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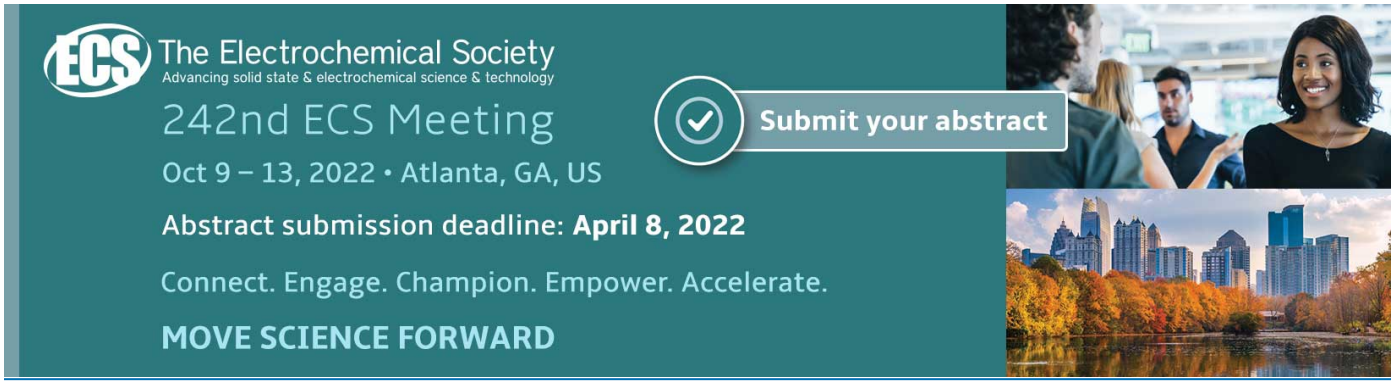

Estimating shear wave velocity with the SCPTu and Bender element

S M Valsson[1], M Dahl[2], E Haugen[3] and S A Degago[4]

[1] Norwegian Public Roads Administration, Directorate, Molde, Norway.
[2] Norwegian Public Roads Administration, Central laboratory, Oslo, Norway.
[3] Norwegian Public Roads Administration, Development division, Drammen, Norway.
[4] Norwegian Public Roads Administration, Directorate, Trondheim, Norway.

sigurdur.mar.valsson@vegvesen.no

Abstract. The shear wave velocity (v_s) is an important soil and rock property that can both be used in several geotechnical problems including for evaluation of dynamic properties of soils as well as in determining the maximum value of soil stiffness at small strain. This property is also seen to give good correlations with other soil parameters used in settlement and stability analyses. The Norwegian Public Roads Administration (NPRA) has recently invested in equipment to measure this fundamental soil property both in the laboratory using bender elements and out in the field using a seismic CPTu (SCPTu). NPRA has also developed internal procedures and techniques to standardize logical interpretations. To assist with this standardization procedure, NPRA has conducted soil investigations at a site in Fredrikstad municipality in the southern part of Norway. The investigations included SCPTu and extraction of high quality mini-block samples. The shear wave velocity is estimated after consolidation in the triaxial apparatus. The laboratory program was done right after the sample extraction and repeated on stored samples a couple of weeks later. Comparison of v_s measured in the laboratory was then made with the field measurements with SCPTu. The work gives comparison of the field and laboratory measurements. Correct interpretation approaches are necessary for the laboratory tests as these are found to be more sensitive to small changes in experimental conditions than the SCPTu. Recommendations on how to reduce discrepancies between laboratory and field data are given.

1. Introduction

Shear wave velocity (v_s) is an important soil and rock property that can be used in several geotechnical problems including for evaluating the dynamic behavior of soils as well as in determining the maximum value of soil stiffness at small strains. This property is also seen to give good correlations with other soil parameters used in settlement and stability analyses. The Norwegian Public Roads Administration (NPRA) has thus invested in equipment to measure the shear wave velocity (v_s) of soils, both *in situ* with SCPTu (seismic CPTu) and in the laboratory with bender element tests. To ensure proper use of the equipment, the department responsible for field- and laboratory testing prepared test procedures and presentation standards. To validate these procedures and to gain an overall experience, it was decided to do a systematic study on the use of this equipment and the

interpretation of v_s. The main goal was to gain knowledge on how v_s results measured in the laboratory compare to those established *in situ*.

Norwegian Geo-Test Sites project (NGTS) has established several test sites, well characterized with extensive and high-quality tests. The sites are meant to be used for research such as to examine performance of equipment and established procedures. For this study, the NGTS soft clay site at Onsøy was used to extract samples and carry out SCPTu tests. Important aspects related to interpretation of v_s are studied in detail. These aspects form important features of spreadsheet programs developed at the NPRA, for interpretation of the tests and are presented in detail. Comparison of interpreted v_s from laboratory and *in situ* is performed. The field measurements are evaluated using existing CPTu correlations from literature.

2. The test site

The soil conditions at the Onsøy site are thoroughly documented in the site characterization report [1]. For the purpose of this work they can be viewed as a two-layer system, where under a dry crust of about 0.5-1.0m there is an approximately 30m thick clay layer above the bedrock. The clay layer is homogenous with a fairly constant grain size, it has an average clay content of about 60%. The plasticity index varies between 30-45% and the water content varies between 40-80%. The clay deposits are normally consolidated. A presentation of active undrained shear strength (c_{uc}) and shear wave velocity taken from [1] is given in Figure 1.

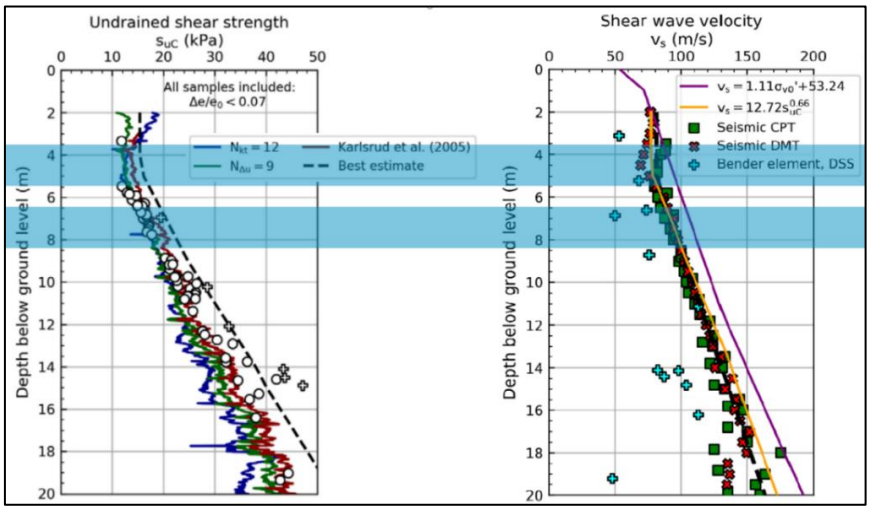

Figure 1. Profiles of c_{uc} and v_s at the test site [1]. Depth intervals covered in this work are shaded blue.

For the current study, the NGTS project allocated 4 boreholes at the Onsøy site, where *in situ* tests and soil sampling could be carried out. Figure 2 shows the location of the boreholes within the site.

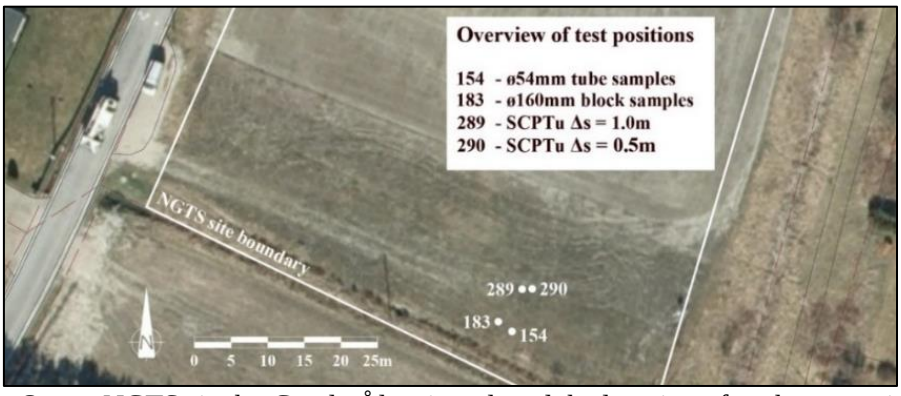

Figure 2. The Onsøy NGTS site by Gamle Ålevei road, and the location of each test position.

3. The SCPTu test

The shear wave velocity of soils can be measured directly with the cone penetration test with pore pressure measurements (CPTu), using specialized equipment. The most common procedure is to interrupt the CPTu test, generate a shear wave at the surface and measuring the response in the sensors placed above the CPTu cone (SCPTu test). Details of the SCPTu equipment at NPRA and the procedure developed for interpretation are given herein.

With the SCPTu equipment at NPRA, it is possible to set the distance between the accelerometers to either 0.5m or 1.0m, but the first sensor offset from the tip is fixed at 0.5m. Each test takes only a few seconds to carry out but requires the normal CPTu procedure to be interrupted. The setup shown in Figure 3 requires data transfer by cable within the rod system. For this study, two SCPTu were carried at location 289 (sensor setup as Figure 3c) and 290 (sensor setup as Figure 3b).

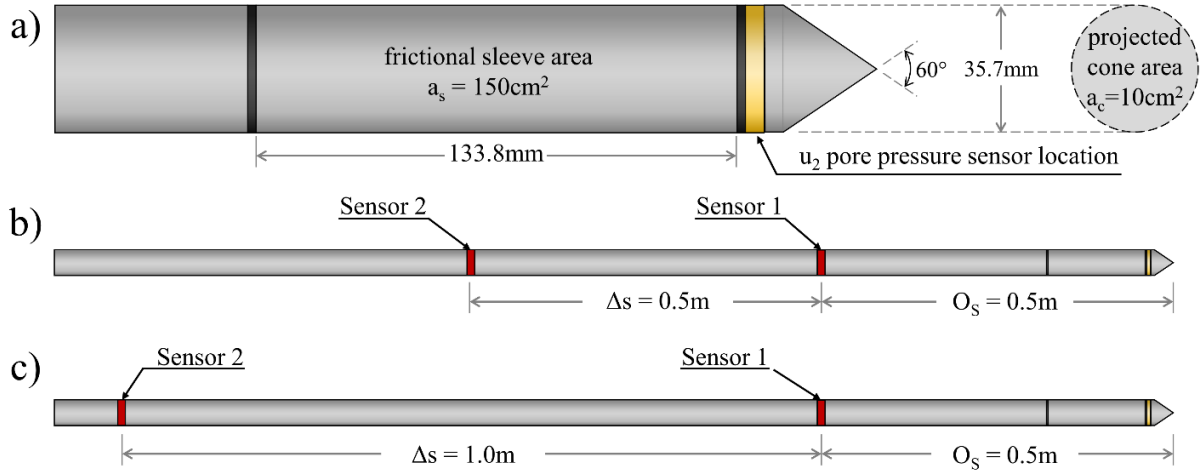

Figure 3. a) Reference CPTu cone and seismic sensor setup used in position **b)** 290 and **c)** 289

In order to correctly calculate the shear wave velocity, the sensor spacing and the horizontal distance to the source must to be considered. The geometry and an example of a wave registrations with opposite polarity is shown in Figure 4.

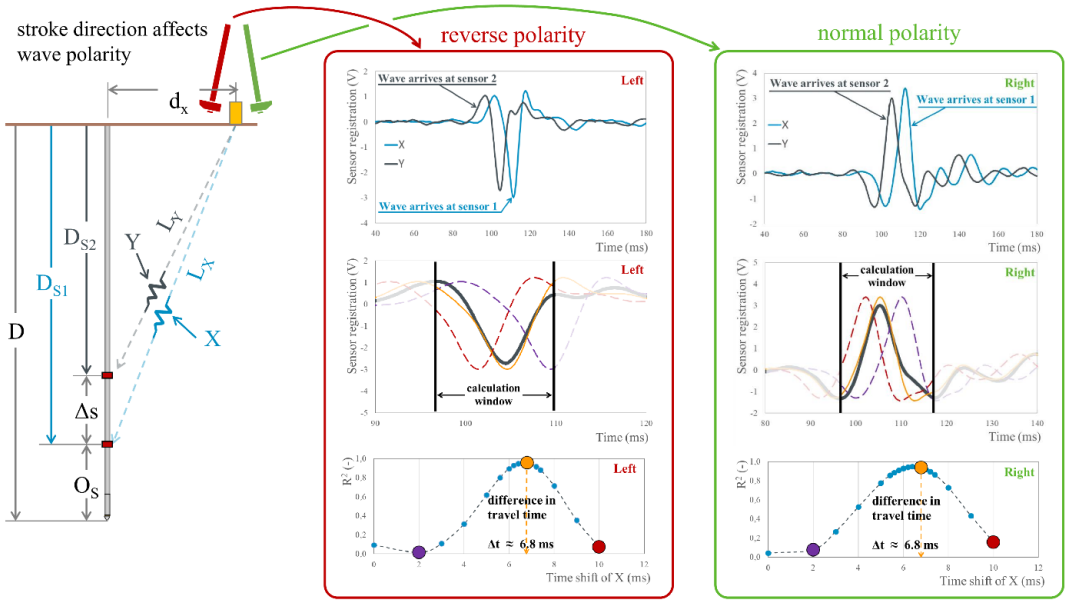

Figure 4. Geometry of a SCPTu test. Travel time difference is found by comparing registrations.

The difference in wave travel distance can from the geometry in Figure 4 be calculated as

$$\Delta L = L_X - L_Y = \sqrt{(D_{S1})^2 + (d_x)^2} - \sqrt{(D_{S2})^2 + (d_x)^2} \quad (1)$$

The average shear wave velocity of the depth interval between the sensors can be estimated by dividing this distance with the difference of the wave travel times from the source to each sensor.

$$v_s = \Delta L / \Delta t \quad (2)$$

where Δt is difference in wave travel time. A few methods for evaluating the travel time difference for the shear wave are known to the authors, but we have found that comparing the arrival curves from each sensor directly within a given window gives control over the interpretation. This utilizes a large portion of the wave to estimate the travel time, rather than just a single property (e.g. peak to peak and first zero crossover [2]). The window is usually set to contain the peak pulse and stop at the next opposite peak responses, but it can be adjusted. The difference between the travel times is then evaluated by calculating the coefficient of determination, R^2, between the two time series at different time shifts and identifying the shift which gives the best fit. R^2 between two sets, X and Y, is defined as

$$R^2(X,Y) = \left(\sum\left((x_i - \bar{x}) \cdot (y_i - \bar{y})\right) / \left(\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2\right)^{1/2}\right)^2 \quad (3)$$

Where $\bar{x}$ and $\bar{y}$ symbolize the sample means of X and Y respectively. Using equation (3) to compare wave travel times has proven to be a robust method, but it is sensitive to cases where the form of either wave is distorted. An example of a wave distortion can be seen in Figure 4 (right side stroke), where the tail of the Y signal deviates from the sinusoidal form. Resetting the calculation window to exclude this part of the signal gives a better fit. This is shown in Figure 5.

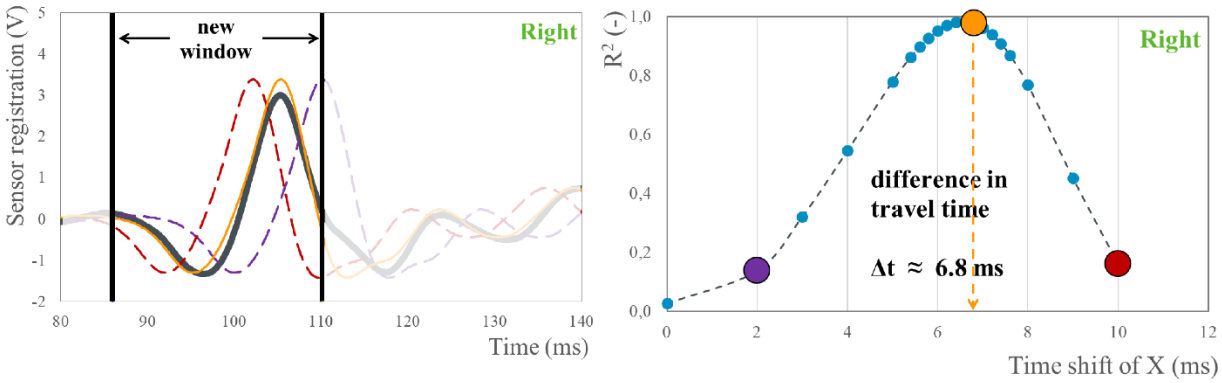

Figure 5. Window is adjusted to reduce effect of distorted wave on travel time interpretation.

Although the interpretation of Δt remains unchanged at about 6.8 milliseconds, the maximum R^2 score is improved from 0.935 to 0.977. The process shown in Figure 4 and 5 has been automated in our spreadsheet and gives a good starting point for the interpretation. Cases with mediocre or poor scores (R^2 < 0.90-0.95) should be analyzed in detail and manually adjusted to improve the interpretation. All left-right SCPTu interpretations presented in this paper are either in total agreement with one another or have a maximum difference of a single time shift (0.2 milliseconds).

The interpreted v_s from the two SCPTu carried out for this study are given in section 6 along with laboratory test results.

4. The bender element test

The shear wave velocity of soil samples can be evaluated with a bender test, using specialized equipment. The test requires that two small elements be inserted into the top and bottom of the sample in order to generate and receive shear waves. The test takes a few milliseconds to conduct and causes small strains in the sample (<10^{-3}% according to [2]), making it ideal to incorporate as a part of other laboratory tests. In this section aspects of the bender test along with its interpretation procedures are given. The NPRA has invested in equipment to conduct the bender test as a part of the triaxial test. The setup and an example of test results is shown in Figure 6.

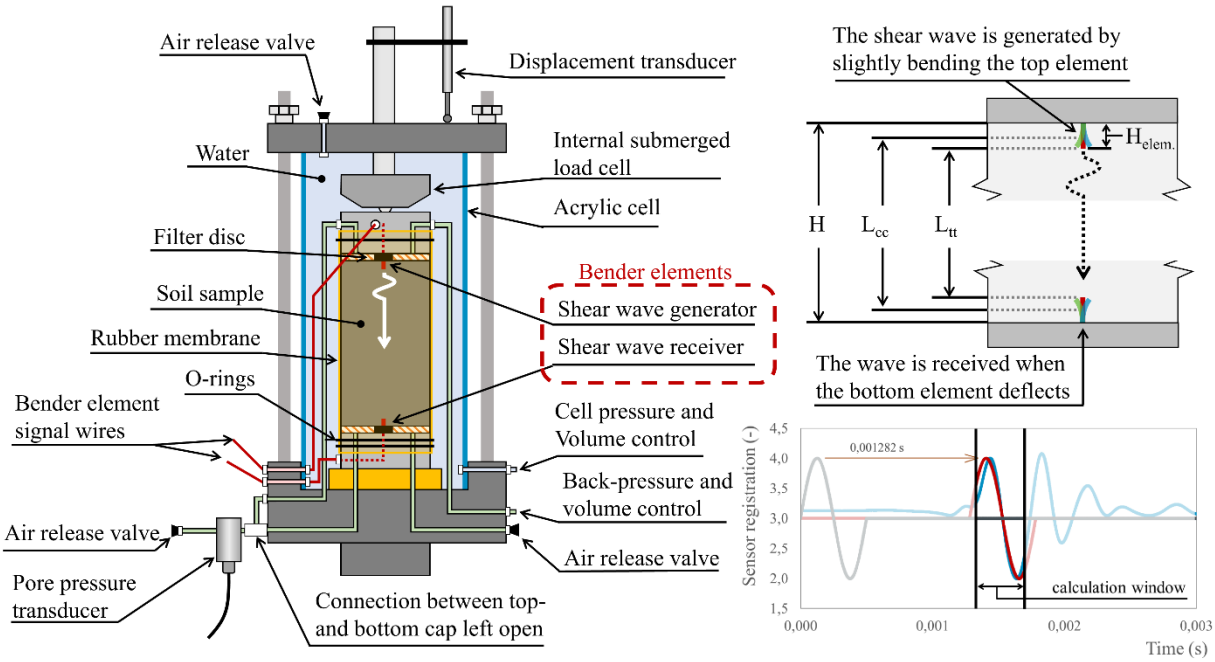

Figure 6. Triaxial test setup with bender elements installed, and an example of test results.

For the bender element test, the interpretation procedure developed at NPRA evaluates the wave travel times in the same manner as for the SCPTu, by comparing the source wave and registered response within a given window using equation (3). The shear wave velocity is then calculated as

$$v_s = L/\Delta t \tag{4}$$

where L is is the wave travel distance and Δt is the travel time as before. As the wave is generated and detected within the system in a bender test, a significant uncertainty is added to the interpretation. The exact point *where* the wave is assumed to be generated and detected has a large impact on the shear wave velocity estimate, and this impact gets larger for smaller samples.

In order to attain good estimates of v_s using bender elements and equation (4) corrections are necessary. These include adjusting either the travel time for the wave, adjusting the travel distance or adjusting both. On the topic of travel distance, a comprehensive study of previous work is found in [3], where it is stated that estimating the travel distance is commonly considered less problematic than determining the travel time and that a variety of authors have assumed that the tip-to-tip distance should be used as the travel distance. This is challenged by the author, who finds that the height should be measured between the center of dynamic pressure of the transducers, which is estimated to be roughly at 60% of the embedded bender element height. An alternative method to correct for the height/system uncertainty is suggested in [2] where v_s is calculated as

$$v_s = L_{tt} / (\Delta t - t_c) \quad (5)$$

where t_c is the system calibration time when L_{tt} is set to zero. To test this, t_c was evaluated at different confining pressures as is shown in Figure 7. Figure 7 shows that the test gave roughly the same delay when pressure was applied to the system, with an average value of t_c = 0.066 milliseconds, but showed little damping of the signal. The test without confining pressure gave a significantly less delay. It is clear from this that applying pressure to the system has altered the test conditions in our setup.

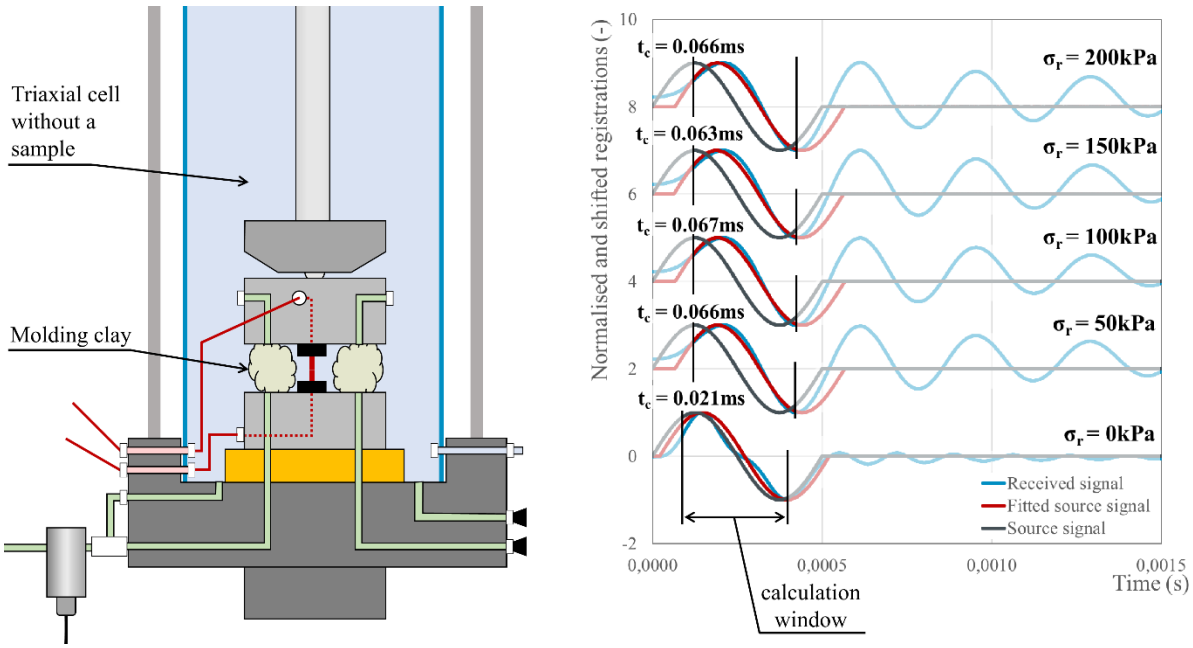

Figure 7. Setup used to investigate t_c (left) and registered results (right).

5. Laboratory tests and results

Four samples with diameter ø160mm were collected from position 183 using the NTNU mini-block soil sampler [4]. The samples were taken from depths 4.0 - 4.3m, 4.35 - 4.65m, 7.1 - 7.4m and 7.4 - 7.7m. Each sample was split in two, where the upper part was used immediately, and the lower part was stored for approximately 3 weeks to investigate storage effects. The bottom halves were packed in moistened paper towels between sheets of plastic wrap and placed in storage at 5°C. The top halves were carved into four ø54mm samples with a height of 10cm. One sample from each half was dedicated to evaluating the shear wave velocity with the bender element in the triaxial apparatus, while the others were used in various tests on triaxial procedures.

The samples were mounted in the triaxial system with the bender element installed as shown in Figure 6. The specimens were brought to *in situ* confining pressures with an anisotropic consolidation process at a rate of 0.25kPa/min. The axial deformation due to consolidation was registered and used to update the sample height before calculating v_s. The target consolidation pressures were evaluated as a function of depth using methods proposed for the site [1]. The shear wave test was carried out after consolidation of the specimen, before the sample was compressed to failure at a strain rate of 2%/hr.

Due to the geometry of the bender elements it is not clear exactly from where the signal originates and where it is received. In order to evaluate how this affects the interpretation with a 10cm sample the shear wave velocity is calculated using six different assumptions. The results are presented in Table 1. The first calculation divides the *tip to tip* distance L_{tt} by the travel time. The second and third use the 60% embedded depth distance and the *center to center* distance respectively. The fourth and

fifth divides L_{tt} by the *corrected* travel time using a t_c of 0.021ms and 0.066ms. The sixth method utilizes the entire sample height divided by the travel time.

Table 1: Shear wave velocities calculated from bender tests and sample quality assessment

Depth (m)	Storage time (days)	v_s from bender test (m/s)						Sample quality	
		$L_{tt}/\Delta t$	$L_{60\%}/\Delta t$	$L_{cc}/\Delta t$	$L_{tt}/(\Delta t-t_{c.1})$	$L_{tt}/(\Delta t-t_{c.2})$	$H/\Delta t$	$\Delta e/e_0$ [a]	$\Delta V/V_0$ [b]
4.15	1	74.6	76.4	76.9	75.9	78.8	79.1	1	B
4.25	19	73.1	74.9	75.3	74.3	77.1	77.5	2	C
4.45	5	72.7	74.4	74.9	73.9	76.6	77.0	1	C
4.55	21	70.9	72.6	73.0	72.0	74.6	75.2	2	C
7.25	3	84.5	86.6	87.1	86.2	89.9	89.6	2	C
7.35	19	82.7	84.7	85.2	84.3	87.9	87.7	2	D
7.55	7	84.9	87.0	87.5	86.6	90.4	90.0	2	C

[a] Sample quality classification by Lunne et a. as proposed in [5], where 1 stands for "Very good to excellent" and 2 stands for "Good to fair"

[b] Sample Quality Designation (SQD) by Terzaghi et al. as proposed in [6]

Storing the samples does not appear to have had a significant effect on the measured shear wave velocities, as the maximum difference between values from a stored and a fresh specimen from the same sample is less than 3%. This is small compared to the undrained shear strength (c_{uC}), where a reduction of about 12 – 18% is found in 3 of 4 block samples as shown in Figure 8. Such a large reduction in c_{uC} was expected and falls in the same range presented for stored ø54mm samples in [7].

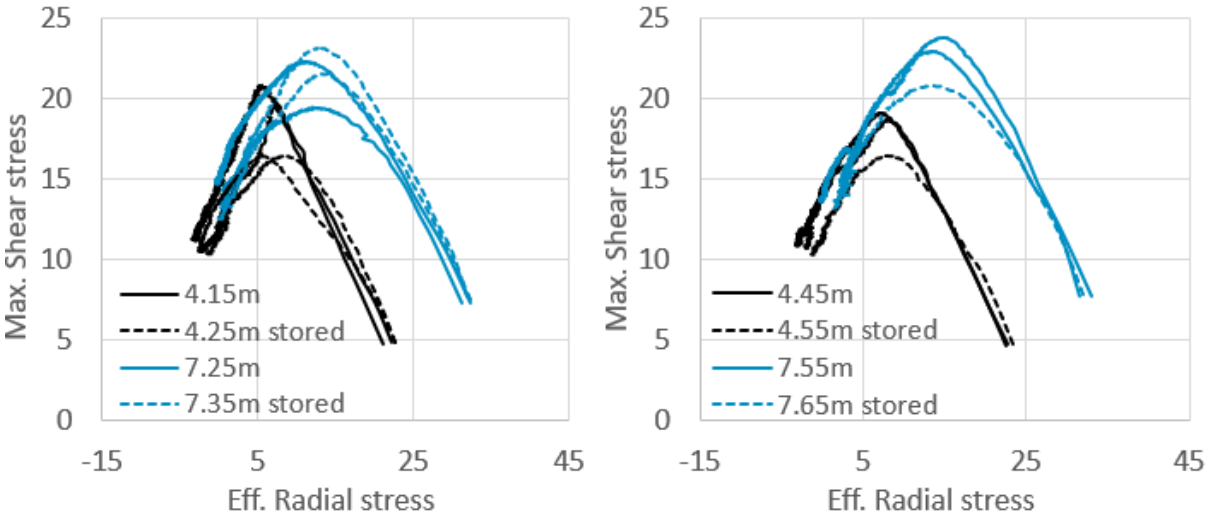

Figure 8: Stress paths from triaxial tests (CAUc) on samples from test position 183.

The confining pressure is seen to have the greatest influence on the bender element test results. Values registered after docking the load cell but before applying confining pressures on the sample were found to be significantly lower than those found after confining pressures were applied as can be seen in Figure 9 (left). The standard triaxial procedure at NPRA recommends that a back pressure should be added to the system after consolidation is finished. This aspect was investigated and it was observed that adding back pressure did not influence the shear wave travel times.

6. Comparing field and laboratory results

The main reason for conducting this study was to investigate how values for v_s found in the field using the SCPTu compared to values found in the laboratory using bender elements. An overview of all tests is given Figure 9, including a presentation of v_s from each of the six assumptions previously discussed.

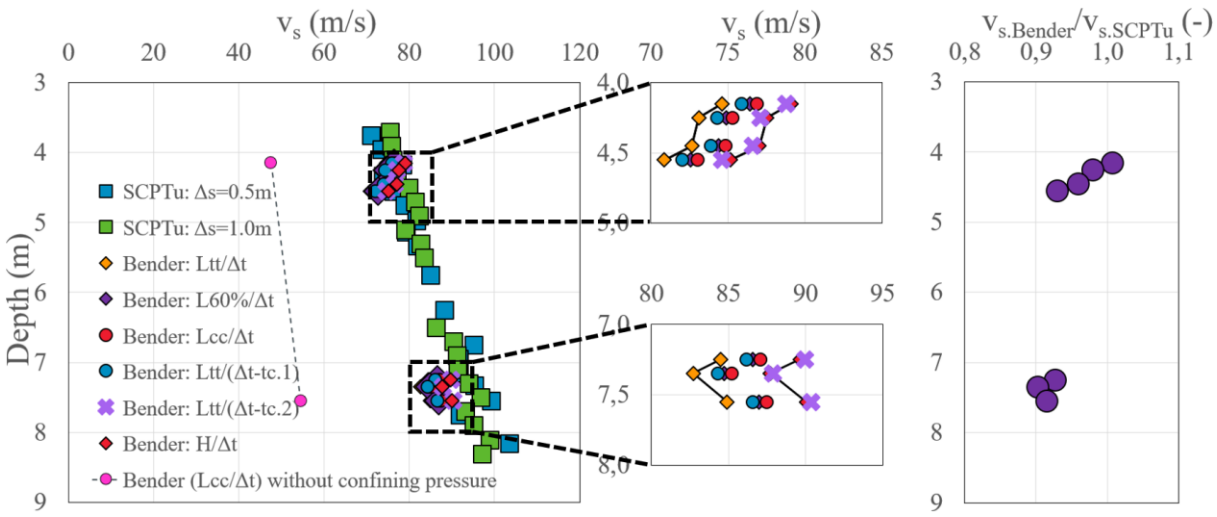

Figure 9: v_s registrations from SCPTu and bender tests.

Figure 9 shows that there is good agreement between values from the field and the laboratory. The geometric assumptions on wave travel distance in the bender test has an impact on the results, amounting to about 6% difference between the highest and lowest values for a 10cm sample. For a 1.6 cm sample (as used in some DSS test) this difference would amount to about 35%.

The t_c registration in Figure 7 show that the registration without confining pressure was the only one where the wave dampened quickly after the initial burst. This would suggest that the cell pressures can have created a small gap between the sensors. Correcting v_s with the first t_c registration is in agreement with both the case where the travel distance is selected as the distance between the center of dynamic pressure for the elements [3] and the center to center distance (our initial assumption). The 60% embedded bender element height assumption is about the same as the average of the two others and is selected as the representative value from the bender test. This value is then compared to the best fit line through all the SCPTu data in order to generate the ratio between v_s values from the field and the laboratory as shown to the right in in Figure 9.

7. Comparison of measurements to CPTu correlations

Several correlations exist in the literature that correlate shear wave velocity with CPTU data. These correlations are useful to provide estimate of v_s when tests to directly determine v_s are not carried out. In this section the obtained field v_s data are compared with some selected correlations. CPTU-based correlations most commonly relate v_s with q_c (e.g. [8]), q_t (e.g. [9] , [10]) and q_t and B_q (e.g. [9], [10] and [11]). A correlation based on effective stress [12] is also looked at.

CPTu data from borehole 289 is used to estimate vs using existing correlations and compared to the measured vs from the SCPTu tests. It should be mentioned that due to insufficient saturation of probe for bore hole 289, the u_2 data was not considered reliable. Therefore, a representative u_2 profile was established based on several CPTu tests carried out within the site. These tests have shown consistent u_2 measurements with low variability. This u_2 profile is combined with qc data taken from borehole 289 for use in the correlations. The estimated vs values using the various correlations are given in Figure 10.

Correlations based on q_c gave significantly lower estimates of v_s as compared to our measurement and are not presented herein. The correlations based on q_t (Figure 10 left) were seen to be better and

especially the correlations by Long and Donohue [9] gave a very good match with the measurement. However, when correlations based on B_q and q_t are used (Figure 10 right), the measured data lies between Cai et al. [10] and Shahri and Naderi [11]. For this case, Long and Donohue [9] gave similar result as the effective stress based correlation proposed by L'Heureux and Long [12] shown in Figure 1. This relation is observed to overestimate the v_s measurements in situ for the current test (Figure 10) as well as other tests at the site (Figure 1).

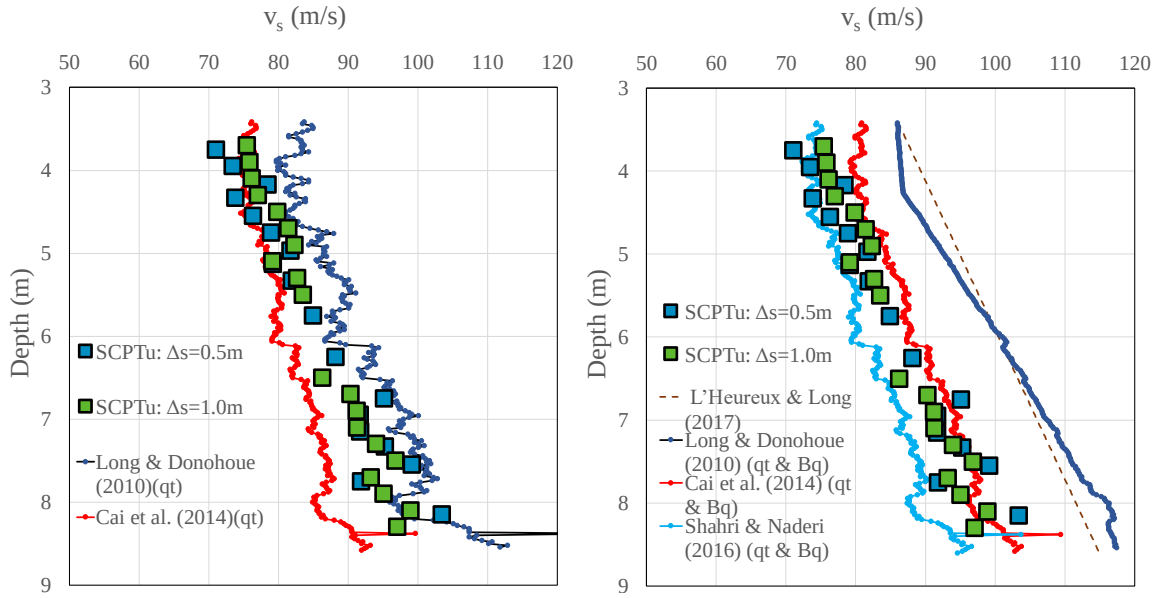

Figure 10: v_s measured in the site as compared to various correlations with q_t (left) and q_t and B_q (right) from literature.

8. Conclusions

In this work, comparison of v_s in laboratory and in situ is carried out. Various aspects related to the determination of v_s have been investigated.

It is clear from Figure 9 that field and laboratory registrations of v_s are in good agreement with each other as the ratio between them range from 0.9 to 1.0. This is a very positive result when compared to other findings given in [1] and [2]. The SCPTu results are slightly higher than those attained with the bender elements and are for the purpose of this work assumed to be the correct value.

Applying confining pressure to the system before conducting the bender test is crucial, as values registered after mounting the sample but before applying confining pressures were found to be about 40% lower than those produced after confining pressures were applied. We allowed the specimens to consolidate before running bender tests. It is unclear if similar results would be attained if the test would be conducted immediately after applying confining pressures before the end of consolidation. This is, however, of limited importance to the NPRA as its procedure allow samples to reach end of consolidation before continuing to other phases in the triaxial test.

Sample storage is found to influence the results from bender tests, but the effect is less than that found for the undrained shear strength. The only bender test that had a ratio of 1.0 to the SCPTu test was conducted the day after sampling, but the stored specimen from the same sample reached a ratio to the SCPTu of 0.98. It is worth noting that samples from larger depths reached lower ratios to the SCPTu than samples taken from shallower depths.

Selected CPTu correlations are compared to the measured v_s values in situ. Some of the correlations tested agreed well with the measured data while others did not fit well. Based on this single CPTu from position 289 correlations by [9] and [10] (based on q_t) as well as correlations by [10] and [11] (based on q_t and B_q) gave a good estimate of the upper and lower bound of the measured data. This is promising as it shows that one could easily develop local CPTu correlations for v_s.

The NPRA method of comparing time series within a given window has proven to be a robust method for an initial interpretation but does require a manual evaluation and the occasional adjustment. In the interpretation method, NPRA is also looking at performing the time delay analysis with a frequency analysis. This will be the focus in future work as this approach is considered to have great potential.

9. Acknowledgements

The authors would like to thank the skilled field operators responsible for the in-situ testing and soil sampling, Tore Westheim, Jon Arvid Reiersen and Ole Vidar Kirkevollen. Without their expertise this project would not have been possible.

We would like to thank the NGTS project for providing access to the site at a very short notice, as well as for the site characterization report, which proved to be instrumental for planning a successful project. Finally, we would like to thank the NPRA for providing funds for this project and encouraging us to write this paper on it.

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