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# Cone penetration tests and dynamic soil properties

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**Abstract.** Current standards like ISO 14837-32:2015 and DIN EN 1998-1/NA:2021 as well as prEN 1997-2:2022 allow for using correlations between the results of in-situ soil penetration tests and shear wave velocity (or shear modulus) to determine soil properties to be used in dynamic analyses. While the ISO and prEN standards even provide some recommendations on specific correlations to be used, the DIN standard does not. Due to the statistical nature of such correlations their general applicability has to be verified. We collected data sets from test sites from Germany as well as New Zealand at which cone penetration tests (CPT) as well as seismic site investigation methods were conducted. These sites comprise sandy soils as well as clayey soils, mixed soils as well as glacial soils. We compare the results of several correlations between CPT results and shear wave velocity. The accuracy of such correlations is assessed with respect to the accuracy of seismic in-situ tests. It turns out that for clean sands such correlations between CPT and  $V_s$  have a similar order of variability as seismic in-situ tests conducted at the same site. The higher the fines portion of the soil, the higher the variability of the statistical correlations, and consequently the less the general applicability. For glacial soils and other special soil types usage of statistical correlations to determine dynamic soil properties is not recommended.

## 1. Introduction

Current standards like ISO/TS 14837-32:2015 and DIN EN 1998-1/NA:2021 as well as prEN 1997-2:2022 allow for using correlations between the results of in-situ soil penetration tests and shear wave velocity (or shear modulus) to determine dynamic soil properties.

The ISO standard [1] discusses thoroughly laboratory and field methods to obtain shear modulus and/or shear wave velocity from index parameters, that is void ratio for frictional soils and plasticity index and undrained shear strength for cohesive soils. Furthermore, the ISO standard provides specific reference to correlations to use for either cohesive or frictional soil. It is pointed out, however, that these correlations provide a rough estimation only. The range of potential deviation from results obtained by direct methods is not provided.

The DIN standard [2] in a brief appendix allows to determine dynamic soil properties either from direct in-situ measurements, empirical correlations to penetration test results, and estimations based on static properties. Only in the latter case it demands to varyate shear wave velocity by  $\pm 20\%$  and shear modulus by  $\pm 20\%$ . Unlike the ISO standard it does not refer to any specific correlation between



sounding results and dynamic soil properties. Note that the DIN standard technically is applicable to seismic analysis only.

The prEN standard [3] provides an extensive discussion of direct and indirect methods to determine dynamic soil properties. For a range of penetration tests specific correlations are provided in an informative appendix. The prEN standard requires that for the specific correlation it must be stated in a ground investigation report if the correlation provides an upper limit, a lower limit or an average value of shear wave velocity. Furthermore, the prEN standard requires that a correlation shall include the influence of soil type, stress state, age, stress history and diagenesis. It is further pointed out that for evaluating the uncertainty of an estimated shear wave velocity the uncertainty of the estimate as well the random error and bias has to be taken into account.

In the ensuing we restrict ourselves to correlations for Cone Penetration Tests (CPT). The reason for that is that very often CPTs are executed in a ground investigation for determining several static soil parameters, like relative density. We will investigate the uncertainty of statistical correlations between CPT tip resistance and friction ratio on the one hand, and shear wave velocity or small strain shear modulus on the other hand by comparing them with direct measurements at the very same location as well as with dynamic properties derived from void ratio.

The dynamic properties derived from correlations are inherently laden by uncertainties. The uncertainties are the higher the more the soil samples from which a correlation has been derived is different from the soil subject to examination. On the other hand, evaluation and interpretation of direct measurements of wave travel times are based on the solution of an inverse problem, for which assumptions concerning layer boundaries and shear wave velocity distribution within a layer must be made in advance. This is superposed by the natural variability of soil. Hence, direct method a laden by uncertainties as well.

In this paper we are concerned with the relationship between the uncertainties of statistical correlations and the uncertainties of direct methods to obtain small strain soil stiffness. A potential field of application are offshore wind parks in which CPT are regularly performed, and for which dynamic properties are required as well due to the cyclic nature of wind and wave loads.

## 2. Uncertainties of direct methods

Common field tests for the determination of dynamic soil properties for foundation design are

- Downhole method (DH), Seismic cone penetration test (SCPT)
- Crosshole method (CH), Direct Push Crosshole method (DPCH)
- Active surface wave methods (SASW, MASW)
- Passive surface wave measurements of ambient noise (MSPAC)

For details see, e. g., [4][5].

Results of downhole measurements and ambient noise measurements at the same site are compared in [6]. In [7][8][9] results from downhole measurements are compared with crosshole measurements and surface wave methods. The mismatch in the shear wave profile is in the order of  $\pm 20\%$  (figure 1 left). Uncertainties originating from combining different evaluation and interpretation methods of travel time recordings from DH and SCPT measurements are reported by [7][10][11][12]. One of the examples from [10] from New Zealand is displayed in figure 1 right. The results scatter by  $\pm 50$  m/s or  $\pm 20\%$ , and the scattering increases with depth.

## 3. Correlations between penetration test results and dynamic soil properties

We will use only correlations which are currently considered in standards or institutional recommendations, e. g. [1][3][5][13].

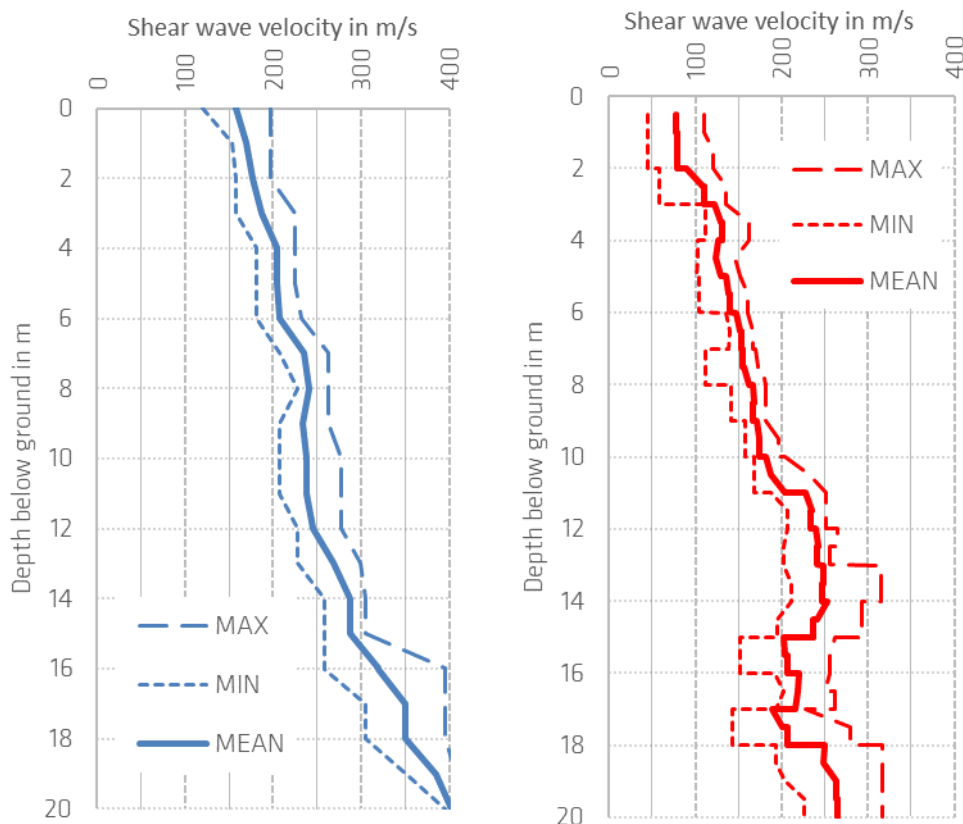


Figure 1. Left: Shear wave profile obtained by three different direct methods, after [14]. Right: Shear wave profiles from downhole and SCPT travel time measurements using different interpretation and evaluation methods, after [10].

These correlations are applicable only to naturally deposited soil, they are not applicable to fill. The soil type is identified by employing the normalized Soil-Behaviour Type chart (SBTn) after [17]. If the impact of overburden pressure is eliminated from cone resistance and shaft friction, and if the normalized quantities

$$Q = [(q_c - \sigma_{vo})/p_a][(p_a/\sigma'_{vo})^n] \quad (1)$$

$$F = [f_s/(q_c - \sigma_{vo})] \times 100 \% \quad (2)$$

$$n = 0.381 I_c + 0.05 \sigma'_{vo}/p_a - 0.15 \leq 1.0 \quad (3)$$

with  $q_c$  the cone resistance,  $\sigma_{vo}$  the total vertical stress,  $\sigma'_{vo}$  the effective vertical stress,  $p_a = 100$  kPa a reference stress and  $n$  a stress exponent are plotted on the axes of a doubly logarithmic line chart, then each section of the chart can be assigned to a different soil type, see figure 2.

The index

$$I_c = [(3.47 - \text{Log}_{10} Q)^2 + (1.22 + \text{Log}_{10} F)^2]^{1/2} \quad (4)$$

quantifies the soil behaviour. The section boundaries in figure 2 can be approximated by concentric circles with constant  $I_c$ . For further details see [15] and [16]. The transition from sand-like behaviour to clay-like behaviour is usually defined as the circle  $I_c = 2.6$ . In this paper we use this value as the distinction between sand and clay in all those cases in which a correlation is by their authors developed for sandy soil or clayey soil only. In our charts in the ensuing subsections we leave gaps whenever  $I_c$  does not match with the soil type to which the correlation is applicable.

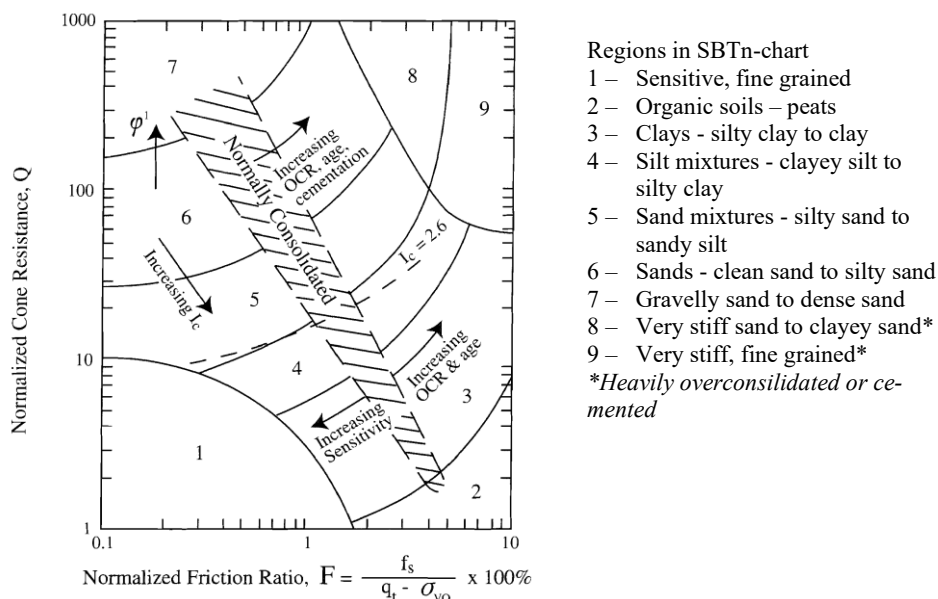


Figure 2. CPT-based Soil Behavior Type-chart (SBTn) after [17]

Figure 2 reveals the reason why prEN 1997-2 demands that correlations for CPT shall include the influence of soil type and in situ stress. For example, a normalized cone resistance  $Q$  between 10 and 50 might indicate sand mixtures (regions 6 and 5) as well as silt mixtures and clays (regions 4 and 3). The shear wave velocity of sandy soil is usually significantly higher than that of clayey soil. Hence, correlations based on cone resistance only, without taking into account the friction ratio, must be used very cautiously only.

### 3.1. Correlation after [18], also recommended by [1] for sandy soil

Based on sand samples equation (5) is proposed for the small strain shear modulus.

$$\frac{G_{\max}}{q_c} = 1634(q_c/\sqrt{\sigma'_v})^{-0.75} \quad (5)$$

All quantities must be used in kPa. After solving for  $G_{\max}$  the well known relationship

$$c_s = (G_{\max}/\rho)^{1/2} \quad (6)$$

yields the shear wave velocity.

### 3.2. Correlation after [19], also recommended by [1] for clay-like soils

From a regression analysis equation (7) is proposed:

$$G_{\max} = 99.5(p_a)^{0.305}(q_c)^{0.695}/(e_0)^{1.130} \quad (7)$$

with  $e_0$  void ratio,  $q_c$  and  $p_a$  in kPa.

### 3.3. Correlation after [16] for sand-like as well as clay-like soils, recommended by [3]

From a large number of SCPT profiles contours of equal normalized shear wave velocities within the SBTn chart have been derived. They can be approximated using equation (8).

$$c_s = (10^{(0.55 I_c + 1.68)} Q_{tn})^{1/2} (\sigma'_{vo}/p_a)^{0.25} \quad (8)$$

Here,  $Q_{tn} \equiv Q$ ,  $c_s$  in m/s and  $I_c$  the soil behaviour type index after equation (4).

### 3.4. Correlation using void ratio and plasticity index for all soils

The well known equation after Hardin [20] is mentioned in the ISO/TS standard [1] as well as in the prEN standard [3], though in slightly different form. We used equation (9)

$$G_{max} = 625 \frac{p_a}{0.3+0.7 e^2} \left( \frac{\bar{\sigma}'}{p_a} \right)^{0.5} \cdot OCR \left( I_p / (1+3I_p^2) \right)^{1/2} \quad (9)$$

to obtain an estimation of  $G_{max}$  from void ratio  $e$  and mean effective stress  $\bar{\sigma}'$ . In our application examples the plasticity index was not available, hence we used  $I_p = 0$ . A severe weakness of equation (9) is the fact that computation of void ratio and mean effective stress requires data about mass density, which in geotechnical reports is usually given for a very small number of samples only, and therefore must be estimated very often from tabulated values, e. g. [21], which is the source of significant uncertainties.

## 4. Application examples

### 4.1. Preliminaries

The correlations listed in section 3 provide either shear wave velocity or shear modulus. For convenience the shear wave velocity was chosen for comparison of results. If required, equation (6) is employed to convert the shear modulus into shear wave velocity. Mass density and, if applicable, ground water level were taken from geotechnical site investigation reports, if available. If not, density was estimated using tabulated values from [21]. The same estimates were used to obtain total and effective stress.

### 4.2. HKWM

The site is located at the outskirts of Berlin, Germany. The distance between bore hole and CPT location is approximately 20 m. The soil profile comprises 4 m of fill, followed by 9 m glacial till, followed by sands. This site is of particular interest because the applicability of correlations to glacial till, quite common in the Berlin area, can be tested. In the SBTn chart (figure 3 right) the glacial till is considered as type 3 silty clay to clay. This does not match with its fines content of less than 40 %, which renders the glacial till as silty or clayey sand.

From figure 3 it is apparent that the dynamic properties of the fill as well as the glacial till is very poorly estimated by equation (8). The reason is most probably the high overconsolidation ratio of the glacial till. Application of correlations to obtain shear wave velocity from CPT to glacial soils are not recommended.

### 4.3. JAH0

The site is located in the center of Berlin. The soil comprises 3 m artificial fill, followed by ca. 14,50 m of sand in which grain size distribution shifts to more fine sand with increasing depth. According to the SBTn chart (figure 4 right) the soil is sand or silty sand, which agrees well with the grain size distribution provided in the geotechnical site report.

With all applied correlations an increase in shear wave velocity with depth is observed in figure 4 left, which is typical for homogeneous soil due to the increase of overburden stress. This is not the case for the results of downhole measurement due to ambiguity of the measured travel times. All correlations yield an excellent agreement at depths below 7 m. Above the level data on void ratio and density might be unreliable, and hence there is some disagreement with equation (9). In this case it might well be that the results from application correlations is even closer to the reality than the downhole results.

It follows that correlations should be considered as a supplement to direct measurements.

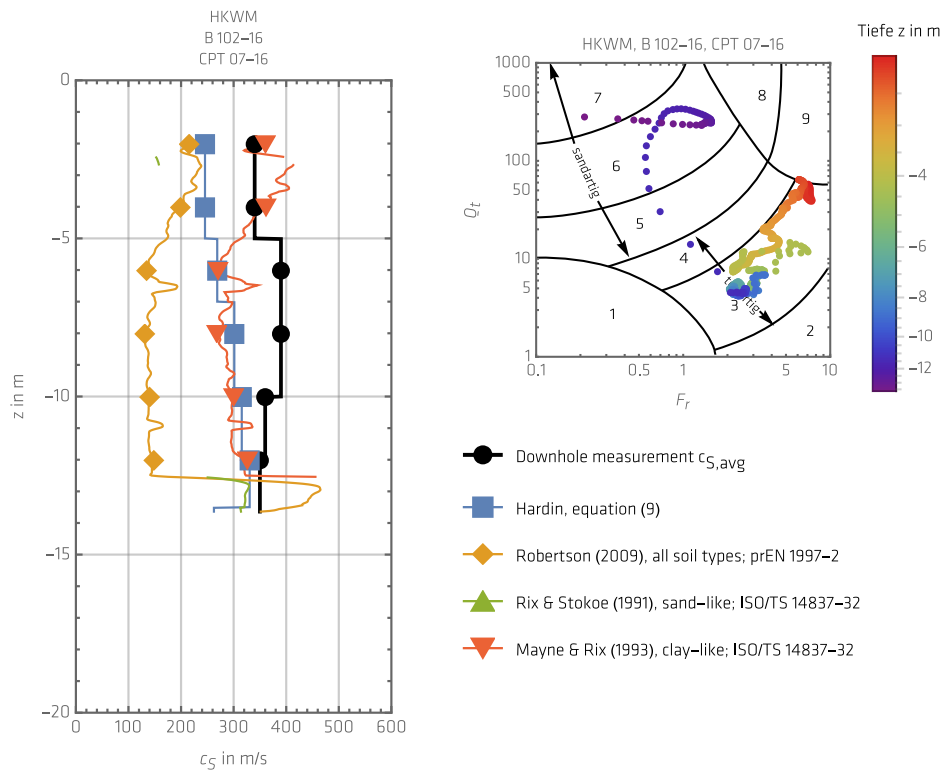


Figure 3. Shear wave velocity profile and SBTn chart of site HKWM

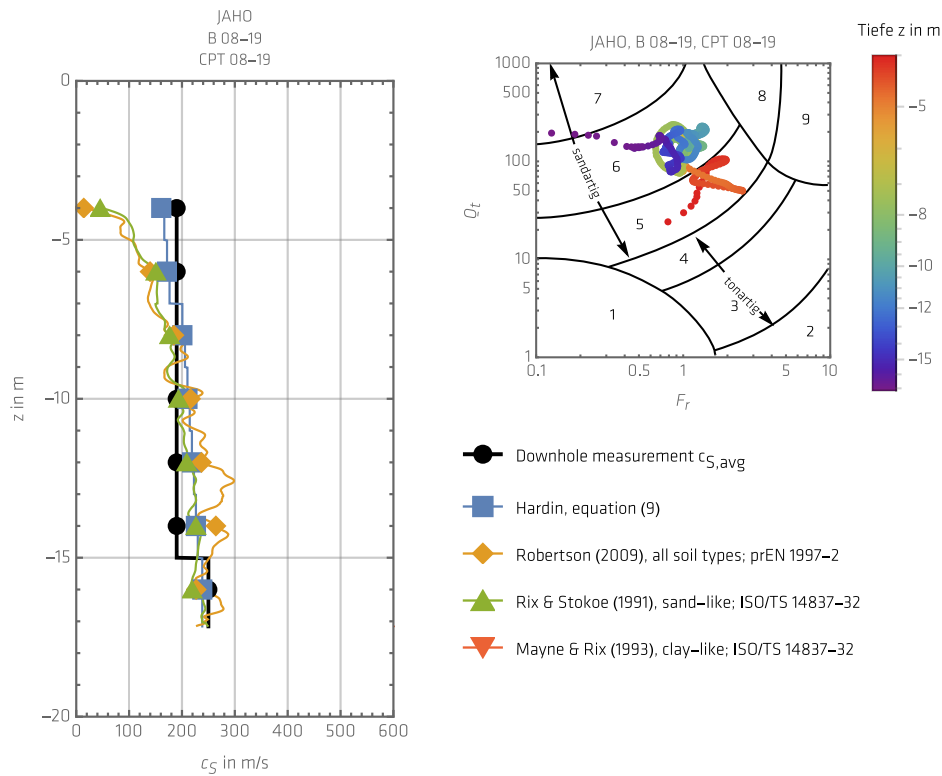


Figure 4. Shear wave velocity and SBTn chart at site JAHO

#### 4.4. BAM

The site is located approximately 50 km south of Berlin, Germany. Details are given in [22]. The soil profile comprises a superficial layer with organic contents, followed by approximately 8 m of medium to fine grained sands with lenses of silt and coal, followed by a second layer of grained sand, but medium grained and with substantially lower density than the upper sand layer.

Figure 5 shows an excellent agreement between direct measurements and correlations below a depth of 6 m, using equation (8) even above that level. The error does not exceed 20 % of the direct measurements. Note that the downhole measurements as well as equation (9) are evaluated at 1 m intervals, while the other correlations are evaluated at the resolution of the CPT results. Differences between in-situ measurements and equation (9) are related to the fact that data about void ratio and density had to be estimated. Using a correlation relying purely on CPT data is advantageous in this case because in particular for sand-like soils the in-situ density cannot be determined accurately due to the intrinsic difficulties of obtaining undisturbed samples.

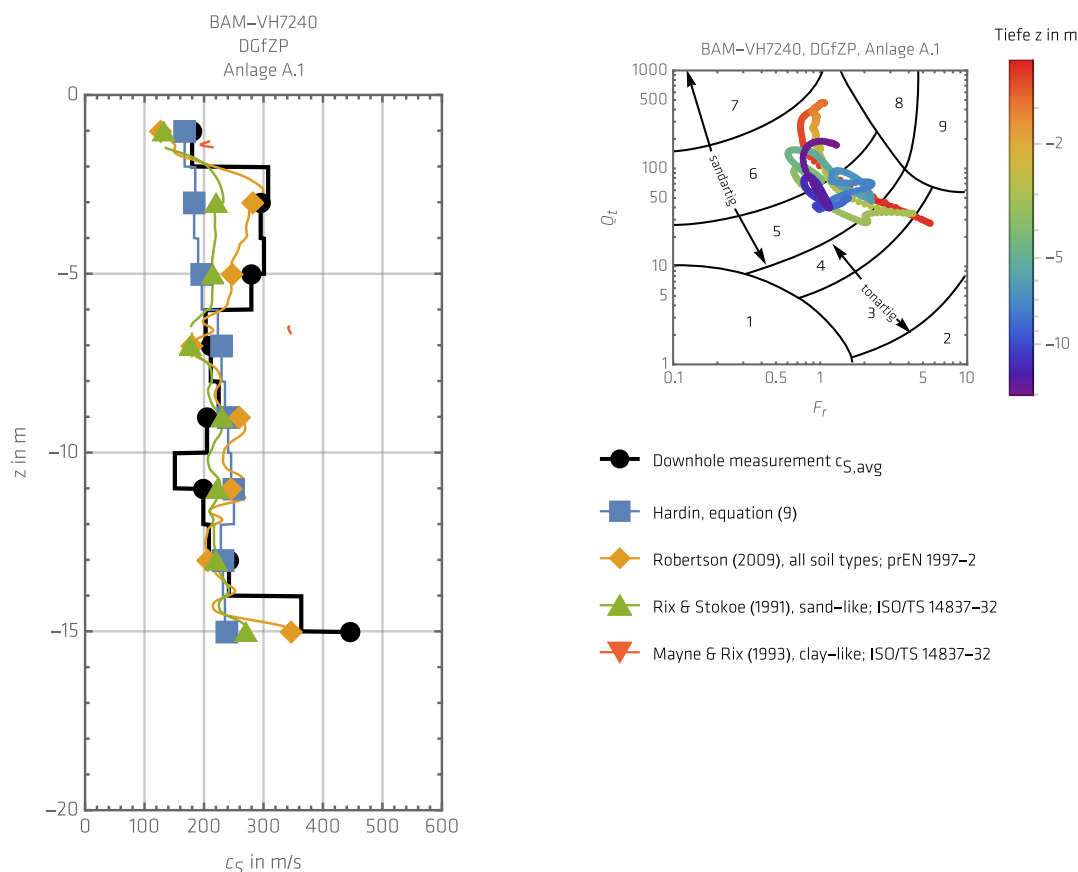


Figure 5. Shear wave velocity and SBTn chart at site BAM

#### 4.5. New Zealand sites

It turned out that CPT soundings and soil profile data of the sites where the downhole measurements plotted in figure 1 right have been undertaken are available from the NZGD [23] for download. This gives the opportunity to apply the correlations also to soils from outside the Berlin region. The SBTn chart for borehole B-57241 suggest the soil to be well graded (figure 7), though from visual inspection only fine sand and silt with organic inclusions were reported. At borehole B-57217 alternating thin fine sand and silt layers until 2.50 m below ground surface are followed by a thick layer of fine to medium grained sand until final depth.



The data plotted in figure 1 right are obtained from evaluation of downhole measurements undertaken near borehole B-57217.

Shear wave velocities from correlations show a very good agreement with the data from direct measurements, see figure 6. In both cases the correlations exceed the direct measurements, but mostly less than 20 % to 30 %. In figure 6 left it can be observed that equations (7) and (5) complement each other and at transitions from sand like soil to clay like soil provide close estimates of the shear wave velocity.

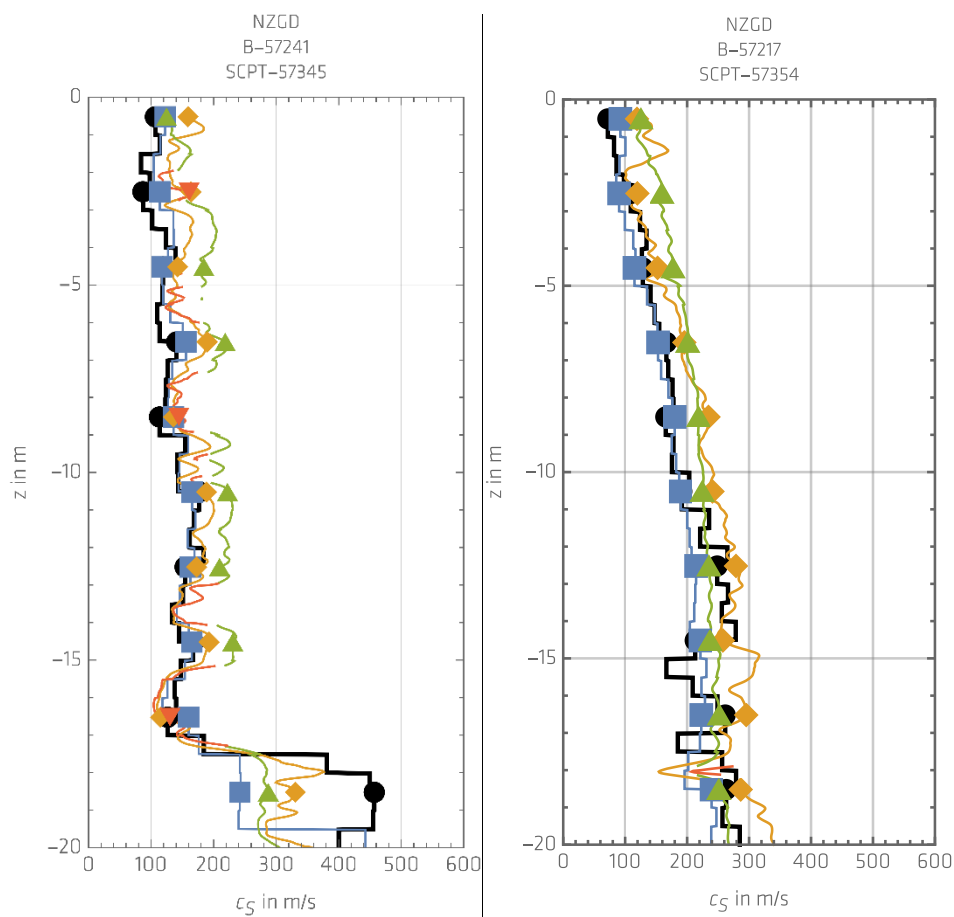


Figure 6. Shear wave velocities of two sites in New Zealand. For a legend see figure 5

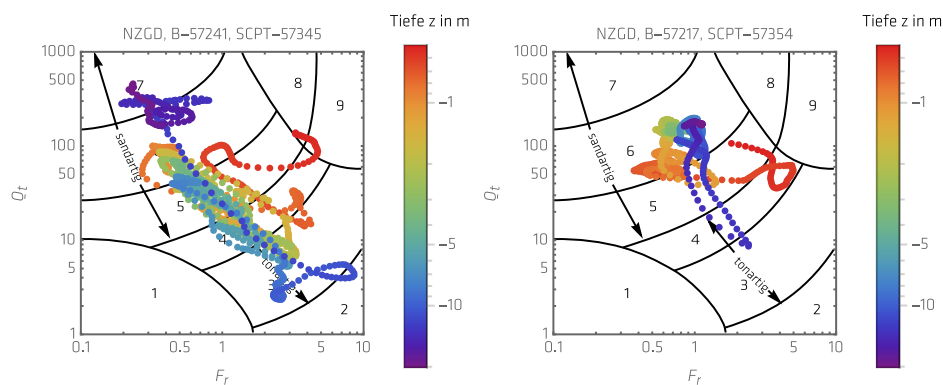


Figure 7. SBTn charts of the sites in New Zealand

#### 4.6. Summary

Examinations of several direct measurements of shear wave velocity by seismic methods reveal that a scatter of  $\pm 20\%$  between several methods at the same site has to be taken into account. The scatter due to applying different evaluation and interpretation procedures to the very same data from downhole measurements is within  $\pm 20\%$  as well. Though direct methods are often called “exact” methods, these findings prove that some substantial uncertainties still have to be taken into account for design purposes.

Application of several correlations between CPT data and shear wave velocity and comparison with direct measurements at the same site reveal that for sand like soil the difference between direct measurement and correlation has the same order of magnitude than the scatter between different direct methods and different interpretation of travel times. Hence for sand-like soil correlations are a reasonable alternative to direct measurements, in particular at locations where seismic measurements are costly, e. g. of offshore wind farm sites. Correlations exhibit the tendency to provide higher estimates of shear wave velocity than direct measurements. Those correlations which do not rely on static index properties of soil, in particular density and void ratio, are advantageous due to the intrinsic difficulties to obtain undisturbed samples which is a necessity to obtain in-situ densities.

The higher the fines content, the higher currently the uncertainties of shear wave velocities obtained from correlations. For glacial soil, and most probably other special soil types as well, the application of correlations is not recommended except if their applicability is proven in advance.

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