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Variation of CPTu- based transformation models for undrained shear strength of Finnish clays

The determination of a design soil property may include multiple sources of uncertainty. One of the sources originates from transformation model used to evaluate soil parameters when they are not measured directly. This study focuses on the transformation uncertainty related to three different transformation models used in evaluation of undrained shear strength from CPTu borings. The used correlation models are common models found in literature and calibrated at Tampere University. The CPTu data used in this study was taken from Knuuti and Länsivaara (2019), and it consisted of four different soft clay sites in Finland. The transformation uncertainty was calculated for each transformation model at each site. Moreover, every CPTu boring was analyzed separately. The results showed that the transformation uncertainty was lowest for models based on the net cone resistance (COV=0.033-0.084) and pore pressure (COV=0.024-0.085). For the third model the uncertainty was little higher as it included more uncertainty in the initial parameters. This suggests that the transformation models based on net cone resistanse (q_{NET}) and pore pressure (u_2) could be more suitable for practice.

Keywords: CPTu; statistics; reliability; coefficient of variation; correlation models; undrained shear strength

1 Introduction

An evaluation of design soil property includes multiple sources of uncertainty. One of the uncertainties come from the transformation models, when the property cannot be measured directly from the ground. In this study, the focus is to investigate the transformation uncertainty related to three different transformation models. The transformation models are correlation models for the undrained shear strength (s_u) of the soft clays based on CPTu measurements. The commonly used models have been calibrated in previous studies at TAU (previously Tampere University of Technology (TUT)) for Finnish soil conditions. The performance of each model for four different clay sites (Knuuti and Länsivaara (2019)) are studied in terms of statistics. The bias and COV (coefficient of variation) are calculated for each model in order to estimate the transformation uncertainty.

2 Uncertainties in soil properties

The main sources of uncertainties in determination of a geotechnical parameter are the inherent variability, the measurement uncertainty and the transformation uncertainty. From these, the inherent variability is more or less a property of the soil and it cannot be reduced. It has been developed during time via multiple physical, geological and chemical processes and is still continuously altered by these. The inherent variability is also known as the spatial variability of the soil. The other two main sources of uncertainty, however, are reducible. The measurement uncertainty arises from the equipment used for the measurements and the operation of this equipment. In addition, some test related random errors might occur during measurements. Together, these factors contribute to the measurement uncertainty, which can be reduced e.g. using more advanced testing methods. The last major uncertainty, the transformation uncertainty, arises when the soil property cannot be measured directly but it is derived via transformation models from measurement results obtained with different investigation methods. This type of uncertainty could be more systematic in nature. Beside these sources of uncertainties, also the model uncertainty and statistical uncertainty affect to the total uncertainty of the parameter. The model uncertainty is similar to transformation uncertainty, but in a bigger scale. The model uncertainty arises, for example, when the actual anchor force measured from the excavation is compared to the calculated anchor force with certain calculation model. The statistical uncertainty is due to a limited amount of data (e.g. measurements), from where the design property is derived from.

The amount of uncertainty that a property have, is usually described with the coefficient of variation (COV), which is a dimensionless ratio between the standard deviation σ and the mean value μ of the property, i.e.:

$$COV = \frac{\sigma}{\mu} \tag{1}$$

Moreover, the uncertainties arising from different sources can be combined to a single total uncertainty by using Eq. (2).

$$COV^2{}_X = COV^2{}_{spat,X} + COV^2{}_{err,X} + COV^2{}_{trans,X} + COV^2{}_{stat,X} + COV^2{}_{\mathrm{mod}} \tag{2}$$

where, $\mathrm{COV}_{\mathrm{spat,X}}$ is spatial variability, $\mathrm{COV}_{\mathrm{err,X}}$ is measurement uncertainty, $\mathrm{COV}_{\mathrm{trans,X}}$ is transformation uncertainty, $\mathrm{COV}_{\mathrm{stat,X}}$ is statistical uncertainty, $\mathrm{COV}_{\mathrm{mod}}$ is model uncertainty and $\mathrm{COV}_{\mathrm{X}}$ is the total uncertainty related to parameter X.

However, in real situation where the data, time and money is limited, separating the uncertainties depending on the source can be impossible. For situations where no better data is available, literature values (e.g. Phoon et al. (1995); Phoon and Kulhawy (1999a; 1999b); Baecher and Christian (2003); Uzielli et al (2005)) can be used as an estimates. These values are presented for single sources of uncertainties as well as for the total uncertainty of a parameter (lumped number). In this study, the focus is to evaluate the transformation uncertainty of the transformation models to undrained shear strength ($\mathrm{COV}_{\mathrm{trans}}$). So the transformation uncertainty is discussed next. The measurement uncertainty is discussed more closely e.g. in Knuuti and Länsivaara (2019).

Transformation uncertainty

Not all of the design properties can be measured directly from the ground. In these situations, design properties are derived from measurements via different correlation and transformation models. These transformation models might be empirical, theoretic or a combination of these. The calibration for these models are usually performed against design properties determined directly by laboratory test, field measurements or by doing back-calculations. The target values are seldom unbiased, while they might suffer e.g. from measurement errors or simplifications and assumptions made in the theoretical models. The initial measurements also have some variability, and the variability of both target and input values can be described by probability density functions (pdf). The transformation model is then calibrated using some criteria to yield the best prediction of the design property. The transformation model always adds more uncertainty into the design process. It must be noted that the total transformation uncertainty evaluated from predicted versus target values includes both inherent uncertainty of the soil and the measurement uncertainty. These quantities must be subtracted in order to evaluate the actual transformation uncertainty. The knowing of the actual transformation uncertainty related to certain transformation model is important, when conducting RBD analyses and estimating soil parameters (e.g. with Bayesian statistics). The preciseness of the transformation model could guide the designers to choose better soil investigations methods (having better transformation models for a certain parameter) on a certain site, as reducing the uncertainty of a soil property could have clear benefits from the economical point of view.

3 Statistical description of soil property

As discussed, the sample sizes are usually very limited in the field of geotechnical engineering. The data sets can also be a combination of results from different soil investigations methods, prior data, engineering judgement etc. with a varying quality. Hence, it is quite impossible to calculate the statistical parameters for the whole population. However, it is possible to estimate the actual population parameters with sample statistics, which are imperfect estimates of the actual population statistics as those are derived from limited sample population. The sample statistics are sufficient to examine the variability of the property and are easier to use in everyday design than complicated probability distributions. The first two statistical moments, sample mean and sample deviation, are the most useful parameters for most of the geotechnical design cases. Also the error and complexity increases for the higher moment parameters.

Estimation of sample mean and standard deviation

Let **X** be a soil variable with existing observations $x_1 \ldots x_n$. If observations are assumed independent (e.g. no trend), the mean μ_X and standard deviation σ_X of variable **X** can be estimated from sample statistics. The sample mean x and sample standard deviation s are calculated with Eq.(3) and Eq.(4) and those are central estimates for the variable **X**.

The sample mean is estimated from Eq.(3) where n is the number of observations:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3}$$

The sample standard deviation is estimated from Eq.(4):

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{4}$$

Estimation of the total transformation uncertainty (COV$_\varepsilon$)

The term total transformation uncertainty (COV$_\varepsilon$) is herein used for the total uncertainty of the evaluated parameter after the transformation model has been applied. It includes thus also the inherent uncertainty and the measurement uncertainty. Afterwards, the actual transformation uncertainty of the transformation model itself is evaluated by extracting the inherent and measurement uncertainty from the results.

According to Ching and Phoon (2014b), the variability term ε can be calculated as;

$$\varepsilon = \frac{\text{actual target value}}{\text{b} \cdot \text{predicted target value}} \tag{5}$$

, where b is the bias factor representing the sample mean of the ratio (actual target value)/(predicted target value), actual target value is the measured value of the soil property and predicted target value is the estimated value of soil property from a transformation model. The product of “constant b” and the predicted value leads to unbiased estimation on the average. The random variable ε has a mean of 1 by definition. The total transformation uncertainty is the COV of the random variable ε ($\mathrm{COV}_{\varepsilon}$).

4 Conducted Soil Investigations

The same soil data was used here as in Knuuti and Länsivaara (2019). Total of four different clay sites, each containing three to five CPTu borings, were studied. The sites were located at Lempäälä, Masku, Murro and Perniö, all in Finland. The CPTu’s were done to the soft clay layer and the maximum penetration depths reached 9 m at Lempäälä and Perniö, 16 m at Masku and 20 m at Murro. All of the CPTu’s were done within 2 meters of each other. A low-capacity (7.5 MPa) and high-sensitivity probe were used aiming to high accuracy in the soft clay (Sandven 2010). The excess pore pressure was measured above the cone tip during the testing. In addition, seismic and resistivity measurements were done for other research purposes. Thus, those results are not included here.

All tests were conducted following the requirements of application class 1 stated in ISO (2012). The same three CPTu's from each site were taken into the statistical analysis as in Knuuti and Länsivaara (2019). The dry crust layer and stiff bottom layer were extracted from the CPTu data based on information given by operator, leaving the soft clay layer to further analyses. Table 1 summarizes the range of basic soil properties of the sites. All of the investigated clay layers were slightly overconsolidated with OCR<3, water content w=66-127% and sensitivity St=16-98. Some of the sites have been discussed in more detail by Di Buó et al. (2016) and Selänpää et al. (2017).

Table 1. Range of index properties from the four clay test sites.

Site	**number of CPtu's**	**range of depth of CPTu (m)**	**OCR (-)**	**w (%)**	**wL (%)**	**Ip (%)**	**St (-)**
Lempäälä	3	2.0-8.0	1.1-1.4	68-127	42-69	16-26	24-54
Masku	3	2.0-10.5	1.4-1.8	80-117	66-95	39-59	18-21
Murro	3	2.0-15.0	1.2-1.9	66-95	58-97	28-53	20-23
Perniö	3	2.0-8.0	1.2-2.5	70-110	44-75	19-47	37-72

Where: OCR = overconsolidation ratio from oedemeter test with constant rate of strain (CRS) of 0.001-0.0025mm/min depending on clay type; w = water content; wL = liquid limit; Ip = plasticity index and St = sensitivity from the fallcone test.

5 Interpretation of undrained shear strength

The characteristic undrained shear strength profile can be interpreted from CPTu tests by using theoretical or empirical correlations. Three different empirical approaches are used in this study. These approaches differ in from which measured value the s_u is interpreted. The s_u can be interpreted from the total cone resistance q_{net} (Eq.6), from the effective cone resistance q_e (Eq.7) or from the excess pore pressure Δu (Eq.8). The equations are shown in below. In the equations, q_T is the corrected cone resistance (measured cone resistance plus the measured pore pressure behind the cone), σ_{v0} is the vertical total stress, u_2 is the measured pore pressure and u_0 is the initial pore pressure in situ.

$$s_u = \frac{q_T - \sigma_{v0}}{N_{kt}} = \frac{q_{net}}{N_{kt}} \tag{6}$$

$$s_u = \frac{q_T - u_2}{N_{ke}} = \frac{q_e}{N_{ke}} \tag{7}$$

$$s_u = \frac{u_2 - u_0}{N_{\Delta u}} = \frac{\Delta u}{N_{\Delta u}} \tag{8}$$

The s_u is related to measured data by means of cone factors N_{kt}, N_{ke} and $N_{\Delta u}$, in each case. The cone factors are typically site or region specific depending on the soil conditions and lot of different correlations are available in the literature in order to specify them. Some typical correlations for Scandinavian soils can be found on Larsson and Mulabdic (1991) and Karslrud et al (2005). In this study, the cone factors were taken from Selänpää et al (2018), where an average cone factors applicable for multiple Finnish clay sites were derived. These cone factors were evaluated from typical Scandinavian cone factor values to match Finnish soil conditions. The values used in this study for all clay sites are N_{kt}=10.7, N_{ke}=5.6 and $N_{\Delta u}$=7.0 (Selänpää et al (2018)).

Generally, the interpretation of s_u from CPTu data consists multiple sources of uncertainty. The main sources when using equations shown above are the measured data (q_T and u_2) and the cone factors (N_{kt}, N_{ke}, $N_{\Delta u}$). The measured data includes the inherent uncertainty within a soil volume and the measurement uncertainty caused by the equipment and the test procedure. These uncertainties are discussed more closely in Knuuti and Länsivaara (2019). The choice of proper cone factors also includes uncertainty as they are usually evaluated from different correlation models and/or calibrated soil conditions. However, in this study we are not interested on actual uncertainty related to interpreted s_u-value, but the uncertainty of the transformation models (Eq.6-Eq.8). The same cone factors are thereby used for each testing site in order to neglect the effect of the uncertainty related to these cone factors. It must be noted that the same factors may not be applicable on each site, thus readers are advised to pay little attention to actual s_u-values shown later in figures (axis- values), and focus more on the variability of the results.

Other sources of uncertainty affecting to interpreted s_u-value are the overburden stress σ_{v0} and the initial pore pressure u_0. The uncertainty in these parameters is usually neglected as these are calculated as unit weight times the depth, and the unit weights of the soil and water are known to include little variability (Phoon and Kulhawy 1999a). However, in real situation the pore water pressure is not necessarily hydrostatic as assumed in here. Therefore, both the initial pore pressure and the effective stress might have some uncertainty.

6 Evaluation of total transformation uncertainty

The evaluation procedure in this study is similar to that used in Knuuti and Länsivaara (2019) where the measurement uncertainties of CPTu data were analysed. The undrained shear strength profiles are evaluated from the measured CPTu data by using each of the given transformation models (Eq.5-Eq.7). Then the statistical mean values (further referred as *mean*) for s_u interpreted with each model are calculated at each site. The calculated statistical mean values corresponds the “actual values” in Eq.(5) to which the single shear strength profiles(further referred as *interpreted*) are compared to.

Generally, only three data points/depth were available per site, which make it hard to compare reliably the measured values at a specific depth. However, as the measurements are taken each 2 cm, the number of data points is sufficient for an analysis of general variability of the given transformation models. For each boring, the bias factor and the COV_ε were calculated (Eq.5). The COV_ε is also calculated for this same ratio combining all three borings from the site (referred as *All* in tables).

The calculated COV$_\varepsilon$'s in tables 2-4 are the total uncertainty of the interpreted parameter. These COV$_\varepsilon$- values include the inherent uncertainty, the measurement uncertainty and the transformation uncertainty caused by the transformation model. The actual transformation uncertainties for used models are calculated from the results by subtracting the measurement uncertainties (+inherent uncertainty) presented in Knuuti and Länsivaara (2019). The calculated bias values in tables 2-4 describe if the chosen transformation model tends to underestimate the s_u-value (b<1.0) or overestimate the s_u-value (b>1.0) in each case.

Undrained shear strength evaluated from the net cone resistance $s_{u,NET}$

The results for interpreted undrained shear strength based on the net cone resistance (Eq.6) are presented in Table 2 and Figure 1. In Figure 1, the comparison between interpreted and mean $s_{u,NET}$ is shown for Lempäälä and Masku site. The calculated bias factors and COV$_\varepsilon$- values for each site and for each boring are presented in Table 2.

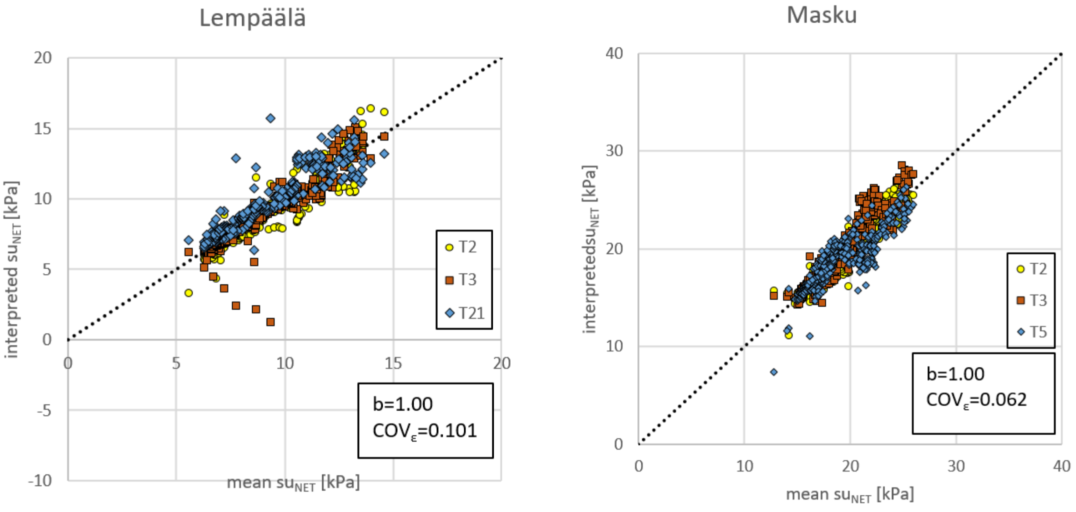

Figure 1. Comparison between interpreted and mean $s_{u,NET}$ at Lempäälä and Masku. In both figures, different colour of dots represent different borings (table 2) at the site.

Table 2. Number of data points (n), bias (b) and coefficient of variation (COV$_\varepsilon$) of s_u evaluated with Eq. (6).

Lempäälä				**Masku**				**Murro**				**Perniö**			
point	n	b	COV$_\varepsilon$	point	n	b	COV$_\varepsilon$	point	n	b	COV$_\varepsilon$	point	n	b	COV$_\varepsilon$
T1	300	0.965	0.085	T2	450	0.992	0.048	T4*	650	0.765	0.373	T2	300	0.975	0.042
T2	300	0.975	0.101	T3	450	1.020	0.060	T2	650	1.003	0.043	T7	300	1.052	0.055
T3	300	1.060	0.088	T5	450	0.988	0.070	T3	650	0.997	0.043	T9	300	0.972	0.053
All	900	1.000	0.101	All	1350	1.000	0.062	All	1300	1.000	0.043	All	900	1.000	0.063

*electrical problems were observed during boring. Results from point T4 were excluded from total number of data points for "All" at Murro.

The results (Fig.1 and Table 2) show that the uncertainty of the interpreted values is moderately low for each site. The COV$_\varepsilon$- values varies between 0.042-0.101, which are very low values considering that these values include the inherent uncertainty, the measurement uncertainty and the transformation uncertainty. Moreover, the bias values are close to 1.0 for different borings within site, indicating that the repeatability of the CPTu is good. The low variability within results can be seen from Figure 1, as most of the points are very close to unity, meaning low deviation between actual and predicted values. The difference in COV$_\varepsilon$- values between Lempäälä (COV$_\varepsilon$=0.101) and Masku (COV$_\varepsilon$=0.062) is illustrated in the Figure 1.

It must be noted that the Murro point T4 is excluded from the calculation of "All" as there were electrical problems in the tip resistance measurements during the testing. The exact source for these electrical problems is hard to know but the most probable cause has been a bad connection or wiring between seismic measurement module and the CPTu equipment. Moreover, part of the deviations in the measurements has caused by the stops made when conducting seismic measurements (consolidation of the soil during pause).

Undrained shear strength evaluated from the effective cone resistance $s_{u,eff}$

The results for interpreted undrained shear strength based on the effective cone resistance (Eq.7) are given in Table 3 and Figure 2. The same comparison between interpreted and mean $s_{u,eff}$ is shown in figure 2 for Lempäälä and Masku site. The calculated bias and COV_{ε}'s for each site are presented in Table 3.

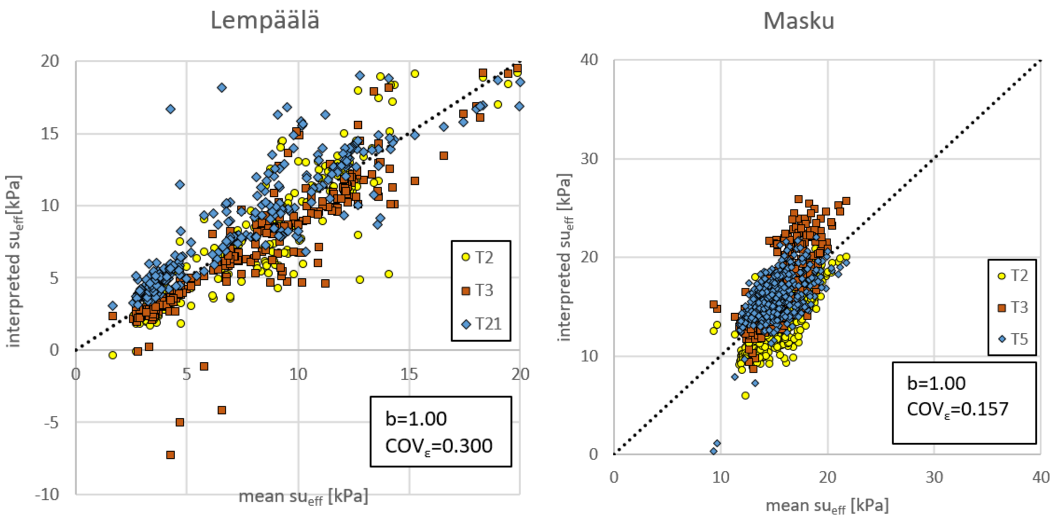

Figure 2. Comparison between interpreted and mean $s_{u,eff}$ at Lempäälä and Masku.

In both figures, different colour of dots represent different borings (table 3) at the site.

Table 3. Number of data points (n), bias (b) and coefficient of variation (COV_{ε}) of s_u evaluated with Eq. (7).

Lempäälä				**Masku**				**Murro**				**Perniö**			
point	n	b	COV_{ε}	point	n	b	COV_{ε}	point	n	b	COV_{ε}	point	n	b	COV_{ε}
T1	300	0.930	0.245	T2	450	0.875	0.126	T4*	650	0.553	1.067	T2	300	0.873	0.129
T2	300	0.871	0.313	T3	450	1.075	0.126	T2	650	1.028	0.079	T7	300	1.291	0.110
T3	300	1.199	0.240	T5	450	1.050	0.134	T3	650	0.972	0.083	T9	300	0.836	0.145
All	900	1.000	0.300	All	1350	1.000	0.157	All	1300	1.000	0.085	All	900	1.000	0.242

*electrical problems were observed during boring. Results from point T4 were excluded from total number of data points for "All" at Murro.

For this transformation model (Eq.7), a greater variation of interpreted values can be seen from the results. Figure 2 shows clearly wider scatter of results compared to Figure 1, indicating greater COV_{ε}- values. The COV_{ε} range is now between 0.083-0.313, where the largest COV_{ε}'s are observed at Lempäälä site. The bigger COV_{ε}- values here are due to the transformation model (Eq.7), which include both the measured cone tip resistance and the pore pressure as a parameter (q_T-u_2/N_{ke}). These both measured values have their own uncertainties, which increase the value of total transformation uncertainty. The "independent deviations" in these measured values cause that even though the measurement uncertainties (including inherent uncertainty) of the measured corrected cone resistance q_T and the pore pressure u_2 are rather low, the transformation uncertainty for Eq.(7) seems to be larger than for other two models. For example in Lempäälä, where the measurement uncertainties are $COV_{qT}=0.056$ and $COV_{u2}=0.068$ (Knuuti and Länsivaara (2019)), the total transformation uncertainty is 0.300. In comparison, the total transformation uncertainty in Lempäälä for the first transformation model Eq.(6) based on corrected cone resistance ($COV_{qT}=0.056$) was 0.101.

The Murro point T4 was again excluded from the calculations.

Undrained shear strength evaluated from the excess pore water pressure $s_{u,u2}$

The results for interpreted undrained shear strength based on the excess pore water pressure (Eq.8) are shown in Figure 3 and Table 4. Figure 3 shows the scatter plot between interpreted and mean value of $s_{u.eff}$ for Lempäälä and Masku sites. The calculated COV_ε- values and bias factors are given in table 4.

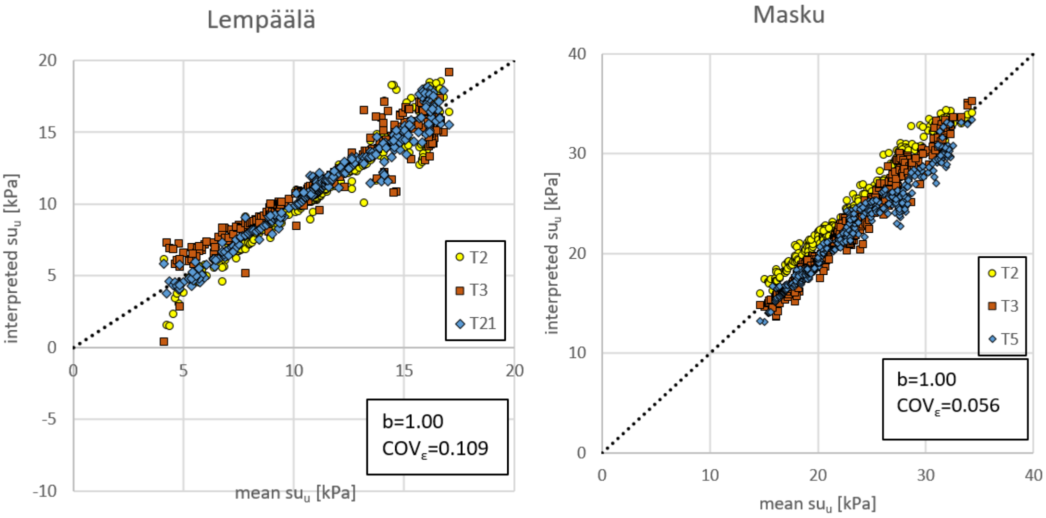

Figure 3. Comparison between interpreted and mean $s_{u,u}$ at Lempäälä and Masku. In both figures, different colour of dots represent different borings (table 4) at the site.

Table 4. Number of data points (n), bias (b) and coefficient of variation (COV$_\varepsilon$) of s_u evaluated with Eq. (8).

Lempäälä				**Masku**				**Murro**				**Perniö**			
point	n	b	COV$_\varepsilon$	point	n	b	COV$_\varepsilon$	point	n	b	COV$_\varepsilon$	point	n	b	COV$_\varepsilon$
T1	300	0.966	0.105	T2	450	1.057	0.031	T4*	650	0.983	0.042	T2	300	1.041	0.085
T2	300	1.043	0.118	T3	450	0.985	0.043	T2	650	0.985	0.034	T7	300	0.907	0.158
T3	300	0.990	0.065	T5	450	0.958	0.038	T3	650	1.015	0.033	T9	300	1.053	0.058
All	900	1.000	0.109	All	1350	1.000	0.056	All	1300	1.000	0.037	All	900	1.000	0.124

*electrical problems were observed during boring. Results from point T4 were excluded from total number of data points for “All” at Murro.

The results for the transformation model (Eq.8), based on pore pressure, show similarity to those observed for the first transformation model, based on net cone resistance. Generally, the COV$_\varepsilon$ –values are now a bit lower compared to the first model, which is also illustrated in Figure 3 by the narrow scatter of results around unity. The only exception is Perniö site, where the COV$_\varepsilon$- values are a bit larger than those calculated in the first case (net cone resistance). However, this is due to higher measurement uncertainty in pore pressure measurements (COV$_{qT}$=0.041, COV$_{u2}$=0.106; Knuuti and Länsivaara (2019)). The COV$_\varepsilon$-values for the interpreted s_u- values are between 0.033 and 0.158 and the biases are again close to 1.0. Even though the Murro point T4 was excluded from “All”, it must be noted that for pore pressure the results were similar compared to other points within site. This was encouraging, as this indicates that it is good to measure more than one parameter at once and that there is a selection of different transformation models available. As in Murro case (point T4), where the measurement of the cone resistance failed and the first transformation model (Eq.7) was rather useless for interpreting the s_u- profile, the pore pressure measurement was successful and the third transformation model (Eq.8) could be used.

Calculation of transformation uncertainty (COV$_{trans}$) of the transformation models

The actual transformation uncertainties of transformation models (Eq.6 and Eq.8) are calculated from the total uncertainties by using Eq. (2). These models were chosen as they are known to produce more stable results than the third model, which was also supported by the results in this paper (e.g. greater scatter in Fig.2). The actual transformation uncertainty is calculated by extracting the measurement uncertainty (including inherent variability) from the calculated total transformation uncertainty (tables 2 and 4). The values for measurement uncertainties at each site for the cone tip resistance and the pore pressure is taken from Knuuti and Länsivaara (2019). The calculation parameters as well as the results are given in tables 5 and 6. The calculation was done only for the whole site together ("All" row in tables). From the results, we can see that the COV_{trans}'s are very low and similar for the two transformation models.

Table 5. Calculated transformation uncertainties COV_{trans} for transformation model (Eq. 6) at each site.

uncertainties	**Lempäälä**	**Masku**	**Murro**	**Perniö**
$COV_{spat}+COV_{err}+COV_{trans}$ (=COV_{ε})	0.101	0.062	0.043	0.063
$COV_{spat}+COV_{err}$ (Knuuti and Länsivaara (2019))	0.056	0.042	0.028	0.041
COV_{trans} (Eq.6)	0.084	0.046	0.033	0.048

Table 6. Calculated transformation uncertainties COV_{trans} for transformation model (Eq. 8) at each site.

uncertainties	**Lempäälä**	**Masku**	**Murro**	**Perniö**
$COV_{spat}+COV_{err}+COV_{trans}$ (=COV_{ε})	0.109	0.056	0.037	0.124
$COV_{spat}+COV_{err}$ (Knuuti and Länsivaara (2019))	0.068	0.044	0.028	0.106
COV_{trans} (Eq.8)	0.085	0.035	0.024	0.064

7 Comparison of the results to other studies

In this study, two different type of transformation uncertainties were calculated for site-specific CPTu data: the total transformation uncertainty (COV_{ε}), including the inherent, the measurement and the transformation model uncertainty, and the actual transformation uncertainty (COV_{trans}), including only the uncertainty arising from the transformation model itself. However, as there was no correct s_u-value to compare the results against, thus, part of the uncertainty may not have been included in these values (e.g. ignoring the uncertainty of the cone factor). The obtained total transformation uncertainties in this study are therefore on the downside of the assumed actual values. This must be kept in mind, when comparing the results of this paper to other literature values.

However, the total transformation uncertainties obtained in this study seemed to be in line with the findings in other studies (e.g. Ching and Phoon (2012a; 2014a; 2014b)) meaning that it is beneficial to use site-specific transformation models and site-specific information if those are available. This can be seen from table 7, where few literature values of COV's of similar transformation models, as used in this study, are presented. Even though a direct and/or full comparison between the results from this study and the other studies is difficult to do due to different assumptions, calculation processes and objectives, it is clear that the magnitude of the uncertainty related to site-specific transformation models is much smaller than that of the global transformation models. The literature values also support the conclusion that the uncertainty related to the second transformation model (Eq.7) is greater than for the other models (e.g. Ching and Phoon (2014b)). Otherwise, in the authors opinion, the values presented for the uncertainty of global transformation models are more or less suitable as prior knowledge, as the COV- values are rather large (COV>0.5). Although, it is considered, that the studied global transformation models are very helpful on sites, where no site-specific information or transformation models are available. Yet, it is seen important to develop and study the site-specific transformation models, from which the designers can choose the most appropriate for practical situations, to which they can rely on and which guides them to do better site investigations, leading to savings in the final design.

Table 7. Calculated bias values (b) and COV’s of various transformation models for s_u from different literature sources. (n=data points)

Author	global/local database	n	transformation model	b	COV (%) (value in literature)
Ching and Phoon (2012a)	global, CPTU-s_u/σ_v'	423	$[(q_T-\sigma_v)/\sigma_v']/[s_u(mob)/\sigma_v']$	0.95	0.49 (0.31)
		428	$[(q_T-u_2)/\sigma_v']/[s_u(mob)/\sigma_v']$	1.11	0.57 (0.34)
		423	$[(u_2-u_0)/\sigma_v']/[s_u(mob)/\sigma_v']$	0.94	0.49 (0.32)
Ching and Phoon (2014a)	global, database/10/7490	862	$(q_T-\sigma_v)/\sigma_v'$		1.17
		668	$(q_T-u_2)/\sigma_v'$		1.37
Ching and Phoon (2014b)	global, Database/6/535	535	$(q_T-\sigma_v)/\sigma_v'$		0.68
		535	$(q_T-u_2)/\sigma_v'$		0.89
		535	$(u_2-u_0)/\sigma_v'$		0.57
Knuuti and Länsivaara (2019)	site-specific, FINNCONE (4 sites, 3CPTu's per site)	12	$(q_T-\sigma_v)/N_{kt}$	1.00	0.04-0.10
		12	$(q_T-u_2)/N_{ke}$		0.08-0.30
		12	$(u_2-u_0)/N_{\Delta u}$		0.03-0.12

Readers are advised to check the references for further information about calculated values. Full comparison between values is difficult due to different assumptions and objectives behind calculations.

8 Conclusions

The results showed that the evaluated transformation uncertainties (COV_{trans}) were low for the model based on the net cone resistance and for the model based on excess pore pressure. For these models, the COV varied between 0.024-0.085. For the third model, the COV’s tended to be higher, probably mainly because this model included both, the cone tip resistance and the measured pore pressure as initial parameters, both having their own uncertainties (Knuuti and Länsivaara (2019)). The literature results (e.g. Ching and Phoon (2014b)) also supported this conclusion.

It must be noted that in these calculations the uncertainties of the total overburden stress and the initial pore water pressure were neglected. By taking these into account would increase the transformation uncertainties (COV_{trans}). Moreover, if the actual s_u value were calculated, the uncertainty defining the proper cone factor should be included. Now a constant cone factor was used in order to eliminate this uncertainty.

Furhtermore, the evaluated transformation uncertainties are representative only for the specific sites. As can be seen from the results the values vary somewhat from site to site. Yet, the results give an indication of the order of magnitude for the transformation model uncertainty in soft clays, and on the qualitative performance of the different transformation models. The comparison to other studies, considering global transformation models (similar to transformation models used in this study), indicated that it is beneficial to use site-specific models when available, as the uncertainty in these is much smaller.

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