Seismic Cone Penetration Test. Experimental results in onshore areas.

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Abstract

The use of cone penetration test (CPTu) is an geotechnical onshore site investigation which is often used as well as other more traditional investigations. To begin with, this article will present a detailed description of CPTu, SCPTu and shear waves types. The field tests description provides with information about the soil conditions and draws an idea of the SCPTu set up. For a better understanding of the soil properties, laboratory tests (water content, particle size distribution, pycnometer and hydrometer methods) were performed. The CPTu along with SCPTu results provide with reliable information about soil stratigraphy and a lot of data to be interpreted. Two different methods of finding S-waves are presented along with one method for P-wave in order to analyze and compare with the theoretical assessments.
Keywords: seismic, cone penetration test, S-wave, P-wave, soil classification test, shear velocity.

1 Introduction

The cone penetration test (CPTu) is frequently used in both onshore and offshore construction as geotechnical investigation. The seismic cone penetrometer can dramatically reduce the cost in time efficiency associated with seismic testing, especially if CPTu is used as part of the regular site investigation program. Comparisons of onshore seismic cone shear wave velocities with those measured by both down-hole and cross-hole techniques at sites in Canada, (Rice, 1984), United States, (J.A. Jendrezejczuk) and Belgium, (Bouhon, 2010) have already validated the seismic cone technique.

This article presents and discusses results from SCPT preformed in sand and clay in Aalborg area. The cone bearing, friction sleeve stress, cone pore pressure and shear velocity data can be used to provide a fast and reliable determination of soil type and shear strength, according to (P. K. Robertson). The data given by the cone can be interpreted to get a good continuous prediction of the soil type and shear strength parameters. When a seismometer is integrated into the cone penetration test procedure, the CPTu becomes SCPTu (Seismic Cone Penetration Test). The use of S-Wave velocity data in foundation investigations has become increasingly popular in recent years, but use of this valuable and diagnostic study has been delayed because of the difficulty of obtaining reliable data, particularly under varying geologic conditions, (Beckstead).

To obtain the measurements a rugged velocity seismometer has been incorporated into the cone penetrometer. Downhole seismic shear wave velocity measurements can be made during brief pauses in the CPTu. In (J.A. Jendrezejczuk) the shear wave speed is computed by dividing the distance between two pairs of receivers by the time for the signal to travel from one receiver to the next. There are four types of seismic waves who propagates through the soil. These can be divided into two categories. The first category are the body waves also named flat/volume waves, their displacement is Longitudinal for the P wave and transversal for the S wave, as seen in Figure 1.

The Compression (P) wave are also referred as irrotational waves which propagate through solid and fluids. They propagate at a higher velocity than shear waves. The Shear (S) as said before their direction is transversal but the S waves are also referred as the rotational waves and are unable to propagate through fluids.

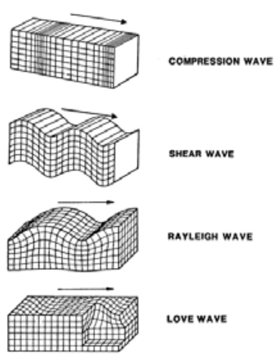


Figure 1: Different types waves. (Rice, 1984)

2 Field test

To have an overview of the two different testing sites, Aalborg is located in Jutland which is part of the north of Denmark as seen in Figure 2. The tests performed in sand were located in the east part of Aalborg, the industrial part of the city. On the location of the site a wind turbine blade deposit will be build. The location for the clay soil is in the center of Aalborg, next to the Train Station and the Bus Terminal.

Figure 2: Position of the field test, Wikimedia (2006)

Concerning the sand field, this site is situated a few meters from the fjord which means it is a basin deposit area. The soils composition is: the top layer (1-4 meters) a fjord deposit of clay/gyttia, while the lower layers are is mostly composed of silty sand. The SCPTu were performed until approx. 8 meters depth.

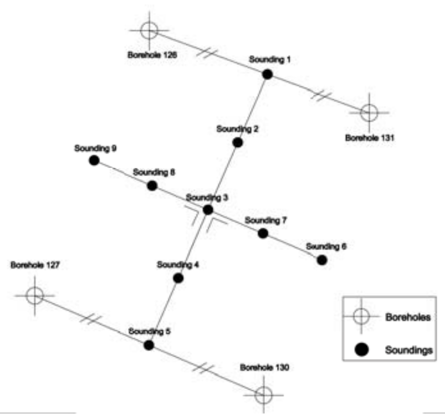


Figure 3: Position of the Boreholes and SCPTu

Nine different SCPTu are executed in a cross-shape positioning. A first line of SCPTu was chosen and the first SCPTu is taken from the middle of Borehole 126 and 131, aligned until reaching the middle of Borehole 127 and 130 (five SCPTu). The distance between SCPTu is of ten meters. From the middle SCPTu a perpendicular line of SCPTu is done keeping the same rule of ten meters between each other so that another four SCPTu are to be done, as seen in Figure 3.

For the clay soil the site is situated in the center of Aalborg. The composition of this in mainly a top layer of sand (2-3) meters of sand and the rest is clay. Five different SCPTu where executed in this location. These SCPTu where realized with a 5 meters distance between each other starting 5 meters away from the Borehole B4 which profile can be seen in Figure 4.

Figure 4: Positioning of SCPTu

Due to a very agglomerate area as the center of the city, different errors could appear in the results of SCPT. These errors can be generated by the construction site situated next to the testing site or the presence of the bus terminal and train station. The works from the site along with the passing of the trains, buses and cars produce mild vibrations that could reach the cone, which is very sensitive on every interference. In addition, another cause for possible errors in the results could be the appearance of the site. The SCPTu were performed on pavement stones and asphalt. The asphalt in comparison with normal soil, or even the pavement stones, absorbs the energy, which causes a poor signal for the waves, therefore errors in the results. The setup can be seen in Figure 5, where for the P-waves, the plate has been mounted into the ground by drilling into the asphalt or removing the pavement stones.

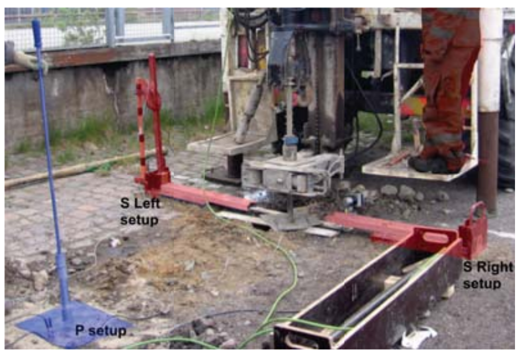


Figure 5: Setup for the shear waves

2.1 Description of the cone.

The cone used for the tests has standard values specified in the E.U and American standards as seen in Figure 6. The friction sleeve, f_s, which is placed above the conical tip, also has a standard dimension of 150 cm^2. A pore pressure transducer is installed to measure the dynamic pore pressure during the penetration.The cone penetrometer is pushed into the soil at a standard speed of 20 mm/s.

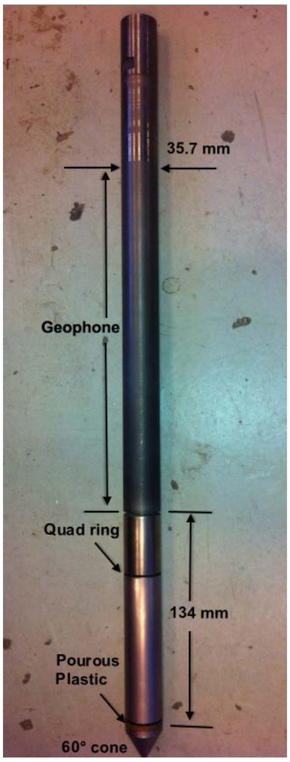


Figure 6: The standard type of cone.

The memo cone used in this SCPT and the equipment has a certain number of standard values (E.U and American) properties:

- A conical tip;
- A $10cm^2$ probe with a tip angle of 60°;
- A 7 channel measuring: point resistance, q_c, local friction, f_s pore pressure, u , tilt, temperature, electric conductivity, seismic, uniaxial for shear wave measurememnts;
- Depth synchronization;
- Data acquisition system and software;
- Data interpretation, CPT-LOG software.

The signal is transmitted up through the steel of the rods to a microphone on the penetrometer. The absence of the cable makes the system very easy and time efficient in usage. The measurements were used until 8m, engineers choice, with a penetration rate of 20 mm/s. In certain cases the soil was pre-drilled due to fill. The cone penetetrometer is advancing through the soil by being pushed firmly and continuously in the ground by the truck machine creating mechanical contact between the seismometer carrier and the soil. Therefore, allowing good coupling and signal response both for clay and sand. Also, the orientation of the cone is controlled by setting up the X and O rings and the depth synchronizer provides with accurate depth measurements.

2.2 Description of machineries and test setup.

The setup of the machinery starts by positioning the CPT truck or cabin crawler over the exact position chosen previously. For the SCPT the seismic sources are a sledge hammer and a piston, which was blown on a steel plate stuck on the ground. After a 1 meter pre-drill, two plates on both sides of the hole are placed in order to insure that the left and the right part of the S wave testing are aligned as seen in Figure 7.

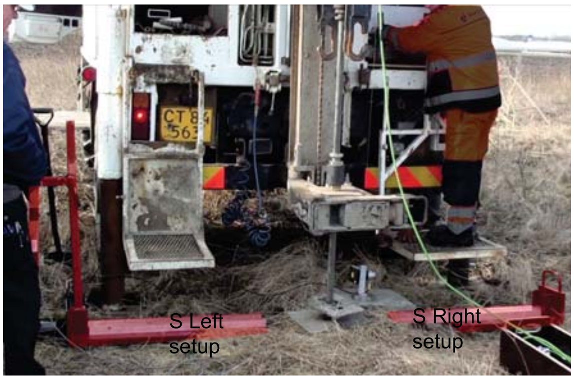


Figure 7: Setup for the shear waves

The plates used in this case are "L" shaped and the bottom of the plate should be equipped with transversal teeth to improve the contact with the ground as seen in Figure 8.

The distance between the place where the hammer hits and the SCPTu hole is of 1,4 meters. To have a constant and exact same force on left and right S wave a mounting has been realized as seen in Figure 9.

Concerning the position for the P waves the distance for this test is at 1,8 meters from the hole through which the rod string is fed. It has to be perpendicular to the S wave set up as seen in Figure 10.

For the P wave generation is a plate with a circular part which is pushed into the soil with a hydraulic or pneumatic piston as seen in Figure 11. The waves were generated by blowing the piston on the steel plate from a free fall.

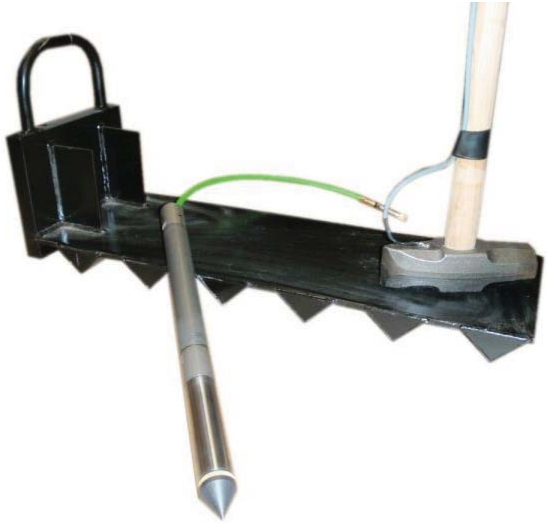


Figure 8: L plate with transversal teeth, Sledge hammer and Penetration Cone Geotech (2012)

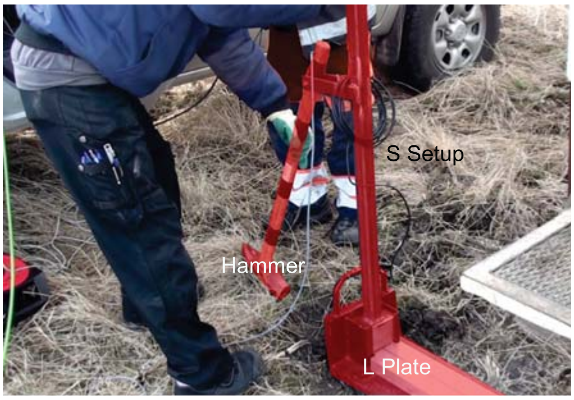


Figure 9: Hammer display

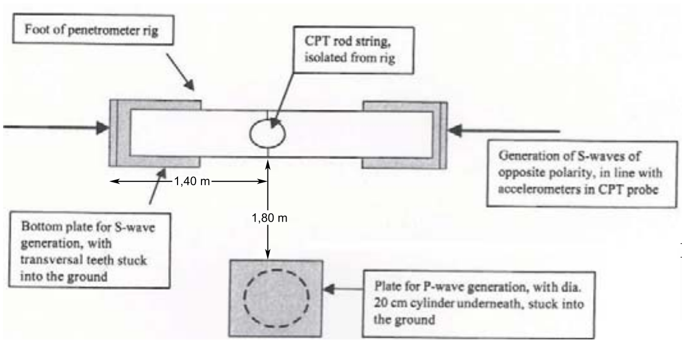


Figure 10: SCPT field setup, Geotech (2004)

Figure 11: Introduction of P wave plate into the ground

A specific hammer has been created to have the comparable wave generated as the one used for the S wave setup. It is also designed to generate a constant hit during the hole test. The hammer is composed a tube of 1,5 meter height which gives a control height on which a chosen weight is dropped off as it can be seen in Figure 12. The seismic signal is generated by striking the L plate pad with the hammer.

Figure 12: Set-up of the P wave test

2.3 Manipulation

The penetration velocity is measured while the rod string is pushed into the soil. Previously, it was defined that the CPT will be performed until 8 meters. The Seismic part of the test is performed every each meter. When the rod string has reached the depth required, the engine of the penetrometer or drill rig are stopped. This is done to give the possibility to realize the SCPT test which is noise sensitive. The interval shear velocity can be easily checked on field, for quality assessment. As soon as the Seismic part is finished the CPT can continue the same way until the desired depth is reached.

3 Soil Classification Tests for Sand

With the data obtained both from the borings and the CPTs results, profiles with soil type stratigraphy, description and corresponding depths were plotted using as in Figure 13. It can be observed that the first layer is a fill layer for the first approx. 2 meters, being followed by a a layer of clay and gyttia and after approx 3 meters fine sand is reached.

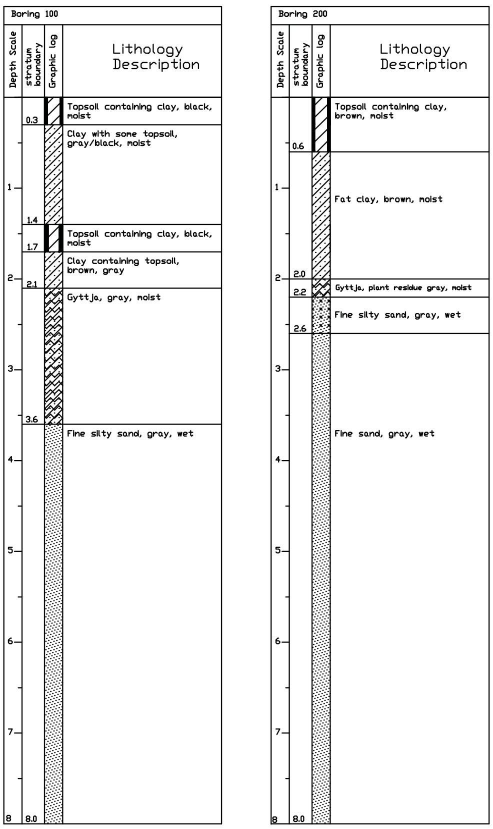


Figure 13: Bore hole 100 and 200 profile with soil type and depth

3.1 Determination of Water Content

From two of the borings seen in Figure 10, soil samples were taken in order to perform several soil classification tests. According to the geotechnical survey from the boreholes, The first test performed was the water content one. This test is performed to determine the water (moisture) content of soils. The water content is required as a guide to classification of natural soils and as a control criterion in re-compacted soils and is measured on samples used for most field and laboratory tests according to (DS/S-19000, 2004a).

The water content, w is defined as the weight loss of the soil in % of the dry weight by drying in an incubator (oven) at a temperature of 105 °C to a constant weight.

$$w = \frac{W_w}{W_s} 100\% \quad (1)$$

$$= \frac{(W + Bowl) - (W_s + Bowl)}{W_s + Bowl} 100\% \quad (2)$$

where,

$Bowl$:	weight of the bowl	[g]
W :	weight of sample before drying	[g]
W_s :	weight of the dried sample	[g]
W_w :	weight of the water sample	[g]

The samples that were tested were taken from half of meter to half of meter until 8 meters were reached. The first two meters of the both borings were covered with topsoil clay. Furthermore, gyttia is found for the first boring until 3.6 meters, whereas for the second one until 2.8 meters. Until 8 meters the presence of fine silty sand was observed.

For all the samples taken from both boreholes Table 1 presents the ranges on which the water content varies in the samples. For Borehole 100, the maximum value represents a gyttia sample situated at 3.5 m depth, whereas the minimum value is fine sand found at 8m. For Borehole 200, the maximum value represents a clay sample situated at aprox. 2.0 m depth, whereas the minimum value is fine sand found at 4 m.

Table 1: Water content results

	Layer	Water content, [%]
Borehole 100	Topsoil - clay	23 - 38
	Gyttia	46 - 62
	Fine sand	17 - 27
Borehole 200	Topsoil - clay	26 - 55
	Gyttia	54 - 56
	Fine sand	20 - 24

3.2 Determination of Particle Size Distribution

After performing the water content test on every sample, 8 samples were chosen for a sieving analysis, 4 out of each boring from different depths as seen in the Table 2.

Table 2: Grain size analysis. Borehole sample details

Borehole no.	Sample no.	Depth [m]	Type of soil
100	9	3.6-4	fine silty sand
	11	4.6-5	fine sand
	14	6.-6.4	fine sand
	17	7.6-8	fine sand
200	25	3-3.4	fine sand
	28	5-5.4	fine sand
	31	6.-6.4	fine sand
	34	7.6-8	fine sand

The screenings on each sieve in % of the dry weight of the total of each sample are plotted into a coordinate system which is function of the sieve dimension, as seen in Figure 14. The screening percentanges are plotted in the vertical axis in an arithmetic scale and the sieve dimensions on the horizontal one in a logarithm scale.

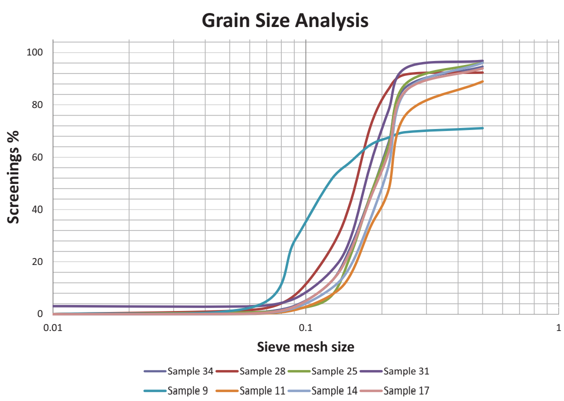


Figure 14: Grain size analysis on sand samples

3.3 Determination of Particle Density - Pycnometer method

From the results observed from the sieving curves four different soil samples were taken in order to perform the pycnometer test in order to obtain the "relative density" found using Equation (3), (DS/S-19000, 2004b).

$$G_s = \frac{W_v}{W_i} \tag{3}$$

where,

W_s : Weight of a given volume soil grain [g]

W_i : Weight of the same volume deionised water at 4°C [g]

The results obtained can be observed in Table 3.

Table 3: Relative density results

Sample no	Relative density, G_s, [-]
9	2.66
14	2.65
25	2.65
34	2.66

3.4 Determination of Particle Size Distribution - Hydrometer test

The hydrometer analysis is the process by which the weight-related distribution of soil grains after size in the silt fraction ($2\mu m$-$60\mu m$). The hydrometer also determines the specific gravity (or density) of the suspension, and this enables the percentage of particles of a certain equivalent particle diameter to be calculated.

According to Section 3.3 the relative density obtained for Sample 9 is 2.66 as seen in Table 3. The grain diameter,d, is found by writing the Stoke's law, (DS/S-19000, 2004c) where the relative density is entered instead of the actual density so it becomes:

$$d = \sqrt{\frac{18\eta * 100}{(G_s - d_0)g * 60}} * \sqrt{\frac{h}{t}} \tag{4}$$

The corresponding values of weight percentages and grain size are put in the same coordinate system as the sieve curve of Sample 9 as seen in Figure 15. The recorded curve part (the beginning one) is considered as the slurry curve.

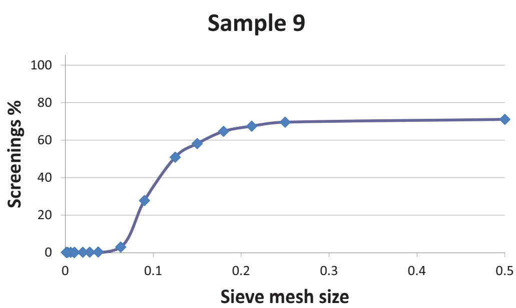
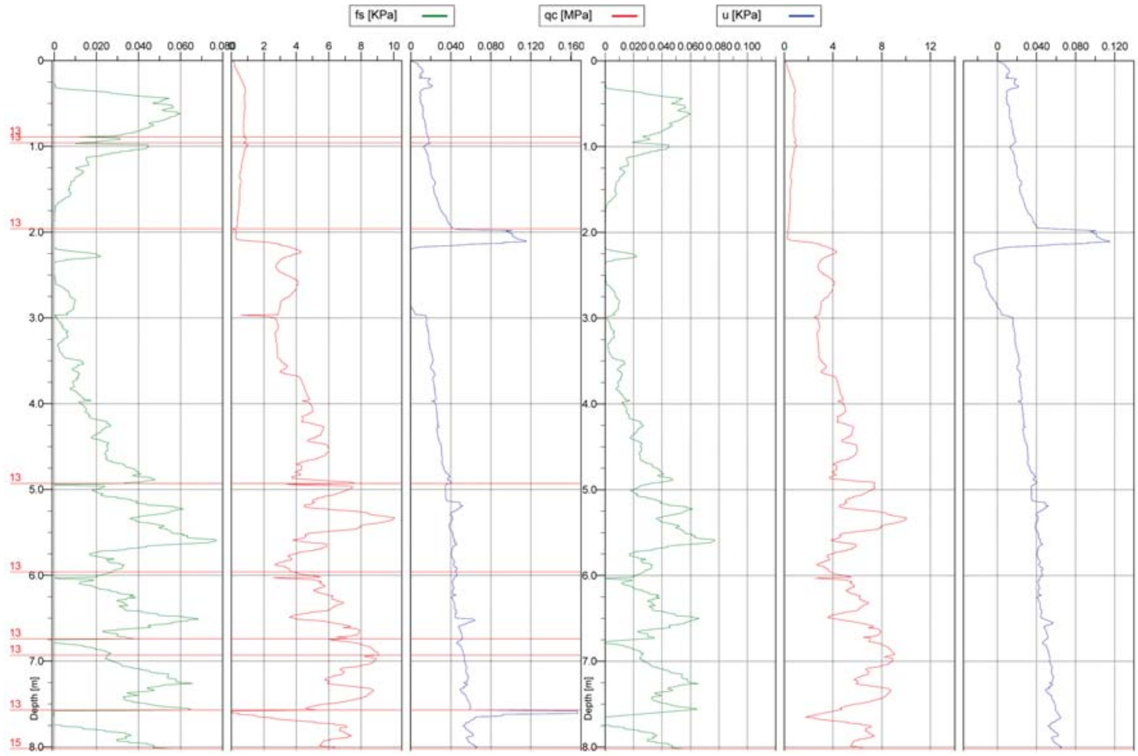
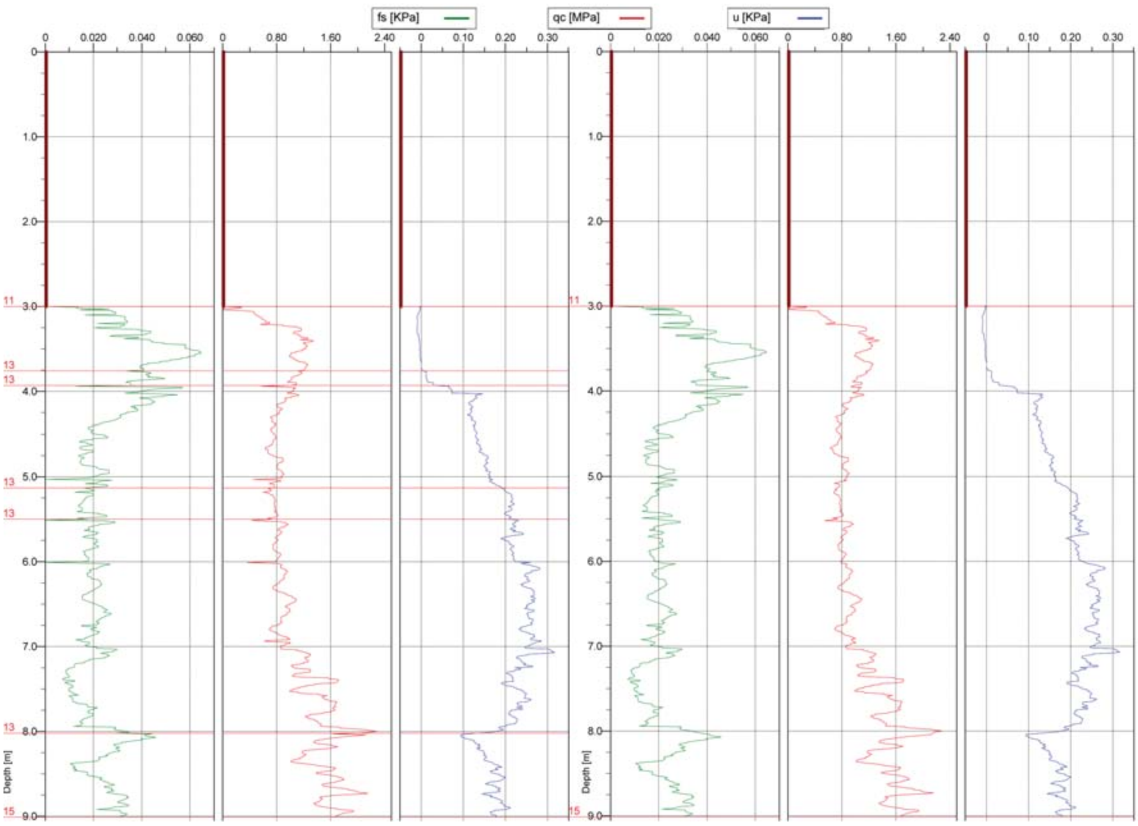


Figure 15: Sample 9 Sieveing curve after Hydrometer Test



(a) Sand



(b) Clay

Figure 16: CPT results before and after error filtering for the soil types seen in Figure 13

4 Interpretation of data

4.1 CPTu Results - Error Filtering

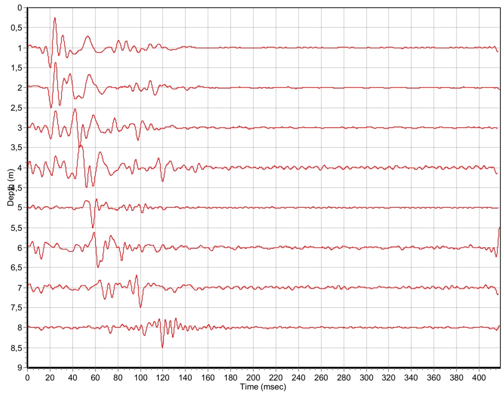
The CPTu is considered as a standard method of assessing soil properties, so measuring errors can occur during the test. Some of them can be detected, other might be, wrongly, assumed to be a real soil property. One of the easiest ways for detecting the errors is by assessing the raw data.

According to (Andersen, 2011) two criteria have formed the base for removing the data. For the first one, measurements with zero cone tip resistance have been removed as a zero cone resistance indicates a cavity in the soil, but for sand deposits is unlikely to happen. The second one takes into account the errors occurring in connection with stops of the cone, during the tests. The stops during the penetration test are caused by the need of attaching new rods or from each meter for performing the seismic tests. These errors are due to halts, and it is often seen as drops in the cone resistance. The rods have a length of 0.95 m and the drops in cone resistance and friction sleeve are seen every meter.

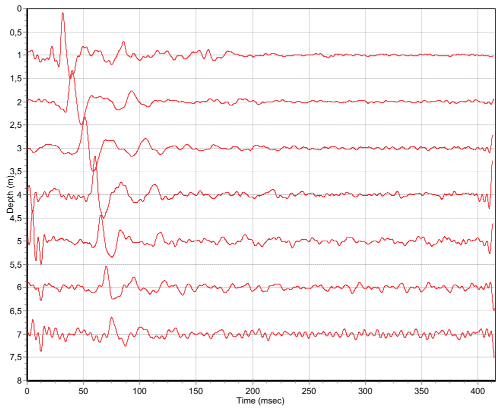
For the sand case, when the sand was getting stiffer, around 7 meters, the cone had to be halted more often, as seen in Figure 16. When the penetrometer is halted, the pressure on the cone and the sleeve friction is released. Cone penetration in sands will not occur completely drained. When the cone stops, small excess pore pressure drains away and again builds up during the penetration. The peaks marked with there lines represent the halts and they were removed as they are not representative of inherent soil properties. This is basically based on engineering judgment. Generally, most of the data removed was errors produced by halts and the final results for clay can be seen in Figure 16.

4.2 SCPTu results - verification of waves

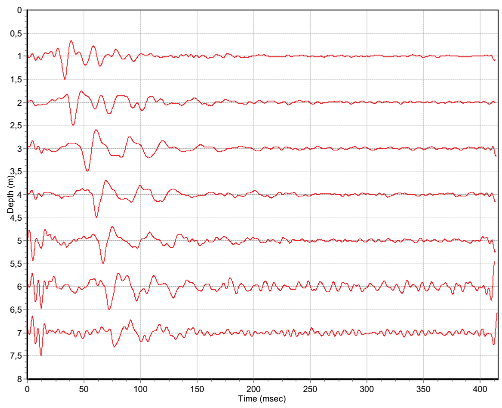
The seismic signal was generated by the blows of the hammer for the S-waves and of the piston for the P-waves, only one blow for each type of wave. The first step of the interpretation of the results was to verify if the signal was spreading in the right direction along with the depth. The profile sheet is used for viewing the seismic signal traces at different depths. For sand, in Figure 17 both compressive and shear waves on the first SCPTu are presented, each graph representing the seismic signal trace loaded file for the corresponding depth. It can be observed that as deep the penetration goes the weaker the signal becomes, which was what it was expected. The difference in the depth is of 1 meter. It can be observed that as deep the penetration goes the weaker the signal becomes.



(a) P-waves



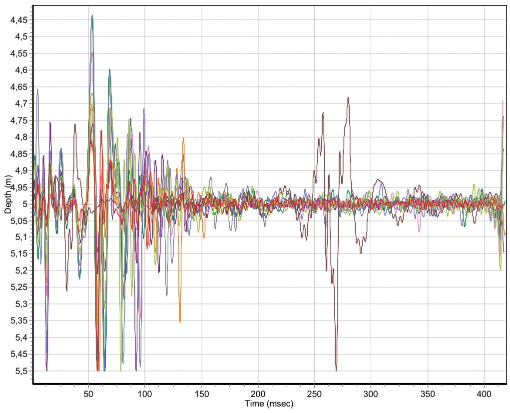
(b) S-waves Left



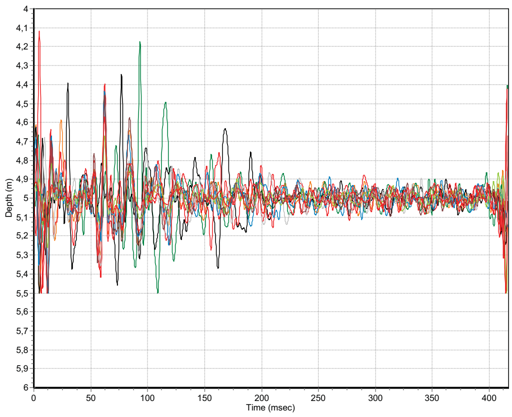
(c) S-waves Right

Figure 17: Shear waves from Sand Sounding

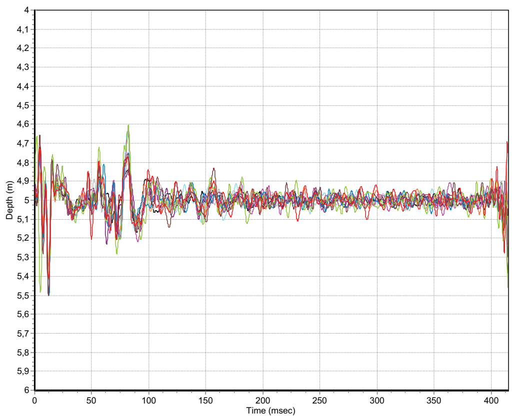
In sand, it was interesting to see if the signal is intercepted correctly by the cone so during one of the SCPTs performed in sand at a depth of 5 meters 10 successive blows were applied for both P-waves and S-waves, left and right and can be seen in Figure 18. Each color represents one blue.



(a) P-waves



(b) S- waves Right



(c) S-waves Left

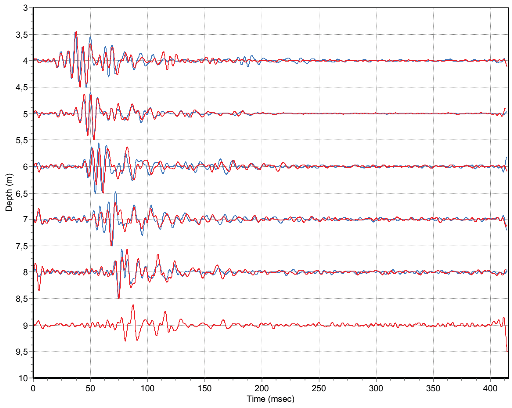
Figure 18: 10 time blow SCPTu waves in 5 meters depth

For the left shear waves it can be observed that the signal is the same after multiple blowing, but for the right one it can be seen that each blow's signal has a different peak at different places in time. As for the P waves it can be mentioned that only one of the blows did not follow the pattern, caused by a possible error in signal, whereas the rest form a peak signal around the same time.

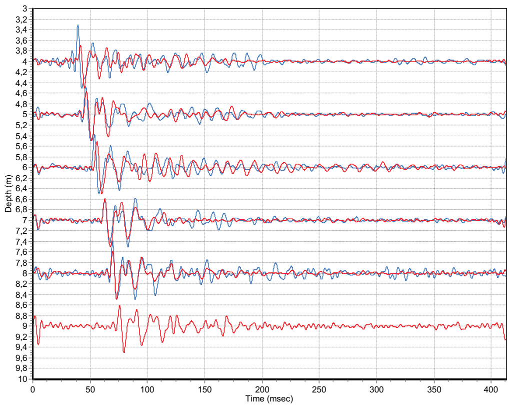
For clay a different approached was used in order to verify the accuracy of the signal. The seismic test was performed both on the cone's way down into the ground but also while removing it, upwards. In Figure 19 are plotted with red color the down direction waves and with blue the up direction ones. It can be observed that on both directions the wave register the same peak, but when it comes to dissipation the ones that are measured on the up direction take more time. This fact can be explained by the void in the SCPTu hole that prevent the propagation and therefore a proper dissipation of the signal into the ground.

Another problem influencing the accuracy of the waves was the location of the tests performed in clay. As mentioned before the location, was next to a bus terminal and the ground was covered with asphalt which made the placing of the SCPTu plates very difficult. In Figure 20 it can be observed that for the P-wave problems were not encountered as the plate was dug into the ground.

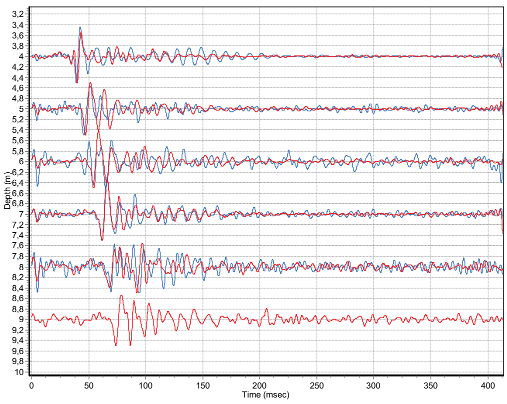
For the S-waves ones it can be observed a difference in signal distribution from one sounding to another. In Figure 21a and Figure 21b it can be seen that in the first meters there is not a defined peak of signal and a possible cause can be the asphalt and the topsoil above the clay layer which can produce delay in signal, hence a faster dissipation. For the last meters the signal registered a peak because at a lower level no surface disturbances are encountered. Therefore for the last SCPTus the S-waves plates were placed on a layer of sand added on the asphalt to reduce the effects of the surface disturbances and so the wave distribution can be seen in Figure 21c and Figure 21c .



(a) P-waves



(b) S-waves Left



(c) S-waves Right

Figure 19: Shear waves from SCPTu in Clay

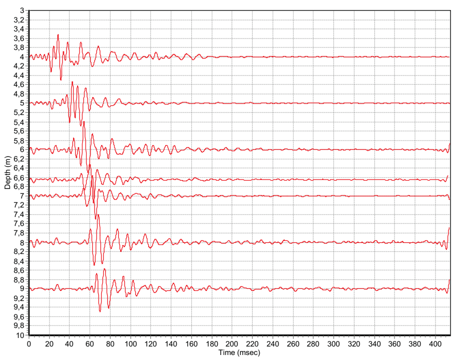
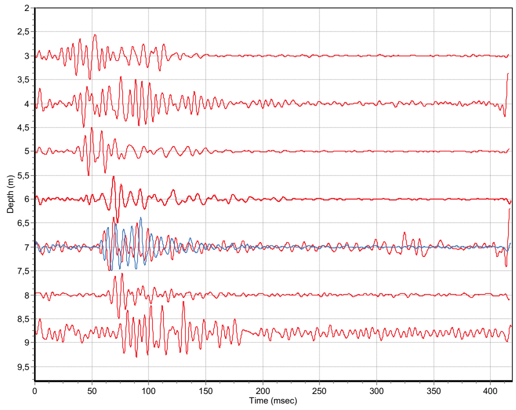
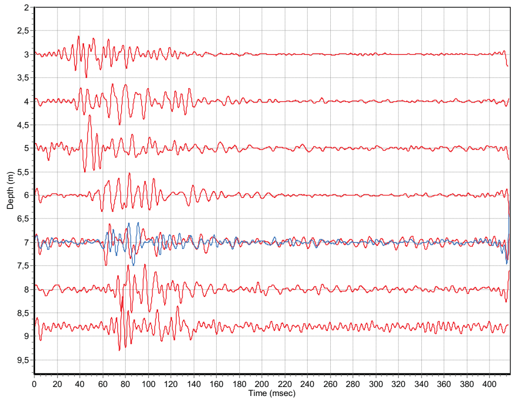


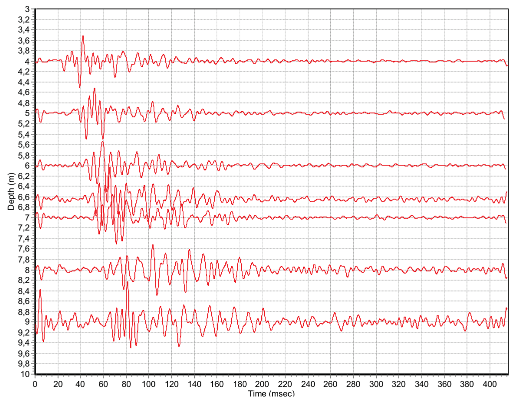
Figure 20: P-waves depth profile for Clay



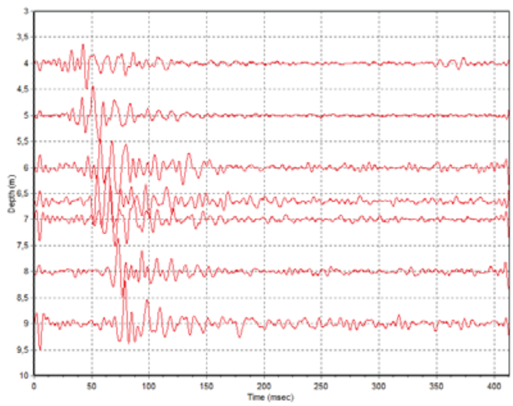
(a) S-waves Left



(b) S-waves Right



(c) S-waves Left



(d) S-waves Right

Figure 21: Shear waves from Clay SCPTu

4.3 SCPTu results - P-waves

4.3.1 Cross-Correlation Method

For obtaining the velocities generated by the P-waves a relative new method has been used. Using a vertical direction hammer, one blow is applied on the plate in order to generate the signal of the wave. In signal processing, cross-correlation is a measure of similarity of two waveforms as a function of a time-lag applied to one of them. According to (Schaff and Waldhauser) in the case of a SCPTu, it is possible to obtain a correlation function by zero-padding in the time domain or to be computed by the inverse Fourier transform of the cross spectrum. In this case though, the difference in depth and wave velocity between the two depths is displayed in Figure22.

The P-velocities are displayed in a chart format depending on depth and type of soil. The results for sand can be seen in Figure 23. The value in the fill layer is considered an error in measurement as its value is negative, also the gyttia values are relative high whereas the sand ones are more or less in the same range of values.

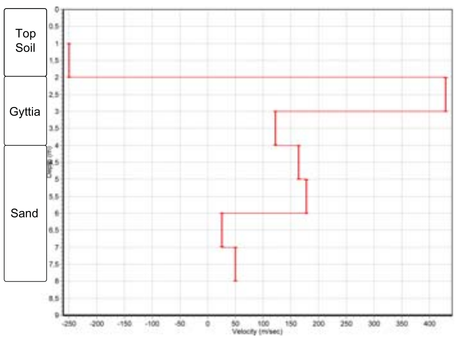


Figure 23: P-velocity for Sand

For clay, the SCPTu results are calculated for both "down" and "up" direction of the test as seen in Figure 24. It can be observed that for the both directions the velocities follow the same pattern and the values are in the same range.

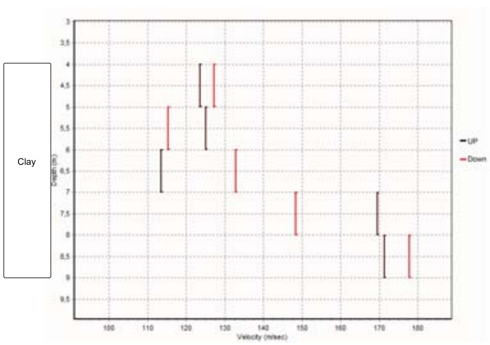


Figure 24: P-velocity for Clay

4.4 SCPTu results - S-waves

4.4.1 Reverse Polarity Method

The method of determining shear wave velocity from seismic CPT data basically involves dividing an increment shear wave travel time into an increment of travel path.

The test procedure consists of generating reverse polarity shear waves, first by impacting one end of the timber, and then by impacting the opposite end (left and right). Acceleration-time traces, corresponding to each impact, are recorded on the computer for subsequent processing and analysis. In analyzing the data, particular attention is paid to the two records made with horizontal impacts. The true shear waves should reverse polarity, and this characteristic is used as the most important identifying characteristic. In some surveys, the shear waves are readily obvious and this is not difficult. In others, there may be numerous other arrivals and noise signals that make identification difficult; hence the need for a clear reversal signature, (J.A. Jendrezejczuk).

The first blow (for example, the left side) represents the seismic record from the SPCTu as seen in Figure 25 part A. To confirm that a real shear wave was obtained, another record is taken by hitting on the other side (in this case, the right) and if the data is correct it should look as Figure 25 part B. The first break is in the opposite direction, which confirms that the reading is a shear wave. Many analysts superimpose the records, for better comparison as shown in Figure 25 part C.

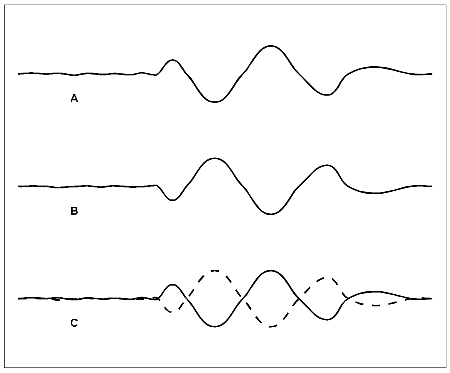


Figure 25: Shear waves reverse polarity when the source polarity is reversed, (Crice).

It has been found that the reverse polarity of the source greatly facilitates the identification of the S-wave and the time for the first cross-over point (shear wave changes sign) is easily identified from the polarized waves (forward and reverse) and provides the most repeatable reference arrival time, (R. G. Campanella, 1986).

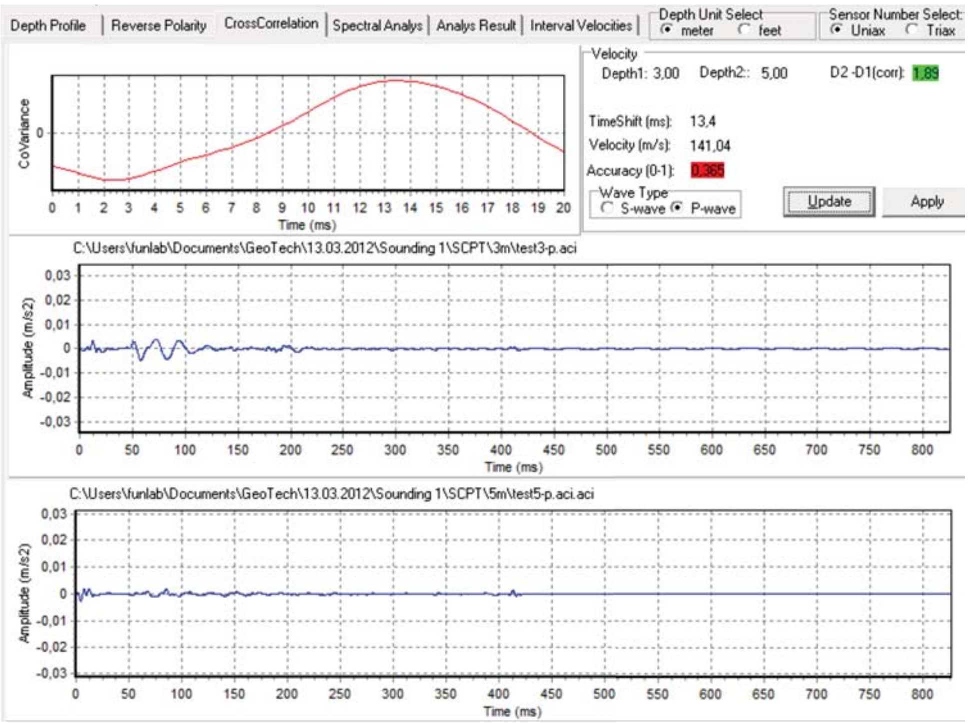


Figure 22: Cross correlation method for P-waves

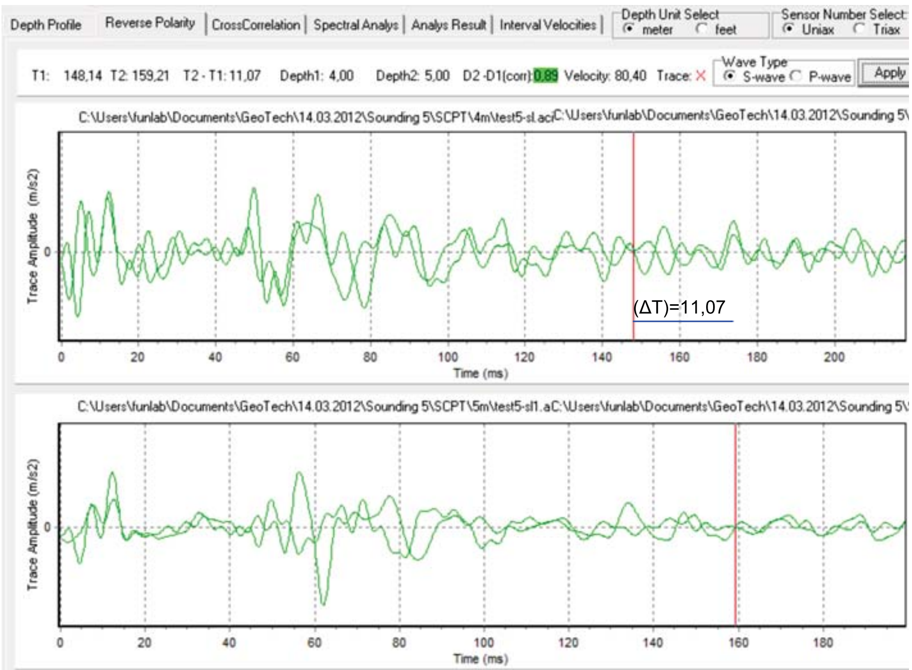


Figure 26: Seismic analysis using reverse polarity,(Geotech, 2004)

4.4.2 SCPTu results - shear velocity

The shear wave velocity is readily computed by dividing the distance between two pairs of receivers by the time for the signal to travel from the one receiver to the next. Travel times can be computed using the start of the S-wave, or any corresponding prominent feature on the time signals (e.g., zero crossing or peak), as the reference.

As an example, using the traces given in Figure 26, with the start of the S-wave as the reference, the shear wave speed is calculated as follows: we consider $X1 = 4m$ and $X2 = 5m$ as the reading depths, $T1 = 148.14ms$ and $T2 = 158.21ms$ as the tracing amplitudes, $\Delta X_{crt} = 0.89m$ as correction factor for the distance by the depth and from Equation (5) we obtain the final result.

$$V_s = \frac{\Delta X_{crt}}{\Delta T} = \frac{0.89}{11.07} = 80.40\frac{m}{s} \qquad (5)$$

The results for all the depths in sand soil are plotted in Figure27

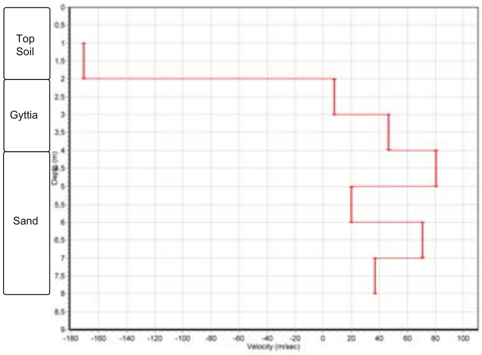


Figure 27: Shear Velocities Sand

For clay, the velocities were displayed as a comparison from the "down" and "up" direction of the SCPTus as in Figure 28.

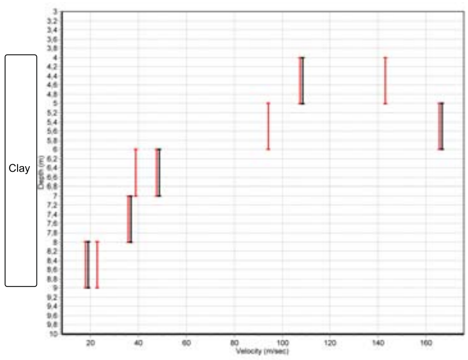
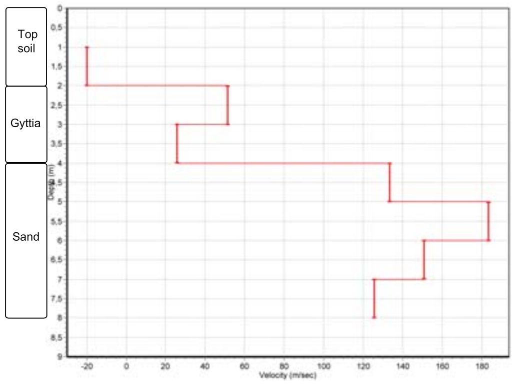


Figure 28: Shear Velocities Clay

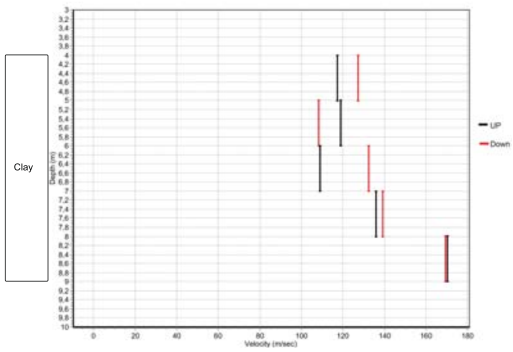
Another approach is to follow the signal's path, choosing the strongest signal point as seen in Figure 29, where the traces are placed on the strongest signal point. The velocities are computed using the same routine as shown by Equation (5).

From the Section 4.2 it was observed that along the depth the signal follows a path and pattern, so it was considered an interesting idea to see the results if the point of the strongest signal is followed.

For sand and clay the results are seen in Figure 30 and there can be seen differences in values. The filling layer has negative values and can be considered as an error in measurement. Unfortunately, the values obtained with the second method are double in value as the first one.



(a) Sand



(b) Clay

Figure 30: Shear waves from Clay SCPTu obtained using Reverse Polarity Method

4.4.3 Cross-Correlation Method

Cross-correlation calculates the time interval by aligning the signal trains in the time axis, and it utilizes considerably more information in the collected shear waves than the first arrival and first cross-over methods, Liao and Mayne (2006).

Cross-correlation works well if two signals are of the same shape. For both sand and clay the S-waves shapes have been verified in previous sections and in Figure 31 can be shown the signal generated by a blow on the left side.

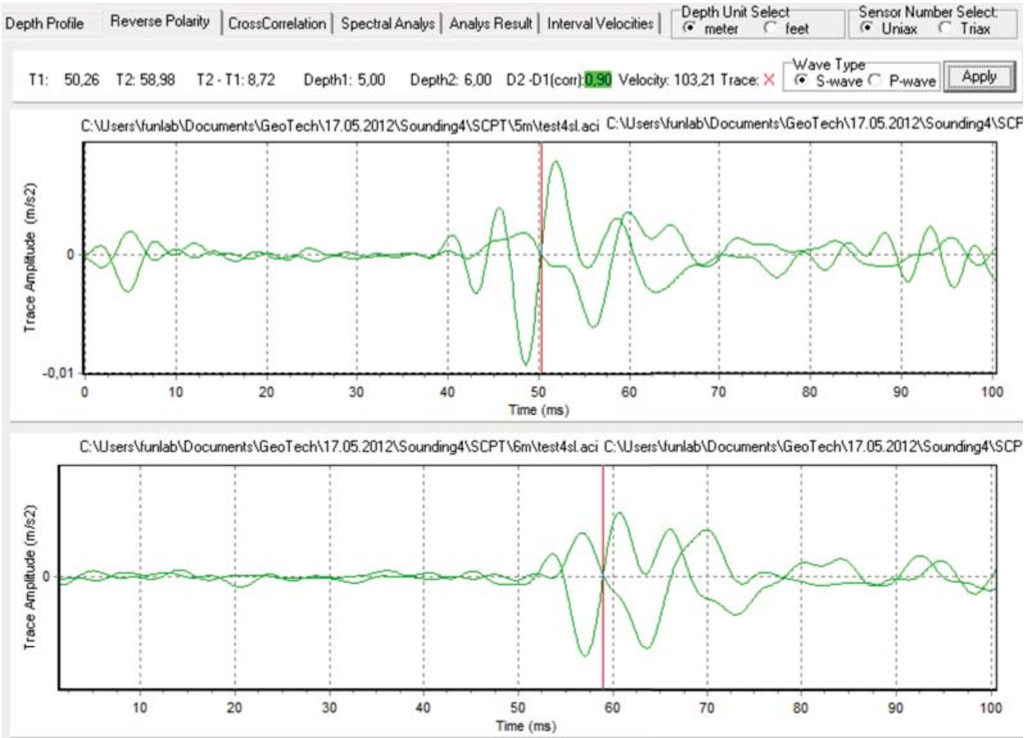


Figure 29: Seismic Analysis using Reverse Polarity

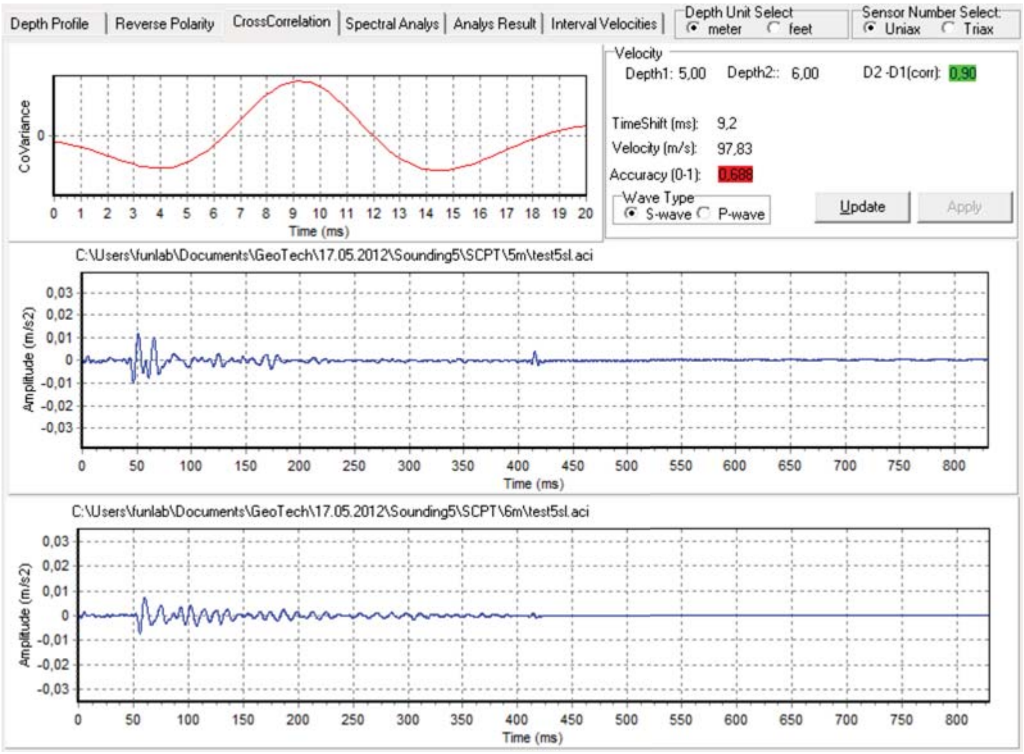
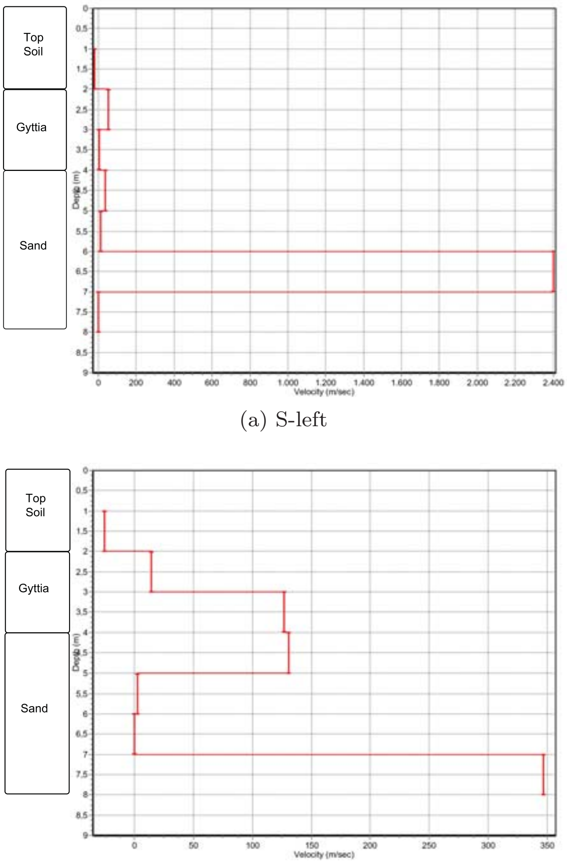


Figure 31: Cross-correlation method for obtaining S-waves

4.4.4 SCPTu results - shear velocity

The results of the cross-correlation method are displayed in a similar matter than the reverse polarity ones. In Figure 32 the sand results are displayed and it can be observed that on the S-left the values are relative small and the $2400 m/s$ value is considered to be an error in measurement, whereas the S-right ones display more realistic values.

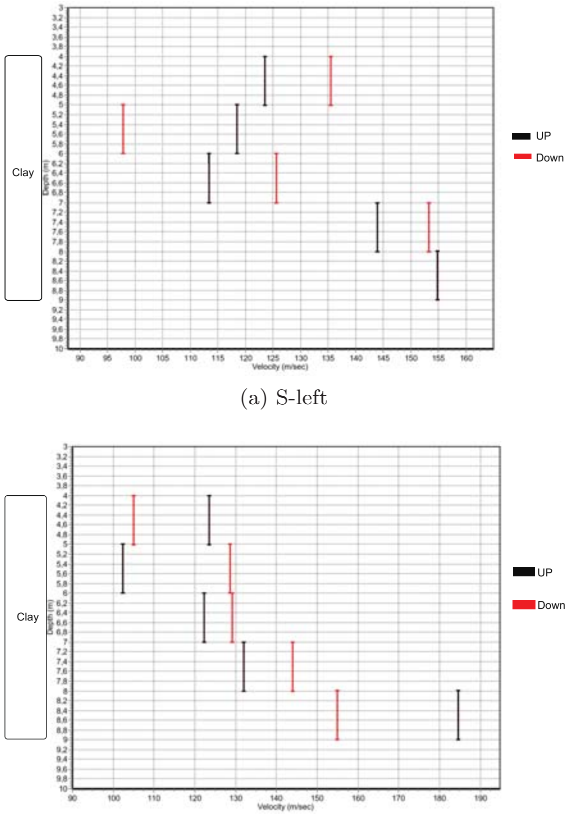


(a) S-left

(b) S-right

Figure 32: Shear waves from Sand SCPTu using Cross-Correlation Method

For clay, the "down" and "up" SCPTu was analyzed and the range of values is similar for both. Also S-left and S-right signals are similar providing with the same results for both sides generated wave velocities.



(a) S-left

(b) S-right

Figure 33: Shear waves from Sand SCPTu using Cross-Correlation Method

5 Conclusion

One of the most important conclusion is that the basic CPTu along with the Seismic test was successful and provided accurate stratigraphic details for both sand and clay. The seismometer on the cone was able to detect both P-waves and S-waves signals. However not all the values are in the ranges. The seismic test was successful, considering that the seismic wave velocities could be determined. According to (Andersen), the ranges for sand and gravel, S-waves are between 0 and 200 m/s, P-waves from 500 to 800 m/s and for clay, S-waves are between 0 and 250 m/s and P-waves from 500 to 700 m/s. This means that the P-waves values are below both ranges. For each site the velocity profiles were determined and the values for shear (S-wave) were in general considered to be correct, ranging between 0 to 300 m/s for sand (with some negative values on the first meter due to the fill in the sand) and from 50 to 200 m/s for clay. As for the P-waves, they are out of range, varying between 0 to 450 m/s for sand and between 0 to 220 m/s for clay.

As highlighted by (R. G. Campanella, 1986), the combination of the seismic downhole method with the CPTu provide rapid and reliable means of determining stratigraphic, soil properties and velocity information in one SCPTu. The addition of seismic measurements significantly can improve the ability of the CPTu, meaning the bearing capacity is obtained from the CPTu and the soil deformation (elastic parameters) are obtained from the SCPTu.

It was observed that closer intervals will result in better resolution of the subsurface layers and more accurate velocities,but also required more time to conduct the test. In the end a one meter interval was a good choice as it could have been possible to notice and compare signal traces for both types of waves.

Another important point that was reached is that the SCPTu downhole survey has advantages like: faster to carry out (in the same time with the CPTu), does not require a different hole from the CPTu, provides with accurate depth determination during and after the tests and geophone orientation is maintained being attached to the cone. Since modern seismographs have digital data storage, computers can simplify the processing and display of data.

Different problems encountered during testing: Since sand was the first time the SCPTu test was realised, it may have caused some errors (wrong way of hitting the hammer, not at the right depth, ect.). This is why it can be observed that a couple of time we have some Shear velocities that are out of range. The water level is pretty high since we are 20 meters from the fyord and this has not been taken in account. In clay was background frequency noise caused by the presence of traffic and concrete and asphalt layer. It was observed that it seriously affected the signal, at least on the first meters, thus the accurate interpretation of the both shear and compressive wave signals.For some soundings (the last 3) it has been tested to put some soil between the asphalt and the plate to have a better connection. To insure a better generation of S waves in Clay compared to Sand an improvement was brought. One person was standing on the S plate while the wave was generated to insure that the wave wouldn't stay in the surface. An other test done was to make the original SCPTu going downwards but a upwards test was also brought as it can be seen a difference is shown the closer the test gets to the surface, this can be explained by the fact that there is more air over and under and the contact surface is not perfect so it does not allow the wave to be properly measured by the geophone. The final conclusion and one of the most important ones is that, the SPCTus were performed for the first time in North of Denmark and that even though some of the results are not accurate, they should be considered as a starting point to more investigations regarding SCPTu.

As a personal statement it would be advised for a greater experience to go back to the same sand site to add all the evolutions brought in the Clay site to observe the difference between the new values and the previously obtained values.

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