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GEOTECHNICAL SITE ASSESSMENT BY SEISMIC PIEZOCONE TEST IN NORTH OF DENMARK

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ABSTRACT

These days cone penetration tests (CPT) have gained more popularity as an alternative to the conventional laboratory tests for subsurface investigation and estimation of soil parameters. Due to increasing interest in soil dynamics in the last decades, there is a development of CPT as a seismic piezocone penetration test (SCPTU) which provides shear wave velocity measurements simultaneously with measurements of tip resistance (q_c), sleeve friction (f_s) and pore pressure (u). The results can be used for determination of deformation parameters of soil. In this regard there have been proposed different empirical correlations between cone data and shear wave velocity measurements to estimate geotechnical parameters but their validity still needs to be verified in a case study and uncertainty remains about the choice of empirical correlations. In this study a site at the East Harbor of Aalborg (sandy site) and another at the Harbor of Frederikshavn (clayey site) in Denmark, where several SCPTU tests have been conducted, are considered. The data were used and analyzed based on different correlations presented in the literature. The results are further compared and verified with the measurements of shear wave velocity achieved from SCPTU tests.

INTRODUCTION

To obtain a proper design in the ultimate limit state as well as the serviceability limit state, various properties of the soil underneath a wind turbine must be known including the strength of the soil and the deformation properties of large and small strain magnitudes. Recently, focus has been on assessment of dynamic properties as well. The seismic piezocone penetration test (SCPTu), which provides multipoint simultaneous measurement of tip resistance (q_t), sleeve friction (f_s), pore pressure (u_2), and shear wave velocity (V_s), appears to be a reliable tool in estimation of geotechnical parameters (Lunne et al., 1997; Mayne and Campanella, 2005; Liu et al., 2008; Cai et al., 2009). During the test, a geophone integrated in a cone measures the waves generated by a shock between a hammer and a steel plate on the ground surface as a down-hole test. When the polarized shear wave is generated, the time is measured for the shear wave to travel a known distance to the geophone in the borehole.

Determination of shear wave velocity (V_s) can be crucial in obtaining information regarding the soil properties. V_s is used in geotechnical seismic design methods (e.g., IBC 2000 code), in soil liquefaction evaluations (e.g. Andrus and Stokoe, 2000), as well as in deriving the small-strain shear modulus ($G_{\max} = \rho V^2$). In the absence of direct measure of shear wave velocity, correlations have been developed between shear wave velocity and several commonly measured geotechnical properties (cone resistance and sleeve friction); however, uncertainty remains about the choice of empirical correlations to determine the constrained modulus, small strain shear modulus and other deformation parameters (Cai, 2010).

The current study will present a description of performed SCPTu and shear wave types in north of Denmark as a case study along with two different methods of finding S-wave velocities in order to analyze and compare with the values obtained from empirical correlations.

FIELD TEST

Two sites located in Alborg in the north of Denmark are assessed: one with sandy soil and one with clayey soil (Fig. 1). The tests performed in sand are located in the east of Aalborg, an industrial part of the city. A wind turbine blade deposit will be constructed in this area. The clayey site is in the center of Aalborg, next to the main train station and bus terminal.

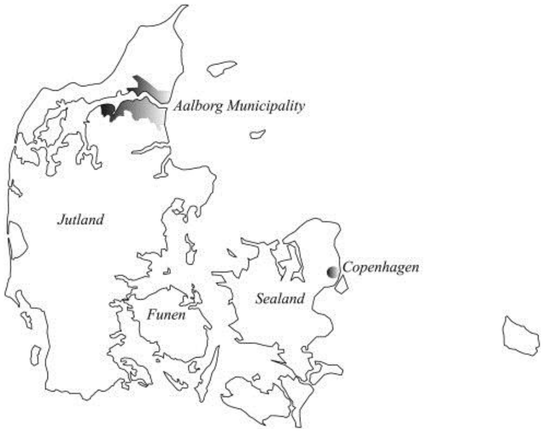


Fig. 1. View of the field test area.

The sandy site is situated a few meters from the Limfjord which means it is a basin deposit area. The upper four meters top layer is a marine deposit of clay/gyttia, while the lower layers are mostly silty sand. The SCPTu tests were performed to approx. 8 meters depth.

Nine soundings are executed in a cross-shaped position on a line separated by a distance of ten meters and four bore-holes have been located in the corners (Fig. 2).

In the clayey site, five SCPTu where executed with a top layer of 2-3 meters sand and the rest as clay. Soundings are aligned by a distance of five meters and one bore-hole as the same distance from the first sounding. The profile is illustrated in Fig. 3.

Description of the cone

The used Geotech SCPT equipment consists of the following

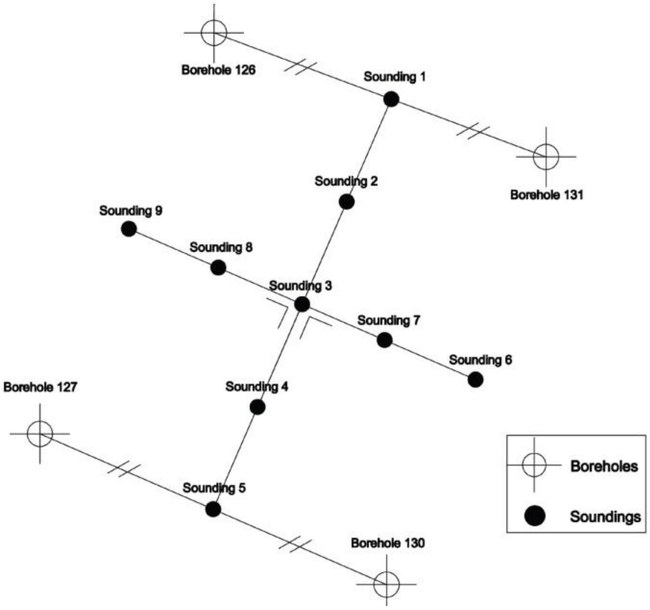


Fig. 2. Position of Boreholes and SCPTu (Sandy site).

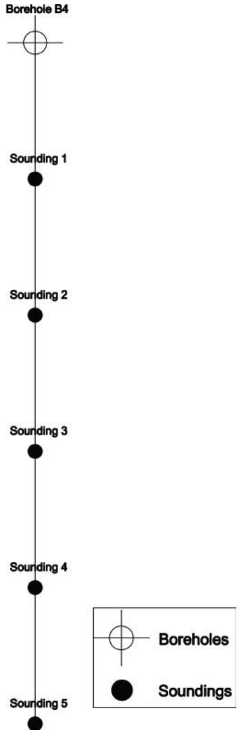
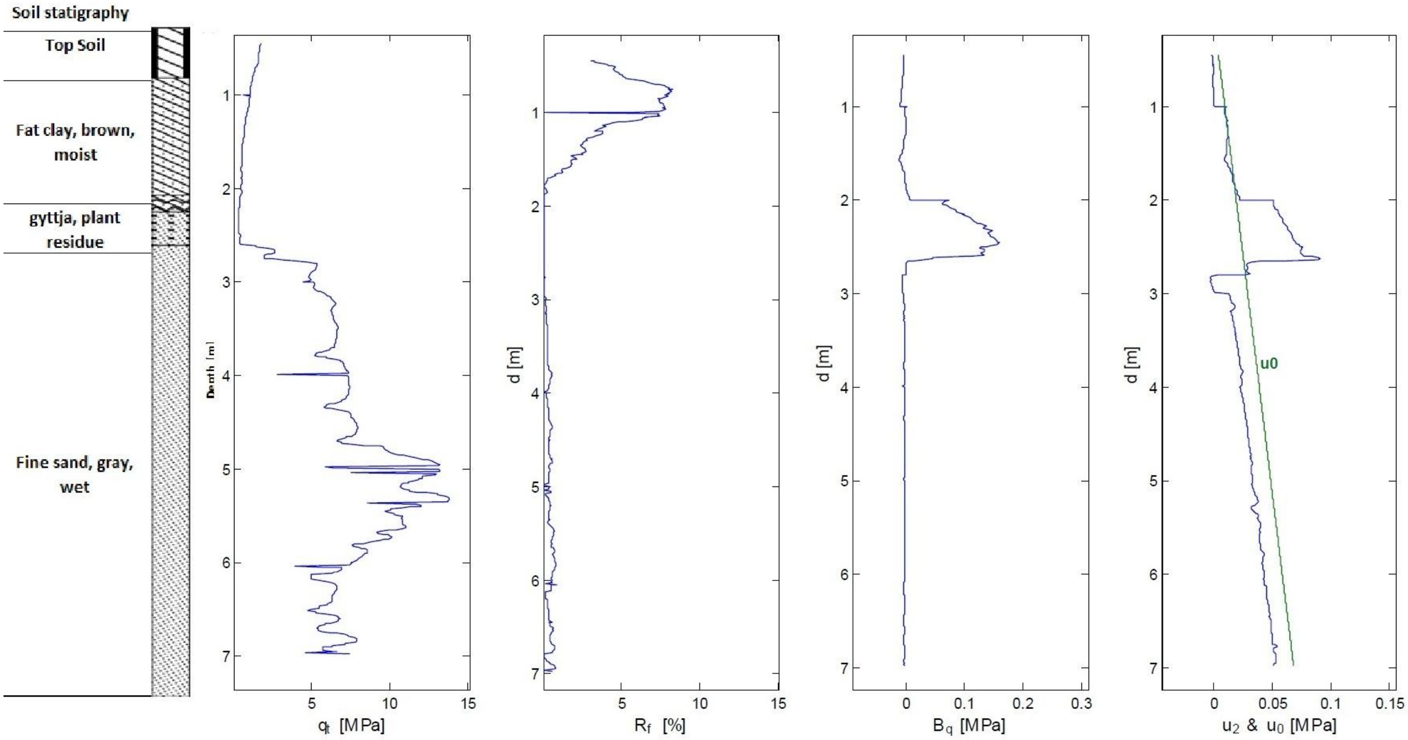


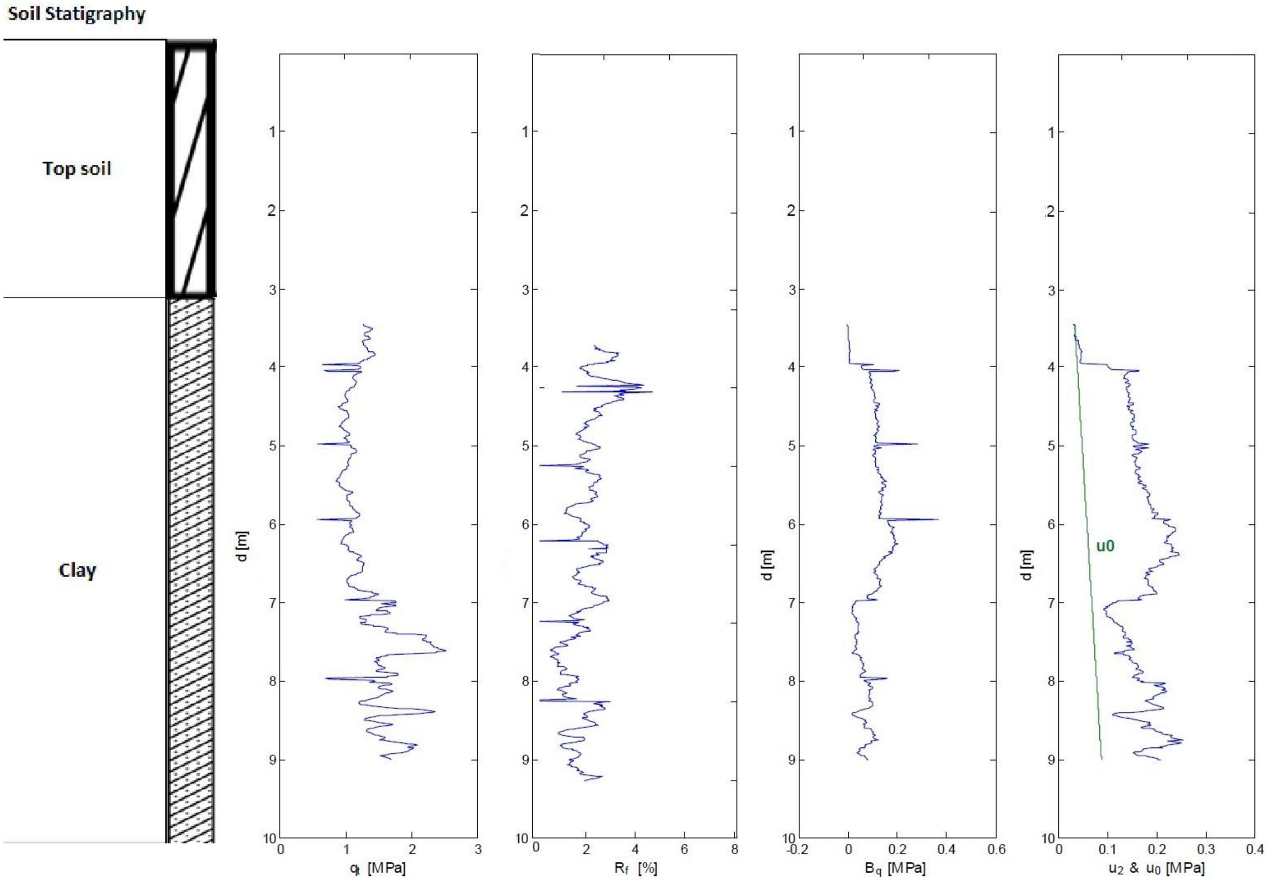
Fig. 3. View of the field test area (Clayey site).

main items:

- A conical tip;
- A 10 cm^2 probe with a tip angle of 60°;
- 7 channels measuring point resistance (q_c), local sleeve friction f_s, pore pressure u, tilt, temperature,



(a) Sand (Bore-hole 09)



(b) Clay

Fig. 4. Borehole profile and CPTu results from field test (Bore-hole 01) .

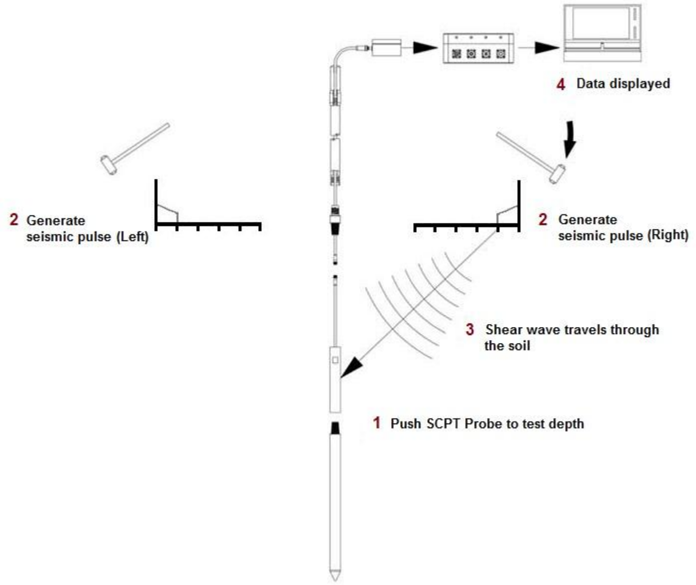


Fig. 5. Layout of source-trigger receiver.

- electric conductivity, seismic, uniaxial for shear wave measurements.
- Depth synchronization;
- Data acquisition system and software;
- Data interpretation, CPT-LOG software.

The friction sleeve is placed above the conical tip and has a standard dimension of 150 cm^2. A pore pressure transducer is installed to measure the pore pressure during the penetration. The cone is pushed into the soil at a standard speed of 20 mm/s. the acoustic transmitter is located just above the CPT probe in 480 mm length and 36 mm diameter. The power supply is 4 LR14 1.5 V Alkalin batteries. The measured values of piezocone data and the results of the bore hole tests are given in Fig. 4 which u_0 is initial pore water pressure.

Test setup

For the S-waves generation, two plates on both sides of the sounding hole are placed considering that the left and the right part of the S wave testing are aligned and a sledge hammer was blown on them, respectively (Fig 5). The sledge hammer and one of the plates can be seen in Fig. 6. These plates are "L" shaped and the bottom of the plates should be equipped with transversal teeth to improve the contact with the ground. The distance between the place where the hammer hits and the sounding hole is 1.4 meters (Fig. 7).

The seismic part of the test is performed every each meter. When the rod string reaches to the desire depth, the engine of the penetrometer or drill rig is stopped. This is done to give the possibility to realize the SCPT test which is noise sensitive. The shear velocity can be easily checked on site, for quality assessment. As soon as the seismic part is finished the CPT can continue.

Fig. 6. L plate and sledge hammer for S waves generation.

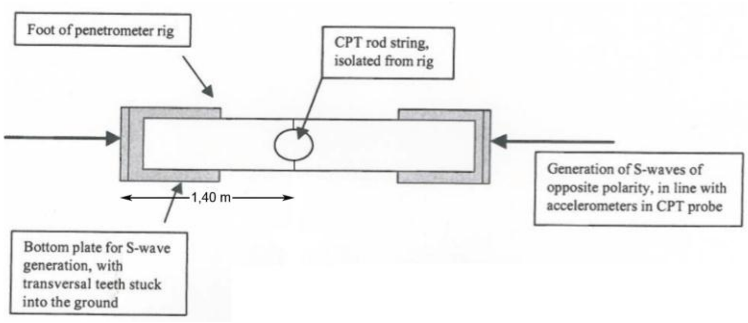


Fig. 7. SCPT field set up, (Geotech 2004).

LABORATORY TESTS

Sand. From boreholes seen in Fig. 4a, soil samples were taken in order to perform soil classification tests. The laboratory testing program included basic soil characterization tests such as grain size distribution, hydrometer tests, relative density and water content. Results from laboratory tests as water content and particle density can be observed in Table 1 and 2, respectively.

Table 1. Water content results for sand

	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

Using water content (w), Specific gravity of soil solid (G_s) and water level surface at depth 0.3, the soil considers saturated and density of soil can be calculated. Final values from laboratory tests are given in Table 2.

Table 2. Specific gravity of soils results (Sand)

Sample No.	Specific gravity of soil solid, Gs, [-]	$Density,\ \rho\ (kg/m^3)$
9	2.66	1853
14	2.65	1675
25	2.65	2042
34	2.66	2047

Clay. As for the sandy site, two samples from the borehole have been taken in the clay site in order to perform common laboratory tests. The results are given in table 3 and 4.

Table 3. Water content results for clay

Sample No.	Water content (%)
22	34-36
13	36-37

Table 4. Specific gravity of soils results (Clay)

Sample No.	Specific gravity of soil solid, Gs, [-]	$Density,\ \rho\ (kg/m^3)$
22	2.69	1853
13	2.72	1890

SHEAR WAVE VELOCITY

There are many empirical correlations proposed by different authors that relate the shear wave velocity to SCPT/CPT results. Based on sleeve friction and cone resistance, for all type of soils Equation (1), (Mayne, 2006) and Equation (2), (Hegazy and Mayne, 1995) can be used:

$$v_s(m/s) = 118.8(m/s)\log_{10}(\frac{f_s}{1Mpa}) + 18.5(m/s) \quad (1)$$

$$v_s(m/s) = [(10.1\log_{10}(q_t/1kPa) - 11.4]^{1.67}\left[100\frac{f_s}{q_t}\right]^{0.3} \quad (2)$$

Shear wave velocity (v_s) is measured in meters per second and tip resistance (q_t) are measured in kPa.

In the correlation proposed by Mayne (2006), if the values of sleeve friction and cone resistance are too low, taking logarithm results in negative values in shear wave velocity which is not rational. So in a case study, consideration should be taken when using this correlation as no limitation has been considered in developing the correlation for such condition.

Based on studies on Po River Sands and Gioia Taura Sands, Baldi et al., (1986) proposed Equation (3) for shear wave velocity from CPT data for clean quartz sands ,

$$v_s(m/s) = 277(q_t/1MPa)^{0.13}(\sigma'_{v0}/1MPa)^{0.27} \quad (3)$$

Shear wave velocity (v_s) is measured in meters per second and tip resistance (q_t) and effective overburden stress (σ'_{v0}) are measured in MPa.

Based on tests on intact and fissured samples from 31 different clay sites, Mayne and Rix (1995) proposed Equation (4) for soft to stiff, intact and fissured clays,

$$v_s(m/s) = 1.75(q_t/1kPa)^{0.627} \quad (4)$$

where q_t is in (kPa).

SHEAR MODULUS

In projects dealing with analyzing and designing wind turbine foundations, information about G_{max} as a key parameter in performing dynamic analysis of foundation response is essential. This is very important since traditional CPT leads to properties that are relevant for the ULS (Ultimate Limit State), but usually wind turbines fail in the FLS (Fatigue Limit State) and this means that small strain parameters for the soil are more important than large-deformation properties including the shear strength.

Shear modulus obtained from SCPT

The low strain shear modulus, G_{max}, can be found using the geotechnical method of Seismic Cone Penetration Test. Elastic theory relates the shear modulus, soil density (ρ) and the shear wave velocity as

$$G_{max} = \rho V_s^2 \quad (5)$$

The shear strain amplitude in seismic test is usually low which allow finding the very low strain level of dynamic shear modulus, G_{max}.

To obtain the shear modulus a seismometer is placed in the horizontal direction and orientated transverse to the signal source to detect the different components of the shear wave (horizontal and transversal). The ideal seismic signal source should generate a large amplitude shear wave with little or no compressional wave component. The signal can be generated by a hammer hitting a plate.

To obtain the measurements a rugged velocity seismometer has been incorporated into the cone penetrometer. It is placed in the horizontal direction and oriented transverse to the signal source to detect the horizontal component of the shear wave arrivals.

Shear modulus obtained from CPT

The value of small-strain shear modulus, G_{max} applies strictly to the nondestructive range of strains where shear strain $\gamma<10^{-4}$ (Cai, 2010). Different correlations for determining G_{max} have been proposed based on cone resistance for a large variety of soils, either granular (Baldi et al., 1989) or cohesive (Mayne and Rix, 1993) or both soils (Hegazy and Mayne, 1995). Based on calibration chamber results and field measurements, Rix and Stokoe (1992) proposed a correlation for cohesionless soils as Equation (6) (T. Lunne, 1997).

$$\frac{G_0}{q_c} = 1634\left(\frac{q_c}{\sqrt{\sigma'_{v0}}}\right)^{-0.75} \tag{6}$$

where

G_0: Small strain shear modulud in kPa

q_c : Cone resistance in kPa

σ'_{v0} : Effective overburden stress in kpa

The major disadvantage of all these correlations is that G_{max} is a parameter determined at very small shear strain levels whereas q_t is a quantity measured at large deformations involving yielding and failure of the soil surrounding the cone. However, Mayne and Rix (1993) showed that the small strain shear modulus varied with in situ void ratio (e_0) and cone penetration resistance (q_t) for a wide range of clays and can be expressed as (Cai, 2010):

$$G_0 = 99.5(P_a)^{0.305}\frac{(q_t)^{0.695}}{(e_0)^{1.130}} \tag{7}$$

P_a : Atmospheric reference pressure in the same units as G_0 and q_t.

e_0 : In-situ void ratio

CORECTION OF MEASURED DATA FOR THE CPT

Considering to this fact that the cone penetration test is always accompanied by several errors due to halts, soil irregularities (thin layers of stiff materials and etc.), then there is a need for these measurements to be corrected. Also the cone resistance and the sleeve friction need to be corrected in order to account for the specific cone design, which influences how the pore water pressure alters the measurements. This is in particular important in the soft normally consolidated or low consolidated soil where the pore pressure behind the cone may be large. The cone resistance and the sleeve friction are corrected using Equation 8 and 9 respectively (T. Lunne, 1997):

$$q_t = q_c + u_2(1-a) \tag{8}$$

$$f_t = f_s - \frac{(u_2A_{sb} - u_3A_{st})}{A_s} \tag{9}$$

where

q_t: Corrected cone resistance in MPa

a: Cone area ratio [$a = \frac{A_n}{A_c}$] which A_n and A_c are cross section area of the shaft and the cone respectively.

u_2: Pore pressure behind the cone

f_t: Corrected sleeve friction

A_{sb}: Cross section area of sleeve bottom

A_{st}: Cross section area of sleeve top

A_{sb}: Friction sleeve surface area

SCPT ANALYSIS

Two different interpretation methods were used to determine the shear velocity, Vs, from SCPTu data as follows:

Cross-Correlation

Cross-correlation refers to the correlation of two independent series, and can be used to measure the degree to which the two series are related (Liao and Mayne, 2006). The cross-correlation function of x(t) and y(t) for a time shift 's' is defined as Equation (10) which x(t) and y(t) are two continuous signals with respect to time 't'.

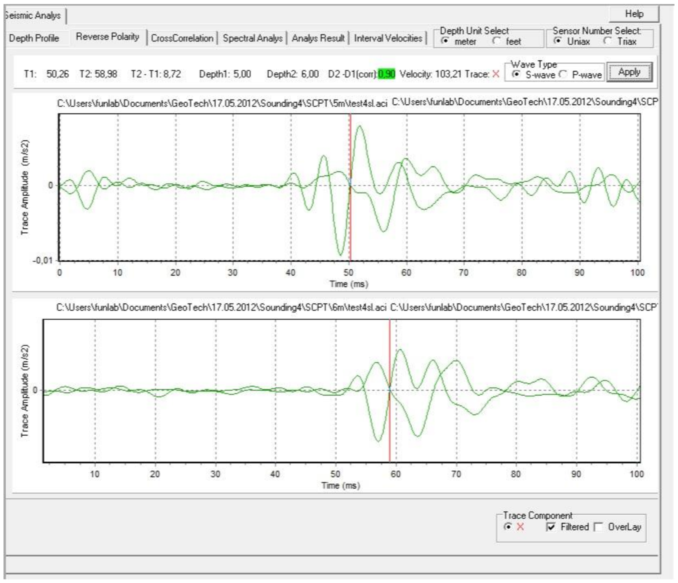
$$z(s) = \int_{-\infty}^{\infty} x(t)y(t+s)dt \tag{10}$$

These series are measured at acoustic transmitter located just behind the sleeve friction in 48 cm length. For two signals of the same shape, the cross-correlation function may be used to calculate their difference in their arrival times, which is equal to the time shift that results in the peak of the cross-correlation function (Liao and Mayne, 2006).

Reverse Polarity

Interpolation of the shear wave velocity from SCPTu data consists of dividing an increment shear wave travel time into an increment of travel path. The test procedure involves generating shear waves with reverse polarity, by impacting opposite sources, for example two ends of a steel beam, (left and right). Subsequent processing and analysis are then applied on recorded acceleration time traces for each impact. Actually, in analyzing the data, the true shear waves should reverse polarity, as the most important identifying characteristic (Jendrezejczuk, 1987). In some surveys, the shear waves are readily obvious and identifying is not so difficult while in others, there may be numerous other arrivals and noise signals that make identification difficult; hence the need for a clear reversal signature may arise.

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, (Campanella, 1987). An example, using the traces is given in Fig. 9.



T1: 50,26 T2: 58,98 T2 - T1: 8,72 Depth1: 5,00 Depth2: 6,00 D2 -D1(corr): 0,90 Velocity: 103,21 Trace: ×

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Fig. 9. Seismic analysis using reverse polarity, (Geotech, 2004).

INTERPRETATION OF RESULTS

Shear wave velocity

For a better understanding and comparison of the value ranges, all the results calculated from the empirical methods to estimate shear velocity have been plotted together with the shear velocities obtained from seismic CPT. Figure 10 illustrates these values for both clayey and sandy sites. estimate shear velocity have been plotted together with the shear velocities obtained from seismic CPT. Figure 10 illustrates these values for both clayey and sandy sites.

For sand, SCPTu results from reverse polarity and cross-correlation are in the same range of values. Both methods have negative shear velocities, which are in the first meters of sounding and doesn't seem reasonable and fit well with values obtained from empirical methods. These irrational values are results of not considering the deposition layout of different soil layers in calculation of shear wave velocities. When the shear wave passes through one layer, the values of velocity is equal to the distance divided by the travel time of the wave. But if during the passage, the wave encounters to a change in the layer, due to the change in the density of the media the direction of the wave will be diverted. It means that traveled distance varies and the mentioned formula is not true. This is the main reason of errors in shear wave velocity calculations in the soil. One way is decreasing in the interval between pals but there is a limitation for this as most general errors identified in cone penetration tests are registered due to halts. So a good knowledge about soil type and condition of layers in the deposit could help in better understanding and interpretation of results.

By increasing the depth in all profiles, the results from analysis using both of reverse polarity and cross-correlation methods give reasonable values which are in the range but the cross-correlation method gives conservative values compare to the reveres polarity.

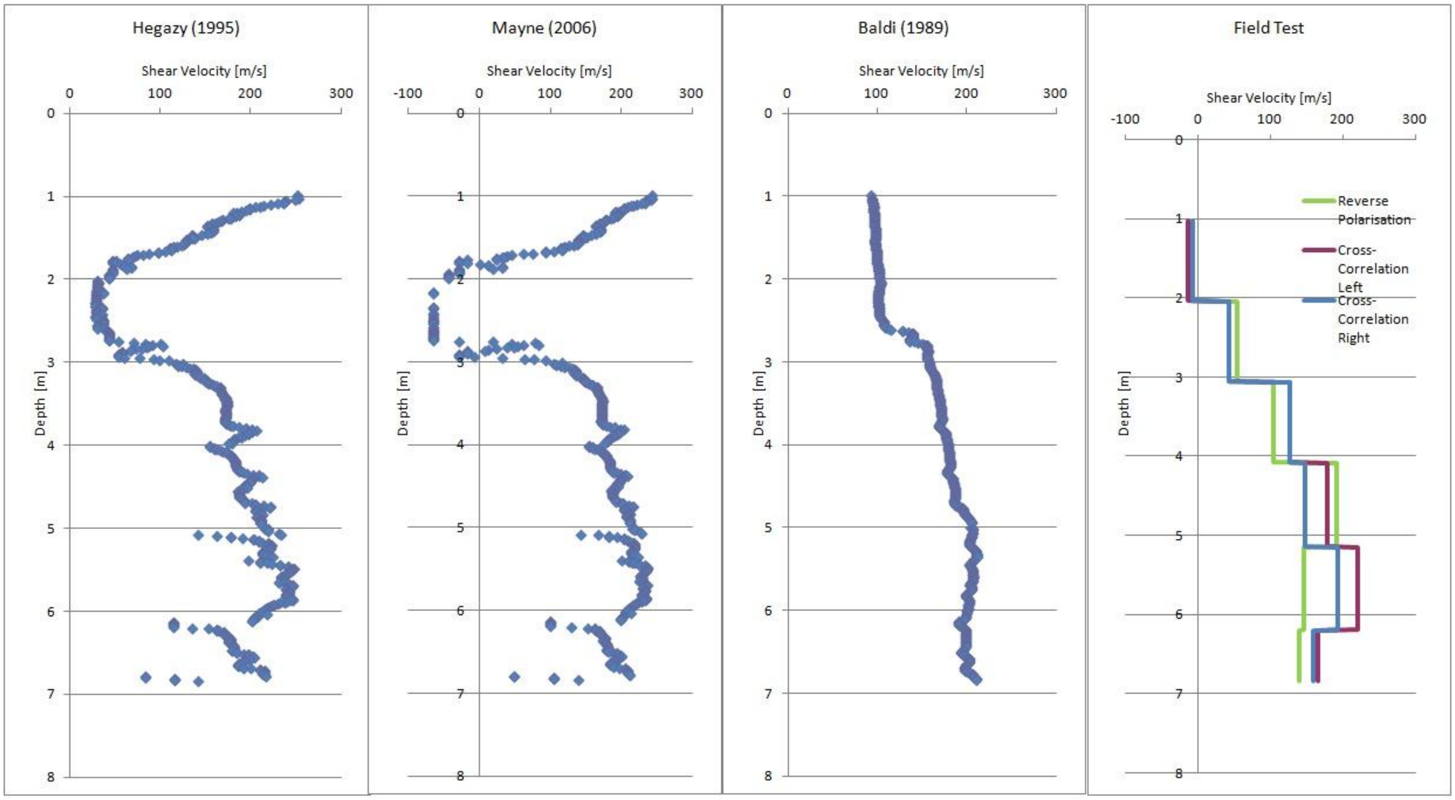
The values obtained from correlation proposed by Mayne (2006) second layer is negative which is not reasonable. This is due to the small values of sleeve friction in this layer which results in the negative values according to Equation (1) after taking the logarithm. It means that this correlation cannot be used for this region because there is no limited range for shear wave velocity in this formula for soils with low sleeve friction.

Also for clay site, cross-correlation results are compatible to the results obtained from the reverse polarization and the field test. The range between the two methods is similar going from 0 to 200 m/s which are in the range.

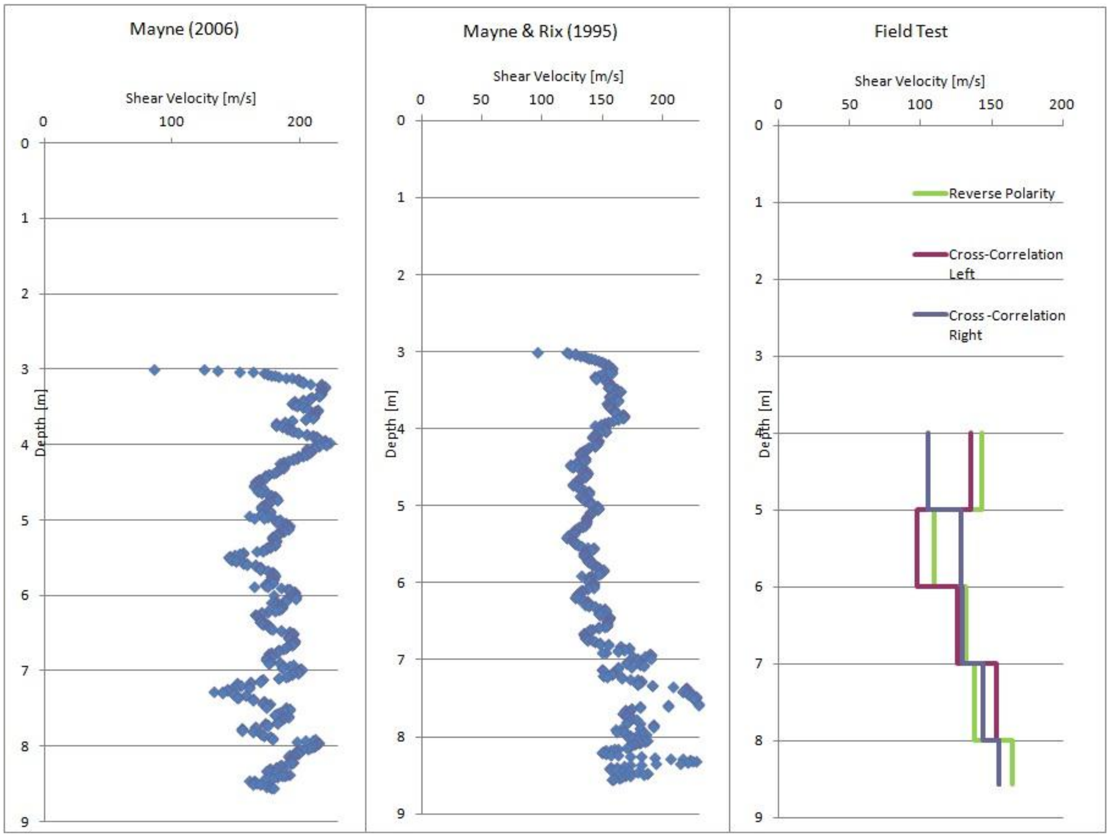
Shear Modulus

Using equation (6) and (7), shear modulus for coarse and fine grained soils are obtained and compared to values from SCPTu field data as seen in (Fig. 11).

In sands, by increasing the depth, the difference between values obtained from two different analysis increased. For both sand and clays, the values from empirical correlations are over estimated.

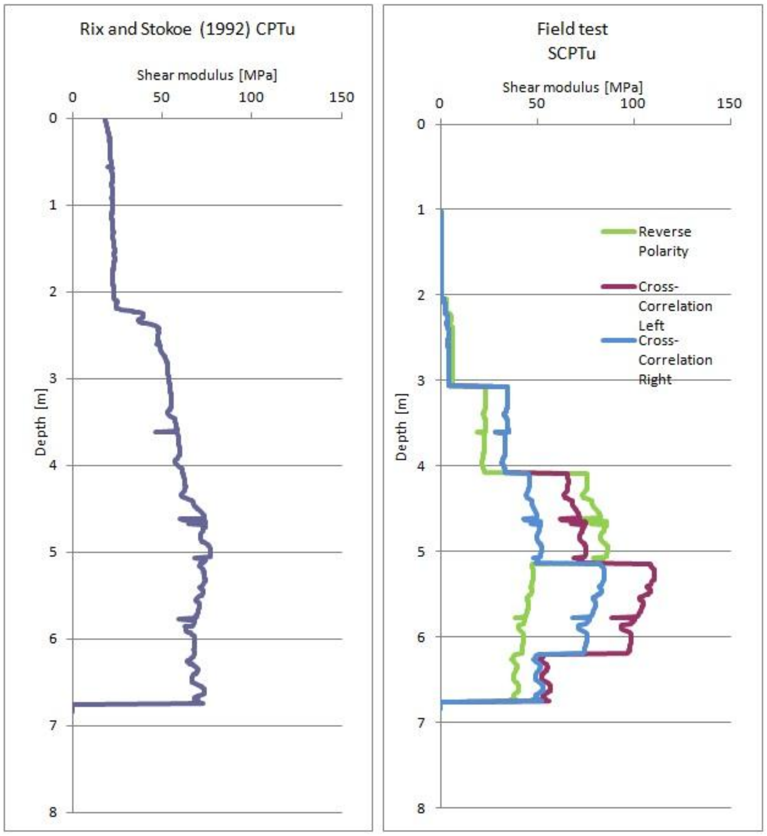


(a) Sand

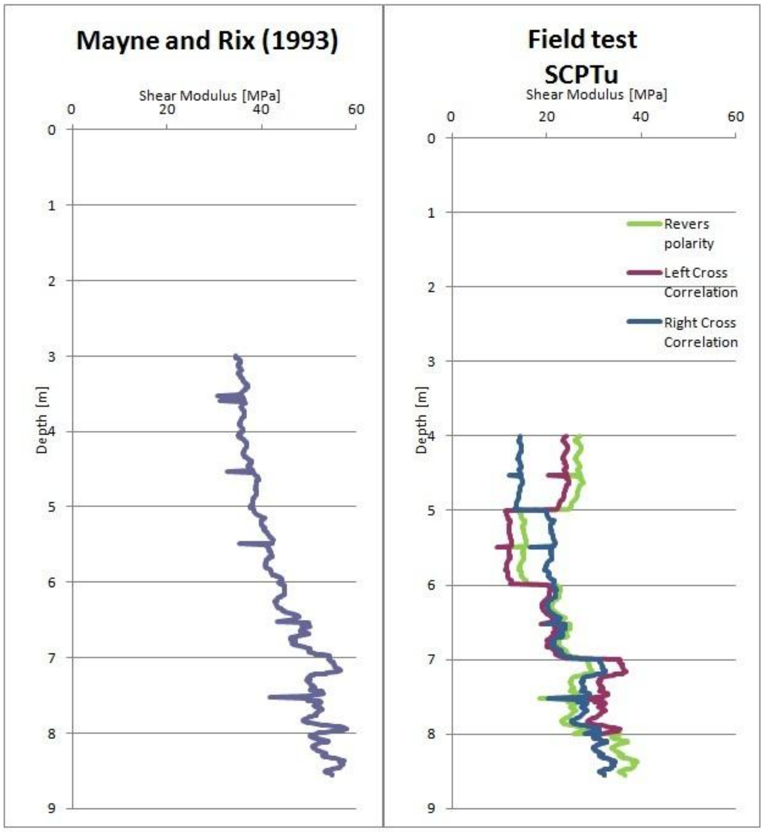


(b) Clay

Fig. 10. Shear velocities obtained from empirical methods and field test results.



(a) Sand



(b) Clay

Fig. 11. Shear modulus results obtained from empirical methods and field data.

CONCLUSION

There are different correlation methods reported to predict shear modulus from CPTu data, but their validity still needs to be verified for a local case as the original soils used in the empirical formula development are different from other region soils. This justifies the need for a case study in large projects and site-specific correlations should be developed based on field tests.

The SCPTu is concluded to be time and cost efficient and to provide reliable results, regarding the fact that is the first time performed in Denmark.

Based on different correlations between shear wave velocity and shear modulus from cone data two sites, one with mostly clayey soil and the other with mostly sand in the north of Denmark have been considered as a case study. Several seismic cone penetration tests were performed and values of shear velocity and cone data were recorded. Also common laboratory tests have been carried out on intact samples taken from boreholes to achieve soil density and void ratio of the region soil. Two methods of analyzing the signal traces of seismic data was chosen as "Reverse polarity" and "Cross-correlation".

In this study, correction of the measured CPTu data has been applied according to Equation (8) and (9), thus no error filtering due to halts on data was performed.

Actually the field test results of SCPTu and CPTu estimations for shear velocities from empirical correlation are in the same range, as it can be seen in Figure 10. Also the values are in the range for shear velocities in clays and sands.

Comparing the shear velocities calculated based on empirical correlations from CPTu data to the SCPTu field test results, it can be stated the empirical methods are over estimated. Also calculations based on correlation proposed by Mayne (2006) results in negative values for shear wave velocities which is not reasonable due to small values of sleeve friction. So this correlation doesn't seem to predict well the values of shear wave velocity from cone data for this region.

Due to a very agglomerate area as the center of the city, different errors could appear in the results of shear velocity in clay site. These errors can be generated by the construction site situated next to the testing site or the presence of the main 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 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.

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