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Evaluation of selected procedures for estimating shear wave velocity with SCPTu and bender element

Évaluation des procédures sélectionnées pour estimer la vitesse de propagation des ondes de cisaillement avec SCPTu et capteurs «Bender elements»

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ABSTRACT: The shear wave velocity (v_s) is an important soil and rock property that can be used in several geotechnical problems including for evaluation of dynamic properties of soils and determining the maximum value of soil stiffness at small strain. The Norwegian Public Roads Administration (NPRA) has developed internal procedures and techniques to standardize logical interpretations of v_s. The modified interpretation procedure that NPRA is adopting is used on raw data extracted from a project where a 5 km long bridge, named Bjørnafjorden bridge, is planned. For this project v_s was evaluated with a bender element as well as in-situ using the SCPTu. The field work is carried out at large water depths and at great cost, which adds to the importance of the investigations yielding useful results for the project. The results from the new NPRA procedure are compared with various interpretation procedures adopted in the current practice. It is seen that correct interpretations are necessary especially for the laboratory tests as these are sensitive to changes in experimental conditions. Recommendations on how to reduce discrepancies between laboratory and field data are given.

RÉSUMÉ: La vitesse de propagation des ondes de cisaillement (v_s) est une propriété importante du sol et de la roche qui peut être utilisée dans plusieurs problèmes géotechniques, notamment pour l'évaluation des propriétés dynamiques des sols et la détermination de la valeur maximale de la rigidité du sol à faible déformation. L'Administration publique des routes norvégiennes (NPRA) a développé des procédures et des techniques internes pour normaliser les interprétations logiques de la v_s. La procédure d'interprétation modifiée développée par la NPRA est utilisée sur des données brutes provenant d'un projet où la construction d'un pont de 5 km de long, appelé pont Bjørnafjorden, est prévue. Pour ce projet, v_s a été évalué avec deux capteurs «Bender elements» ainsi que sur place à l'aide d'un piezocone séismique (SCPTu). Le travail sur le terrain est effectué à de grandes profondeurs d'eau et à un coût élevé, ce qui ajoute à l'importance des enquêtes donnant des résultats utiles pour le projet. Les résultats de la nouvelle procédure NPRA sont comparés aux différentes procédures d'interprétation adoptées dans la pratique actuelle. On constate que des interprétations correctes sont nécessaires en particulier pour les tests de laboratoire car ceux-ci sont sensibles aux changements des conditions expérimentales. Des recommandations sur la manière de réduire les écarts entre les données de laboratoire et de terrain sont proposées.

KEYWORDS: bender elements, shear wave velocity, scptu, geotechnical laboratory testing

1 INTERPRETING SHEAR WAVE VELOCITY

The shear wave velocity, v_s is measured by the NPRA either in the field by using a seismic CPTu (SCPTu) or in the laboratory using bender elements. The principle for both is to create a shear wave in the soil and measure with one or more receivers when the wave reaches the receiver(s). In order to correctly calculate v_s the exact time of arrival and distance from the wave origin must be determined. In the laboratory accurately measuring the distance of the wave path is crucial in order to produce accurate results because the limited size of the specimen will cause inaccuracies to have a much greater influence on the calculated velocity than for field measurements.

1.1 *NPRA procedures*

In 2019 the NPRA conducted a series of laboratory and field investigations in order to establish internal procedures for evaluating shear wave velocity. [6] The tests were conducted at a geotechnical test site in Onsøy, Norway using SCPTu field measurements and high quality, ø160mm block samples for bender element tests in a triaxial apparatus. By assuming six different plausible wave travel lengths for the bender element tests results showed a variation in v_s by 4.3-5.5m/s for a 10cm sample. This is an average of 5.7% uncertainty when compared to v_s acquired from the SCPTu at the corresponding depths and comparably this uncertainty would increase to about 35% for a sample with a 1.6cm height which is used for instance in a DSS test.

The NPRA procedure for laboratory measurements of shear wave velocity was established as bender element tests on a (H≈100mm) triaxial specimen after consolidation to *in situ* conditions is complete. The deformation during consolidation is to be accounted for and the shear wave travel length is chosen as L_{60}, using 60% of the embedded bender element depth as illustrated in figure 4.

1.1.1 *Interpreting the data and calculating v_s*

The SCPTu is a CPTu equipped with two sensors at a fixed distance which are used to capture a shear wave generated at surface level. By measuring the arrival time of the shear wave for the two sensors it is possible to calculate the velocity of the shear wave. A visualization of the SCPTu is provided in Figure 1.

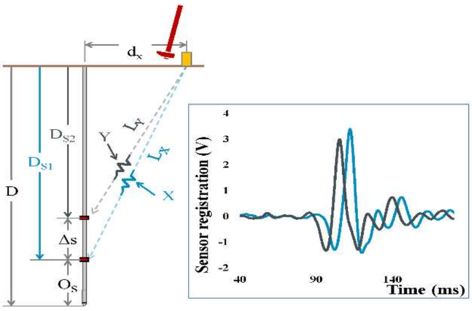

Figure 1. Generating and measuring a shear wave using the SCPTu. The arrival time of each wave is plotted and the difference between the wave arrivals is the travel time Δt.

In order to correctly calculate the velocity of the wave the sensor spacing and the horizontal distance to the wave source must be known. The NPRA procedures uses a comparison of the waves within a given window in order to establish the correct time difference between the arrival of the waves at each sensor. This is considered to be a more robust interpretation than comparing single points, such as peak to peak. The window is set to contain the first peak point and stop at the opposite peak. The window may be manually adjusted to fit the specific data if needed. Within the window of calculation, shown in Figure 2, the coefficient of determination, R^2 between the two data sets is used to find the time shift at which the two waves correspond.

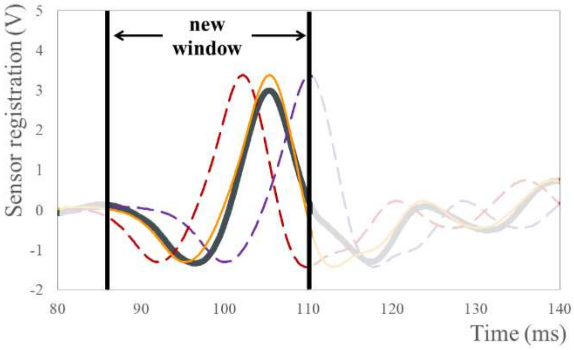

Figure 2. Establishing a window of calculation in which the waves from each sensor are compared by shifting one wave along the time axis and calculating R^2.

The coefficient of determination, R^2 is found using Eq.1

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

Where $\bar{x}$ and $\bar{y}$ are the sample means of X and Y. The R^2 values are then plotted against the time shift for each calculation within the window and the optimal R^2 value is chosen to determine the wave travel time as shown in Figure 3.

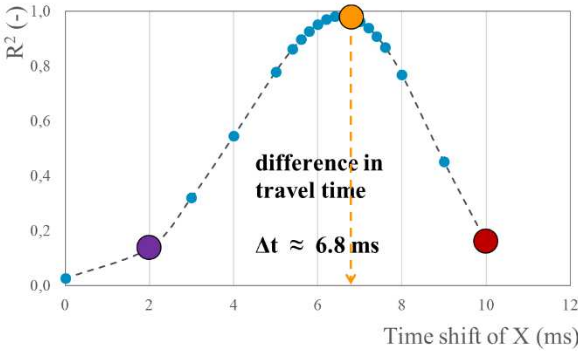

Figure 3. R^2 for different time shifts of one wave in order to find best possible fit to the other wave.

The travel distance, in accordance with the geometry presented in Figure 1 is calculated using Eq.2

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

Where Lx and Ly are the travel lengths of waves X and Y, D_{S1} and D_{S2} are the depths of the sensors and d_x is the horizontal distance to the wave source. The shear wave velocity is then given as travel distance ΔL divided by time shift Δt.

Similarly to the wave analysis used on the SCPTu data, the same R^2 over time shift procedure is used when interpreting the data from bender element tests in the laboratory. In accordance with the findings from the 2019 NPRA project [6] the wave travel distance is chosen as the distance between the bender elements at 60% embedded depth (Figure 4), taking into account the vertical deformation of the specimen during consolidation. As opposed to the SCPTu method, the generated shear wave in the bender element test is controlled by input settings and is therefore a perfect sinusoidal wave. Establishing a good fit to the received wave may therefore require some manual adjustments to the calculation window in order to acquire an acceptable R^2 value as the received wave will be a somewhat distorted version of the source wave.

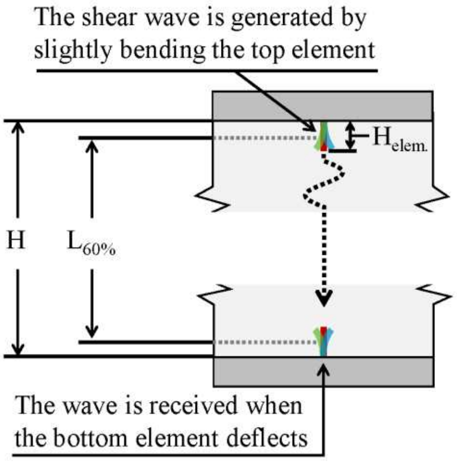

Figure 4. Bender elements principle drawing.

The calculation window used by the NPRA for data from the bender element tests is illustrated in Figure 5.

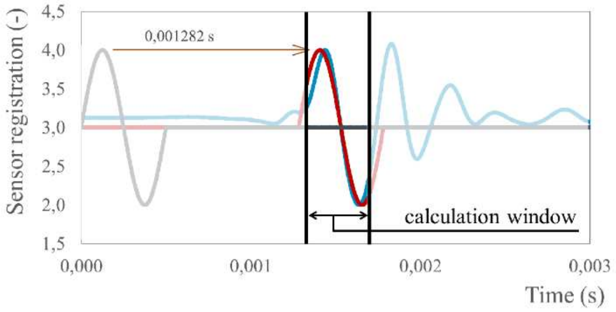

Figure 5. Principle for calculating travel time of the generated wave to reach the receiver with the bender element test method.

2 EFFECTS OF CONSOLIDATION STRESS WHEN INVESTIGATING SHEAR WAVE VELOCITY

The shear wave is transmitted through the grain skeleton and is therefore dependent on how densely the soil particles are packed [2,3]. Closer packed particles increase the density and increases the stiffness of the material. The effective stress working on the soil matrix directly affects the void ratio and density of the material and therefore it must also directly affect the shear wave velocity and small strain stiffness. A larger effective stress will lead to a greater compaction of the grains and a higher stiffness. When a soil specimen is extracted from the ground and opened in the laboratory it has the opportunity to "swell" due to the lack of confining pressure. Changes in effective stress, temperature and mechanical disturbance during sampling and transport of the sample will further contribute to some permanent changes in the soil matrix from *in situ* condition. When applying consolidation stress before a triaxial shear test the goal is to bring the specimen as close as possible to the state it had *in situ.* By reapplying the confining pressures, the sample will become denser and given that the sample is virtually undisturbed the grain matrix will approach its original state when allowed to consolidate at the correct stress. Some disturbance and permanent mechanical changes from sampling and transportation is, however, inevitable.[2]

The NPRA geotechnical laboratory investigated the significance of using the right confining pressures on high quality ø160mm block samples from Skoppum, Norway. The clay is a low-plasticity, quick clay with a sensitivity ranging from 240 at 4.5m depth to 390 at 10m depth. All samples have a remolded undrained shear strength > 0.1kPa and a water content between 35-40% with a plasticity index of 3% and 6%. The shear wave velocity was measured *in situ* using SCPTu. The confining pressure used for consolidation before bender element tests in the triaxial apparatus were calculated based on CPTu, pore pressure measurements nearby and previous laboratory investigations from the area. The goal was to investigate the effect of effective stress application on laboratory shear wave measurements while working within the range of realistic stresses based on common methods for deciding consolidation stress. Active triaxial tests were conducted with shear wave velocity measurements on the lowest realistic effective stresses, assuming a higher ground water table and lower mean weight of soil for overbearing pressure. The second set of tests were conducted at higher effective stresses, still within a realistic window for soil testing during construction projects. Table 1 shows the confining pressure and information for the tests:

Table 1. Assumed *in situ* stress of triaxial specimens. Specimens with high assumed overbearing pressure are shown in gray.

Depth	Mean overburden weight	Pore pressure	Eff. axial stress	Eff. radial stress	K'0
[m]	[kN/m^3]	[kPa]	[kPa]	[kPa]	[-]
4.55	18.5	56.70	27.48	21.98	0.8
4.65	19.5	48.00	43.65	34.92	0.8
6.07	18.5	77.98	34.56	27.65	0.8
10.07	18.5	133.98	52.32	41.85	0.8
10.15	19.5	129.75	68.18	54.54	0.8

The over-consolidation ratio (OCR) is the relationship between the highest stress the soil has been subjected to, commonly referred to as the preconsolidation pressure, p'$_c$, and the current pressure conditions, σ'$_v$. The OCR of the Skoppum clay was investigated using CRS oedometer tests to establish p'$_c$. This is interesting in order to evaluate where the bender element tests were conducted within the yield surface area and in relation to the *in situ* stress state. Figure 6 shows the stress-strain relationship as well as the stiffness measured by the oedometer modulus, E$_{oed}$ of the tests at depths 4.55m, 6.07m and 10.07m.

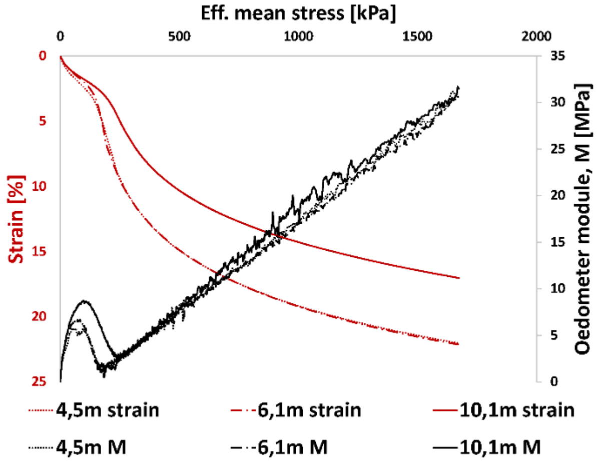

Figure 6. CRS oedometer tests on Skoppum clay samples. Effective stress(top) vs strain(left) and vs oedometer modulus, stiffness(right).

Index parameters of Skoppum clay and parameters based on results of oedometer tests are listed in table 2 and 3.

Table 2. Index parameters of Skoppum clay. Liquid limit, w$_l$, plasticity index, Ip, Sensitivity, St and natural water content, w.

Depth [m]	w$_l$ [%]	Ip [%]	St [-]	w [%]
4.55	23	3	240	38
6.07	24	6	283	39
10.07	24	3	387	34

Table 3. Earth pressure conditions based on results of oedometer tests

Depth [m]	OCR [-]	K'0 [-]	p'$_c$ [kPa]
4.55	3.6	0.8	160
6.07	3.4	0.8	170
10.07	3.3	0.8	225

The oedometer results indicate an *in situ* OCR of 3.3 - 3.6 and good sample quality. The triaxial tests with bender elements were consolidated as shown in table 1. The over-consolidation ratios at the time of bender element testing are shown together with resulting shear wave velocities in table 4. When approaching the same OCR as the assumed *in situ* state, the shear wave velocity is 4.2 and 3.7% closer to the mean SCPTu readings at the corresponding depths for the 10.07m and 4.55m samples, respectively.

The triaxial shear tests from the Skoppum mini block samples are presented in Figure 7 as maximum shear stress versus effective radial stress. The stress paths of the samples with lower consolidation pressure, shown in black, are showing similar behavior to the highly over consolidated sample in figure 8. This is to be expected for a low plasticity sample consolidated well within its yield surface, as illustrated in the figure.

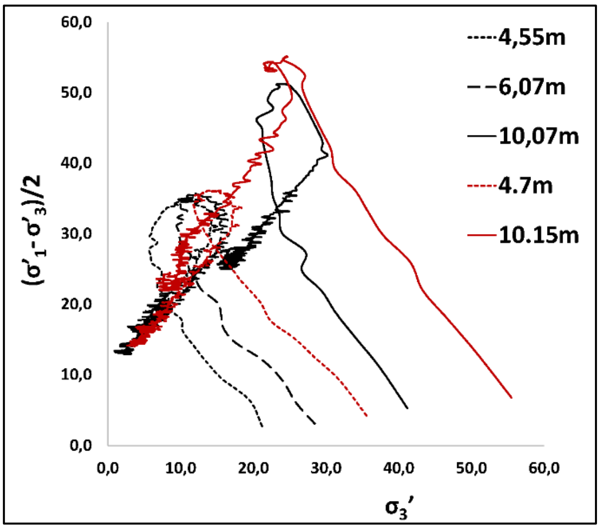

Figure 7. Triaxial shear tests from Skoppum. Tests conducted on samples from 4.5m, 6.07m and 10.07m consolidated to lower range of assumed stress state in black and samples from 4.65m and 10.15m consolidated to highest assumed stress state in red

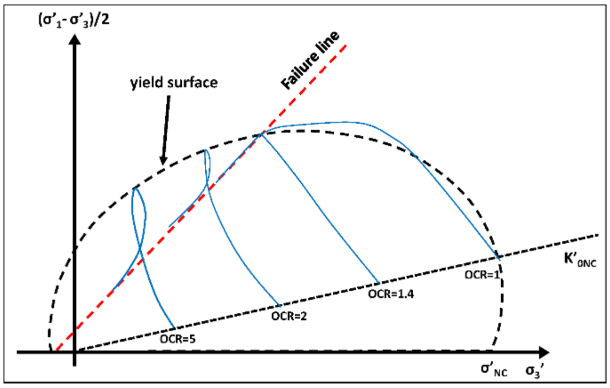

Figure 8. Stress history effects on triaxial shear test. Example of different consolidation stress within materials yield surface. [7]

The shear wave velocity has been measured with bender elements for each of these samples after consolidation is complete and before continuing the triaxial tests. The results from 4.5m depth are presented in Figure 9a and b, as triaxial shear stress path and measured shear wave velocities, respectively. The results from 10m depth are presented in Figure 10a and b. In addition, the shear wave velocities are listed in table 4.

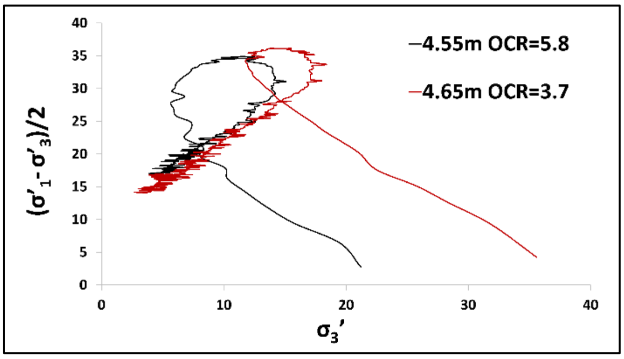

Figure 9a. Shear stress path of triaxial specimens from Skoppum, Norway. Lower-consolidated samples are presented in black and the higher-consolidated samples are in red.

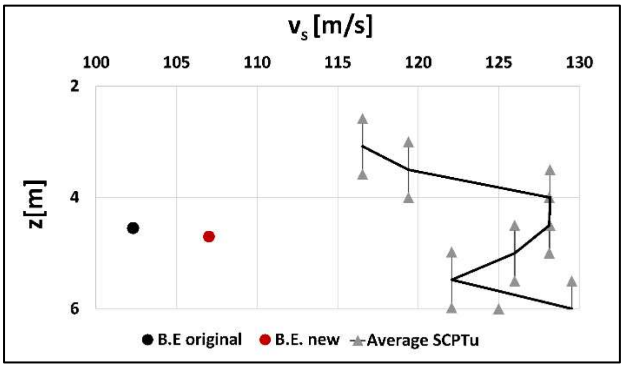

Figure 9b. Shear wave velocity measured with bender elements and SCPTu from Skoppum, Norway. The Lower-consolidated sample is presented in black and the higher-consolidated sample in red, average SCPTu shear wave velocities are shown in gray.

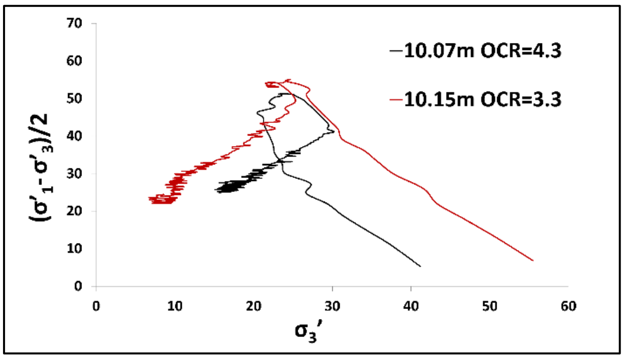

Figure 10a. Shear stress path of triaxial specimens from Skoppum, Norway. Lower-consolidated samples are presented in black and the higher-consolidated samples are in red.

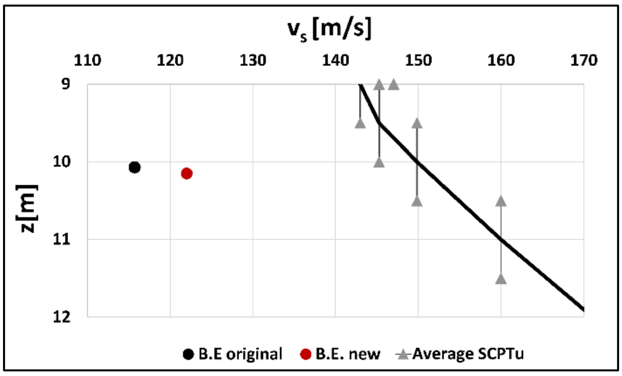

Figure 10b. Shear wave velocity measured with bender elements and SCPTu from Skoppum, Norway. The Lower-consolidated sample is presented in black and the higher-consolidated sample in red, average SCPTu shear wave velocities are shown in gray.

Table 4. Shear wave velocities from mini block samples and SCPTu. OCR refer to the preconsolidation pressure created by the stress history versus the triaxial consolidation pressure of the specimen.

Depth [m]	$v_{s,}$ SCPTu [m/s]	$v_{s,}$ b.e. [m/s]	b.e./SCPTu [%]	OCR [-]	Days in storage
4.55	128.1	102.3	79.8	5.8	5
4.65	128.1	107.0	83.5	3.7	14
6.07	129.5	102.7	79.3	4.9	1
10.07	149.8	115.7	77.2	4.3	3
10.15	149.8	122.0	81.4	3.3	16

The results show that the shear wave velocity of the under consolidated samples deviates from the average SCPTu measurements at the corresponding depths by roughly 20 - 23%. The samples that were consolidated closer to the assumed *in situ* stress state are closer to *in situ* mean measurement by approximately 4%. It is important to note that these samples are stored approximately 10 days more than those consolidated to a higher OCR, as shown in table 4. Previous investigations by the NPRA revealed a decrease in v_s for stored mini block samples with high-plasticity Onsøy clay of 1.9 - 2.4% of the original v_s after 3 weeks in storage [6].

The NPRA conducted a similar test scheme with bender elements on consolidated triaxial specimen versus SCPTu measurements on high plasticity (Ip = 30% - 45%), normally consolidated Onsøy clay in 2019 with laboratory results ranging from 90 - 100% of the mean corresponding SCPTu values [6]. That the increased consolidation pressure leads to an increase in v_s is expected, however, the increase is not enough to bring the laboratory test results from Skoppum within 90% of the SCPTu measurements. One key difference between the cases is the plasticity of the clays. A soil is considered to be plastic when the water content is within the liquid and plastic limits, this range is referred to as the plasticity index, Ip. The Ip therefore works an indicator of how much a change in water content will affect the soil. A low plasticity clay will be much more affected by small changes in water content and pore pressure that occur during sampling, than a high plasticity soil. [3] It is reasonable to assume that the low plasticity of the Skoppum clay is a contributing factor to the lower correlation between laboratory and field tests as these materials are generally more prone to disturbance from sampling and transportation.[1] Further laboratory testing of shear wave velocity on different materials is necessary in order to gain experience and increase understanding of shear wave velocity tests with bender elements.

3 INTERPRETING BENDER ELEMENT TESTS FROM DIRECT SHEAR STRESS(DSS) SAMPLES FROM BJØRNAFJORDEN

The shear wave velocity investigations at Bjørnafjorden consists of SCPTu in 8 locations as well as three triaxial specimens equipped with bender elements from three locations and five direct shear specimens (DSS) with bender elements from four locations [5,6]. The data from the bender elements were originally interpreted as transmitted wave top to first clear wave top of the received wave. The shear wave velocity was then calculated based on a travel length equal to:

$$L = H_0 - \Delta H - H_{elements}$$

Where H_0 is the original specimen height, ΔH is the change in specimen height after consolidation and $H_{elements}$ is the full height of both bender elements. When re-examining the tests, the raw data of each shear wave has been fitted to the origin wave by optimizing the R^2 value of the two waves and the travel time of the shear wave has then been divided by $L_{60\%}$, as described in chapter 1. The original and the new shear wave velocities are presented in figure 11 and table 5 together with the corresponding SCPTu v_s values.

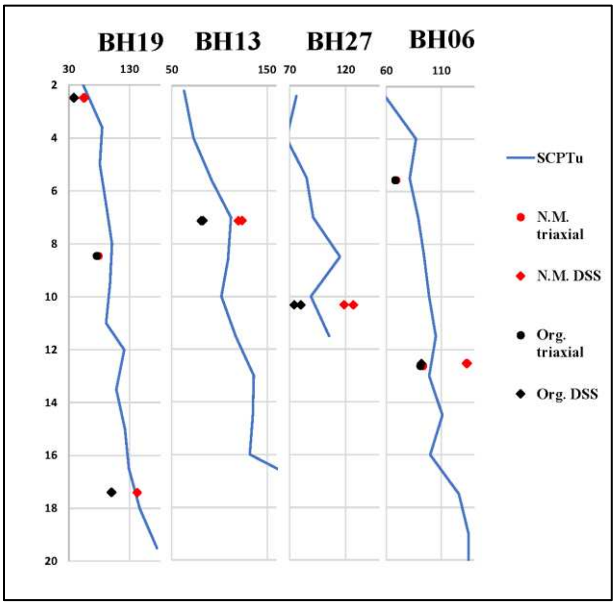

Figure 11. Shear wave velocities from Bjørnafjorden, Norway. Original v_s from bender elements in black, new NPRA method in red and SCPTu in blue.

Table 5. Original and new NPRA method shear wave velocity results from Bjørnafjorden.

BH	z [m]	Travel time [ms]		V_s B.E. [m/s]		V_s, SCPTu [m/s]	
		Org.	New	Org.	New		
19	2.48	0.181	0.186	38	54	54	DSS
19	2.48	0.186	0.181	38	56	54	DSS
19	8.46	1.317	1.308	76	78	101	TR
19	17.4	0.075	0.075	100	142	138	DSS
13	7.13	0.085	0.084	81	120	112	DSS
13	7.13	0.081	0.081	83	124	112	DSS
27	10.32	0.071	0.071	80	127	89	DSS
27	10.32	0.077	0.076	74	119	89	DSS
06	5.57	1.977	1.983	68	69	81	TR
06	12.53	0.078	0.078	92	134	102	DSS
06	12.53	0.078	0.078	92	133	102	DSS
06	12.63	1.102	1.103	91	93	102	TR

The Bjørnafjorden bender element tests range in height from the tallest triaxial specimen of 14cm to the DSS specimens of 1.6cm. In addition, the height of the bender elements ranges from 0.55cm to 0.81cm. A shear wave signal may be difficult to interpret due to signal disturbance and in some cases elements of wave distortion. The source of error in determining the wave travel time is impossible to eliminate completely. Accepting that there is some uncertainty in the wave travel time, we must strive to limit the effect of it. As can be seen from the results in Figure 11 and table 5, the DSS samples are much more sensitive to changes in interpretation of the data, with some results getting closer to the field measurements while some are further off than before. Figure 12 shows the $L_{60\%}$ of the original specimen before consolidation, original specimen height minus 60% of the height of both elements, and the percent change in v_s with the NPRA interpretation versus the original. The triaxial tests (in black) with $L_{60\%}$ starting height of 10.5cm shows a 3% increase in v_s with the NPRA method. This is consistent with the findings at Onsøy where the increase was about 4%. The DSS specimens (in blue) show an increase in v_s between 40 - 60% because of the change in interpretation method.

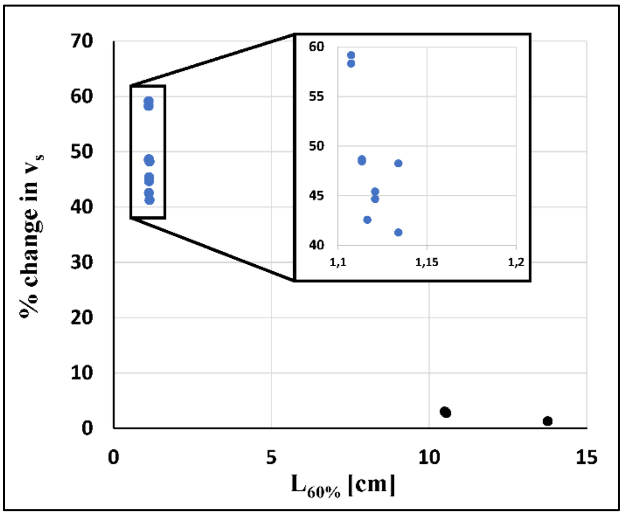

Figure 12. Change in shear wave velocity with varying specimen height. Triaxial tests in black are not as sensitive to interpretation method as the DSS tests in blue.

The results show that whenever possible, bender element tests should be carried out on triaxial specimens where the height of the sample is sufficiently large to decrease the uncertainty of interpretation below 5%.

4 CONCLUSIONS

The low plasticity clay from Skoppum show a significant discrepancy between laboratory bender element results and *in situ* SCPTu measurements with results approximately 20% lower than field measurements. While further study and experience is needed with different types of materials, it is clear that the plasticity is an important factor when studying the shear wave velocity of sampled soils in the laboratory. When assuming a low overburden pressure and higher pore water pressure within what is reasonable to assume, the shear wave velocities were about 4% further from the SCPTu data than the tests where a higher overburden pressure and somewhat lower pore pressure were assumed. That the consolidation stress affects v_s is not surprising however, the impact on v_s while operating within reasonable assumptions of *in situ* stress conditions are not well documented. Specimen height is seen to have a much more significant effect on the interpretation of v_s with reduced travel distance causing a significantly reduced accuracy based on the Bjørnafjorden data. Choosing the right consolidation pressures is important to get as accurate results as possible.

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