to these criteria on Figure 11. The same pattern as found above is also evident here, i.e. although the [25] criteria suggest the samples are mostly SQ1 or SQ2, the [4] criteria suggest the samples fall in the SQ3 zone.

7. Discussion

It would seem that the criteria of [4] are too strict for the clays under study here and that a new set of criteria need to be developed. The reasons for this are thought to be mostly due to the low plasticity and highly sensitive nature of the materials which are much more susceptible to sample disturbance that the materials considered by [4]. In addition some of Landon's work [26] was done on the large block samples as recovered on site whereas all of the testing here was done on samples trimmed to 70 mm x 70 mm x 70 mm cubes.

Another reason could be linked to the fact that the $V_{s,0}$ in the work by [4] is a mixture of measurement performed in the field and in the laboratory. As seen from Figures 3 to 6, V_s results decrease due to transport of samples to the laboratory and this impacts on the ratio $V_{s,0}/V_{s,insitu}$.

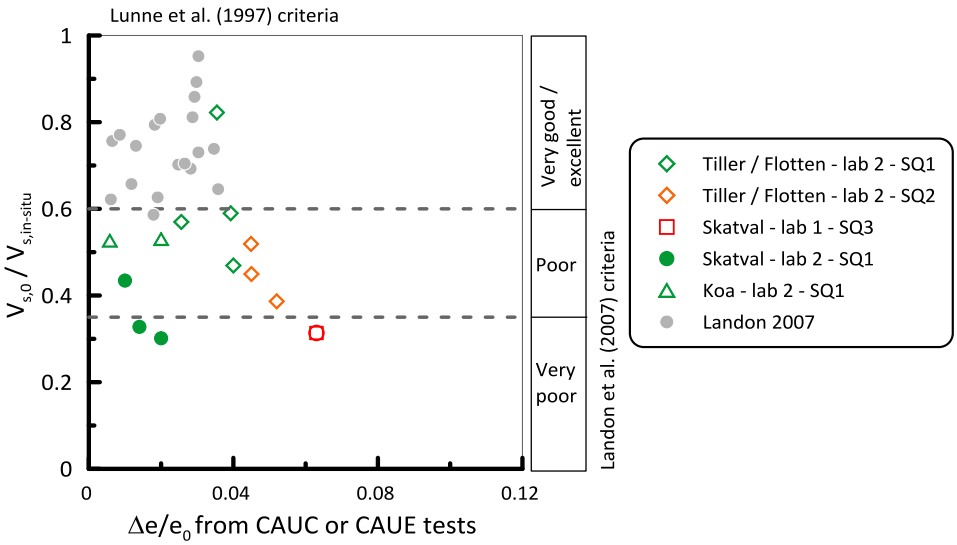

Figure 9. Comparison of shear wave velocity ratio and normalised void ratio for CAUC and CAUE tests

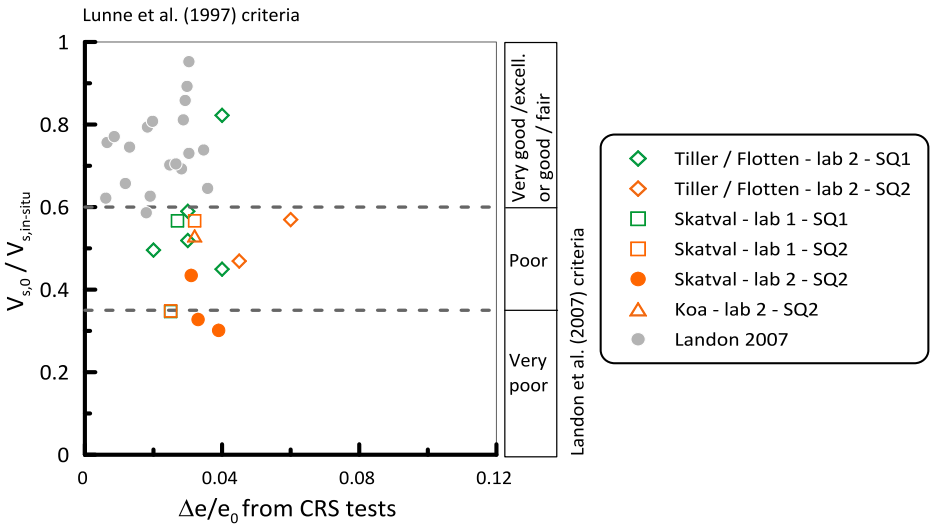

Figure 10. Comparison of shear wave velocity ratio and normalized void ra-

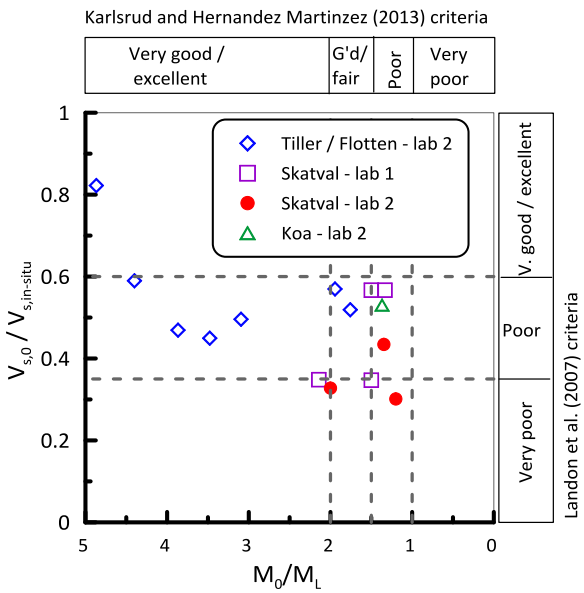

Figure 11. Comparison of shear wave velocity and M_0/M_L ratio

Landon's in situ V_s profiling was done using the SCPTU. Here a mixture of techniques was used. However as can be seen in Figure 3c all the techniques give more or less identical profiles.

Although other factors could play a minor role in the findings it is thought that the results found are in large part due to the significant difference in the materials studied here compared to previous investigations.

8. Conclusions

The aim of this study was to explore the use of shear wave velocity measurements for the purposes of sample quality assessment. It was not intended to find a method to replace some of the more well-known existing techniques but to devlop a rapid cost-effective approach which could be used for screening / cross-checking purposes.

High quality data from four Norwegian sites were studied. All the materials involved had relatively low water content and plasticity, moderate OCR and high sensitivity.

The basis of the study was the criteria of [4] which were developed for materials significantly diffferent from those under study here, i.e. they had high plasticity and low sensitivity. Landon et al's criteria [4] were found to work well when applied to Singapore clay which has very similar properties to those used in the original study

It is concluded that the criteria of [4] are too strict for the materials under study here. It is suggested that a lower $V_{s,0}/V_{s,insitu}$ limit of 0.35 (compared to 0.6) would be more appropriate for low plasticity sensitive clays when the shear wave velocity is measured at the laboratory. When measuring the shear velocity in the field a slightly greater lowerbound $V_{s,0}/V_{s,insitu}$ limit may be considered but insufficient data exits here to give a definitive recommendation.

Acknowledgements

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