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Watch out for the use of global correlations and "black box" interpretation of CPTU data

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ABSTRACT: Many people interpret soil properties from CPTU measurements based on correlations embedded in software packages without ever questioning the validity of those correlations. This could be termed the 'black box' approach! This paper aims to show how dangerous this can be but also the power of the CPTU in helping to show the variations in soil properties within profiles. Based on correlations properties can be both over and under-estimated, which can of course result in both unsafe design and over design. Too often one correlation must be used to derive a soil property required in another correlation, further compounding the potential for errors. A range of sites will be examined with a range of soils varying from very soft clays and silts to stiff clays, sands and soft rocks.

1 INTRODUCTION

The Cone Penetration Test (CPT) or Cone Penetration Test with pore water pressure measurement (CPTU) is almost certainly the most widely used in-situ test both onshore and offshore. Its equipment and operation are well standardised (ISO 22476-1 and ASTM D5778). If these standards are followed and the necessary quality checks are performed, then reliable measured results should be easily obtained and can then be used to derive estimates of the geotechnical parameters to assist the geotechnical design. This is when problems start. Most of the interpretations are semi-empirical in nature and over the years many correlations have been published, linking the measured CPT/U data to the required soil properties. Many people interpret soils from CPTU based on these correlations, which have also been embedded in various software packages without ever questioning their validity. Unfortunately, this is being increasingly done and could be termed the 'black box' approach!

Clients are forcing/encouraging CPT contractors to derive soils properties without providing any additional input. It should be acknowledged that these derivations might be guesses, not even best estimates.

Processing of CPT/U raw data starts from converting voltages to engineering units, plotting the results on soil behaviour type charts and ends on generating all possible soils properties. This is an easy electronic process even without proper user input.

This paper aims to show how dangerous data processing without the proper input can be and how knowledge is required on reliable interpretations. But it also shows how if done with care, the power of the CPTU in determining the variations of soil properties is still so very worthwhile. Based on correlations, properties can be both over and under-estimated, which can of course result in both unsafe design and over-design. Too often one correlation must be used to derive a soil parameter required in another correlation. To further confuse the situation, some of the derived parameters are obtained by using values from other derived/ guessed parameters, adding more errors. It is not intended to mention correlations by name, but to point out the problems that can occur if outputs from software are taken without any user interaction. The packages used are commercially available. No pre-selection of correlations has been made.

For this purpose, 18 commercial sites and 14 test bed sites, which include 100s of CPTUs with a maximum depth of 40m have been studied. Different soils examined vary from very soft to stiff clays, silts, sands and soft rocks. Data cannot be presented for all the sites, but the conclusions are drawn based on all the data that the authors have reviewed. Guidance and advise will be given where possible.

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2 SOFTWARE DERIVATION

2.1 *Parameters*

Some of the geotechnical parameters that can be derived from CPTU test results by using various correlations published in the literature and incorporated into various software packages are listed in Table 1.

Table 1. List of possible parameters to derive from correlations available in the literature.

Parameters	Symbols	Unit
Relative Density	D_r	%
Undrained Shear Strength	s_u	kPa
Water Content	w_c	%
SPT number	N_{60}	-
Shear Wave Velocity	v_s	m/s
Unit weight	γ	kN/m
Small Strain Shear Modulus	G_0	MPa
Small Strain Youngs Modulus	E_0	MPa
Constrained Modulus	M	MPa
Coefficient of volume change	m_v	m^2/MN
Compression Index	C_c	-
Overconsolidation Ratio	OCR	-
Friction Angle	φ’	°
Effective Cohesion	c’	kPa
Sensitivity	St	-
Coefficient of Lateral Earth Pressure	K_0	-
Rigidity Index	I_r	-
Hydraulic Conductivity	k (k_h and k_v)	m/s

The process of deriving all geotechnical parameters from CPTU results after gathering the measured data from site, which consists of cone resistance q_c, sleeve friction f_s, and porewater pressure u_2 starts with generating the corrected cone resistance, q_t and friction ratio, R_f through very simple calculations which involve measured results only. At this phase of data processing Soil Behaviour Type, SBT can be plotted on one of the charts available based on q_c/ q_t and R_f.

To derive more soil properties, it is nearly always necessary to have information on groundwater conditions, GWL and density/unit weight, γ to establish total and effective vertical stresses, σ_{v0} and σ'_v, to derive pore pressure ratio, B_q and other normalized parameters, Q_t and F_R.

Information about GWL from the CPTU can only be obtained if full dissipation tests are run and this is seldom done. Hence, guessed GWL must be used as an input to the software if the client cannot supply any information from monitoring it on site. Regarding γ more details are given in the following section.

2.2 *Unit weight/ density (γ) and water content (w_c)*

When γ is derived from the equations available in the literature and found in many software packages q_t, f_s, and specific gravity of solids, G_s are required to run these calculations. One of the correlations require also shear wave velocity, V_s which is one of the parameters that will be discussed later in the paper.

In Figure 1 are shown some examples of derived γ which are compared with laboratory γ. A significant and consistent underestimation of γ for the glacial till at Cowden (Powell & Butcher, 2002) in England and the silt at Lierstranda (Lunne, 2002) in Norway can be observed. The same behaviour was present at 2 other till sites and 2 more silty clay sites.

In the same figure results from the London clay site at Canons Park (Powell et al., 2003) are also included. Again, derived γ profiles are on the low side of the measured profile. One of the correlations is giving results on the opposite direction of the measured. This pattern of results was apparent for all 5 London clay sites investigated by the authors and was similar in other heavily overconsolidated and aged clay sites. Underestimation is not always the case. γ results for the soft clay at Cran (Shields et al.,

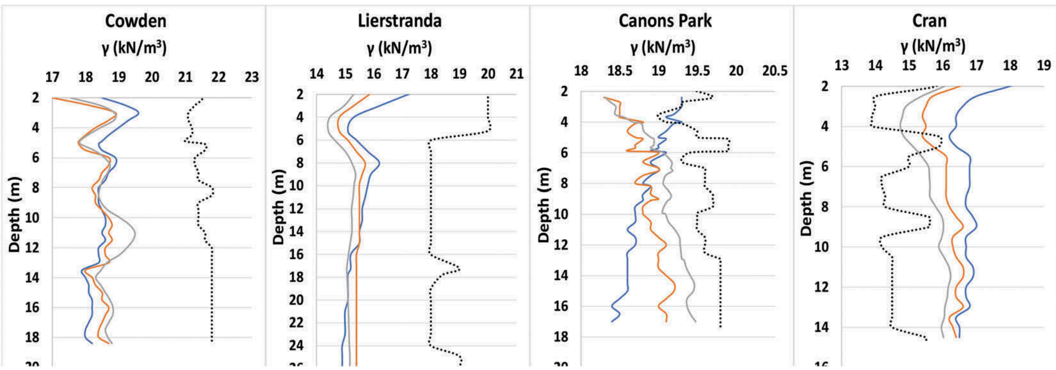

Figure 1. Examples of underestimated and overestimated γ derived from various correlations in use.

1996), in France are highly overestimated, as can be seen from the last graph in Figure 1.

Some packages give also w_c as an output parameter. As might be expected, these results tend to be mirror images of the density profiles using a selected G_s.

2.3 *Relative Density (Dr)*

When considering sand then D_r is often a desired parameter. In order to derive D_r from CPTU results, q_c, q_t, σ_{v0} and σ_{atm} are typically necessary input. Figure 2 shows results from the sand site at Dunkirk (McAdam et al., 2020), which is partially placed and partially natural deposit. The wide range of derived D_r results after using some of the correlations available in the software is worrying. Generally, underestimation is seen at shallower depths and overestimation at deeper depths. Incorporating the correct γ values and the correct GWL, will significantly improve the results and better define the two layers that comprise this site. The second graph in Figure 2, shows derived D_r before and after compaction of a sand fill. Four different correlations available in the specialist software are used to derive D_r, noted in the figure as C1, C2, C3 and C4 Pre and Post, respectively. Once again, the wide range of results, especially those being highly overestimated after compaction is worrying.

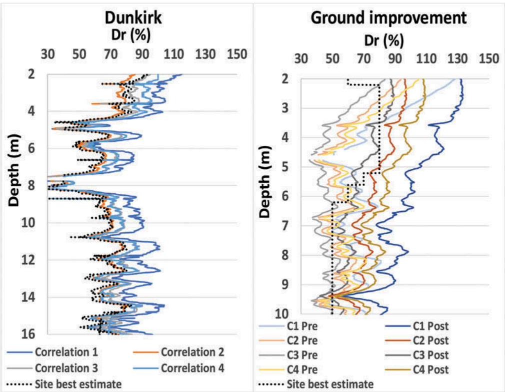

Figure 2. Examples of derived D_r in sands showing under and overestimation of site best estimate values.

2.4 *Overconsolidation Ratio (OCR)*

When considering OCR or alternatively yield stress, CPTU is known to be a powerful tool to profile it. Some correlations can estimate OCR based on q_t, u_2, Δu, σ_{v0}, σ'_v and σ_{atm}. Some others require φ' and G_0, which on the other hand require q_c, q_t and/or Qt and γ. The long list of measured and derived parameters to estimate OCR makes its calculation prone to errors. It is worth mentioning, that OCR is the parameter with the largest number of correlations available.

Figure 3 shows results from some of the sites studied and it can be observed that the shape of the profiles generally follows the sites best estimate. However, the absolute values vary considerably. From all the results we have processed, one of the correlations consistently gives the same results of OCR around 1 for all ground conditions and soil types!

Looking into more details, for the glacial till at Cowden some of the profiles match well with the site best estimates, especially below 22m, where OCR increases. There are results from correlations that highly overestimate OCR, which are not correct. The first attempt for Cowden was done using the default value of γ set up in the specialist software. The second analysis of the results was carried out used the true γ of $22kN/m^3$. Using the correct γ rather than the software generated values for this site, improves the derived OCR results, especially for correlation 6 which is now closer to the best estimate site characteristic values. Although, it is worth mentioning that two of the correlations that seem to not agree are both based on porewater pressure.

At a London Clay site in Canons Park the results presented in this Figure show significant underestimation compared to the site best estimated values,

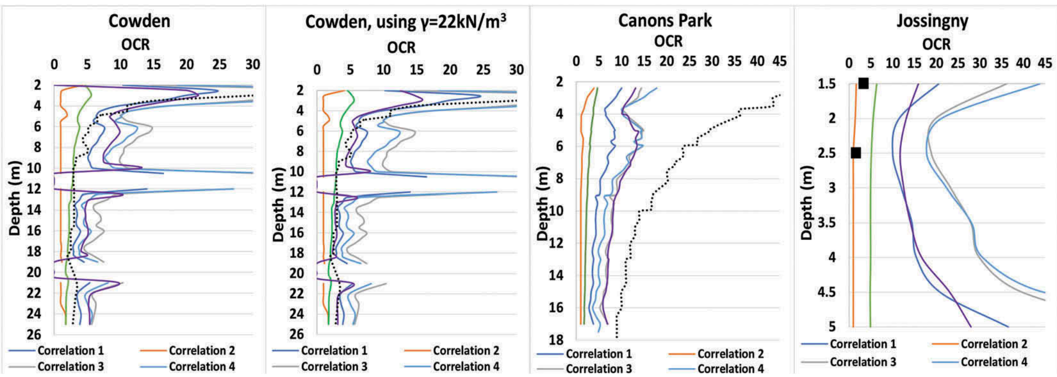

Figure 3. Examples of derived and site best estimate OCR results for 4 sites comprising glacial till, London clay and clayey sand.

although in most cases generated graphs have the correct shape, with values being reduced with depth.

Things can go very wrong indeed, a clayey sand site in Jossingny (Shields et al., 1996), shows unrealistic overestimation as seen in Figure 3.

Using these correlations without questioning the applicability of them in certain soil conditions is seen to give wildly wrong results. Uniform sites (like Cowden) have been examined to show that some correlations respond to changes in OCR caused by erosion. However, what happens if the geology changes, as well? Turning back to the examples above and many more results that authors reviewed for the purpose of this paper, it is not uncommon that a value of around 1 is derived for the full profile-raising concerns on applicability of this specific correlation.

OCR is one of the parameters most influenced by the GWL. Even 1m of GWL change can affect the predicted OCR results from as little as 5% for stiff clays to as high as 45% for soft clays. Therefore, correlations involving GWL as input parameter should be avoided when this information is not accurate.

2.5 *Standard Penetration Test (SPT) N Value*

The SPT, love it or hate is still one of the widely used in-situ tests worldwide. It has been said that "the best way to get reliable N values is from correlations with CPTU". The correlations available use q_c, Soil Behaviour Type Index, I_c and σ_{atm} to calculate N. Figures 4 and 5 show CPTU derived SPT profiles and compare them to the in-situ measured SPTs. Four different sites in England are chosen as representative examples, which include the London Clay site of Heathrow Terminal 5 (Hight et al., 2002b) and three commercial sites in Glasgow, Hull and Hemel Hempstead of mixed glacial deposits, silt mixtures underlain soft clay and silt underlain Chalk, respectively.

For London clay at T5, it can be seen that although the generated scattered CPTU profile has almost the same shape, it is below the in-situ measured profile.

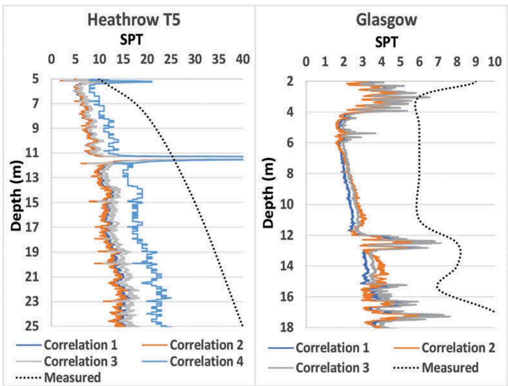

Figure 4. Examples of derived SPT profiles in London and soft clay showing under and overestimation of measured values.

This pattern has been observed on many other clay sites studied, including the soft clays in Glasgow.

However, on two sites presented in Figure 5 results are over and underestimated, in sandy layers and in clayey layers, respectively. Regarding soft rocks, in the second graph below are shown the Chalk results, where in the upper meters in the very weathered Chalk, all SPT profiles seem to agree well. When penetrating through competent Chalk there is a greater difference, with derived results being higher than the measured ones.

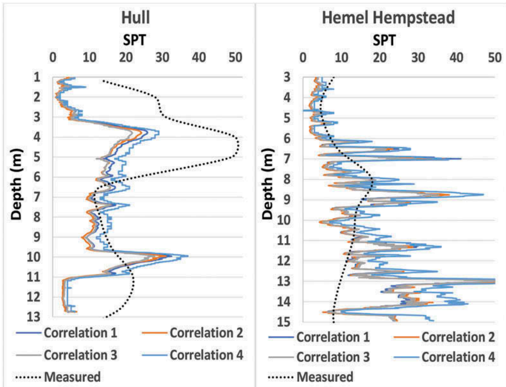

Figure 5. Examples of derived SPT profiles in other soils.

An interesting observation for silt layers from all the studied sites (two also included in Figures 5, the silt layer 6-9.5m in Hull results and 2-6m in Hemel Hempstead results) indicates that measured and derived results show a better agreement in this soil type.

2.6 *Shear wave velocity (V_s) and Small Strain Stiffness (G_0)*

When V_s and G_0 are considered, it is needed to ensure that anisotropy in the ground is not ignored. This affects the strength and the stiffness of the soils. Results generated from standard geophysical tests, which are typically referred to as downhole and crosshole can be different because of anisotropy. There is a less common crosshole test that allows a third orientation of stiffness to be considered (Butcher & Powell, 2004). As a result, is not enough to know what is being measured, but also which measured direction (vertical or lateral) is the most appropriate for design. For clarity, the following subscripts have been added to V and G to define the orientation of the values: vh for downhole tests and seismic cone, hv for standard crosshole tests and hh for results in a true horizontal plane. The importance of V_s and G_0 means that these parameters are widely desired and therefore derived from measured CPTU results.

Their derivation involves q_t, f_s, σ_{v0} and γ. In the following graphs, derived results are compared with the measured ones from seismic cone tests and are noted as V_{vh}. Figure 6 presents results from four sites, with different geology.

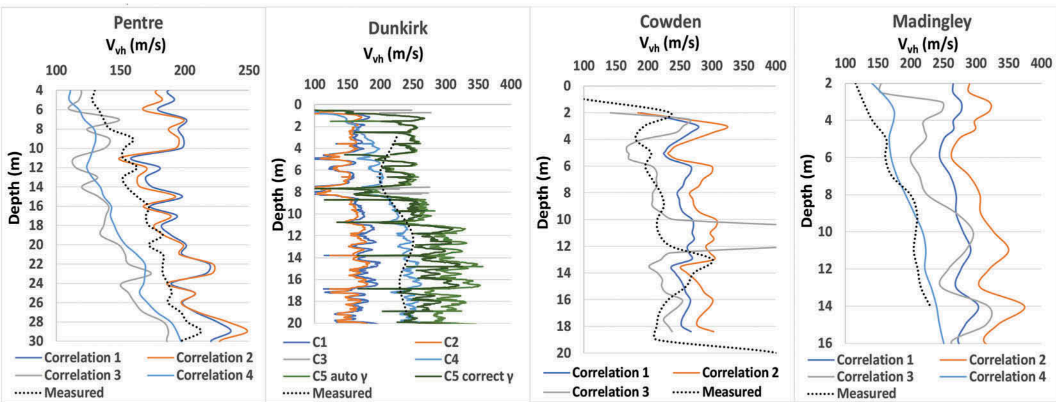

Figure 6. Comparison between measured and derived V_{vh} results in clay sit, sand, glacial till and stiff clay.

Pentre (Lambson et al., 1993) represents a clayey silt site, where the measured V_{vh} profile fall in between the derived one.

For the sands at Dunkirk, which show the largest scatter of derived results the measured V_{vh} profile falls towards the upper bound of the derived values. For the glacial till deposits at Cowden the measured V_{vh} falls towards the lower bound of derived profiles. Although the scatter here is not as large as the one observed for Dunkirk, below 16m derived V_{vh} are overestimated. Furthermore, big differences between are also seen for the stiff clays in Madingley (Butcher & Lord, 1993). Surprisingly, the greatest differences noticed are when deriving V_{vh} from the correlation which is suggested to work best in clays. This indicates that even if some correlations are recommended for one soil type, big differences can still be present. Does this mean that soil type is not the only limitation to the applicability of some correlations?

However, overestimation is not always the case. Figure 7 shows results from very stiff clays in Banbury and dense sands in Machynlleth, where derived V_{vh} are significantly lower than the measured one.

The behaviours seen in Figures 6 and 7 for V_{vh} are also noticed for derived and measured G_{vh}, Figure 8.

The results patterns for G_{vh} match those of Powell (2017) using a wider range of correlations, with the measured values for normally and lightly overconsolidated soils resulting in between derived ones. Meanwhile, the measured G_{vh} for heavily overconsolidated clays fall in the lower bound of derived results.

Derivations of G_{vh} is generally linked to CPTU data. However, derived V_{vh} and γ can be used to calculate $G_{vh.}$ In this case, even if V_{vh} is realistic G_{vh} could have errors for incorrect γ. Results from Dunkirk support this. The G_{vh} profile generated from the software is closer to the site measured profile when correct γ is used. This again shows the importance of accurate input parameters to derive more parameters. Powell and Butcher (2004) and later Powell et al. (2016) suggested that it was the horizontal stresses and stiffnesses that influence q_t and that q_t correlates better with G_{hh}. This idea is further supported by Long (2022) who, using the same and additional data suggests that V_{hh} correlates better to q_t than V_{vh} does.

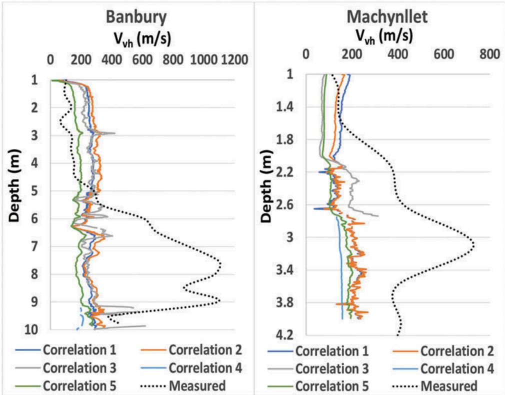

Figure 7. Examples of underestimated derived V_{vh} results.

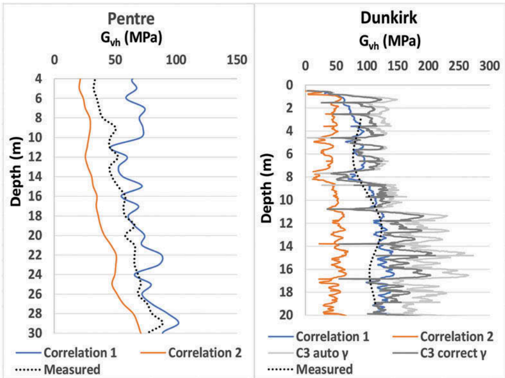

Figure 8. Examples of derived and measured G_{vh} profiles.

2.7 *Other parameters*

Undrained shear strength, s_u is highly affected by the choice of cone factor, N_{kt}. This is the principal problem, although γ and GWL should ideally be known. Some of the software can generate N_{kt} values. Great care must be taken when this is done. It has been found on the studied sites that it can lead to under and overestimation of s_u. Values of N_{kt} should ideally be selected by the designers based on past experiences and the shear test types required, for example compression, extension or simple shear.

Another problem is the assessment of coefficient of lateral earth pressure, K_0. Correlations exist and are incorporated into software, as well. But, realistic assessment of K_0 from CPTU is still extremely weak and should be treated with great caution.

Another parameter that needs to be treated with growing awareness is permeability (hydraulic conductivity), k, which is widely required for settlement calculations as an input parameter in design software. k from CPTU is a rough guide of possible values for each SBT, giving lower and upper bounds. The importance of dissipation tests to estimate coefficient of consolidation, c_v is crucial. c_v is acceptable when dissipations are carried out below GWL. When GWL is unknown, dissipation tests need to run to equilibrium.

3 DISCUSSIONS AND CONCLUSIONS

In this paper has been suggested that the use of software to process CPTU results into geotechnical information should be done with care. Although these packages perform the mathematical calculations correctly, they are often used with too little basic information, experience and/ or knowledge.

It has been shown that many of the embedded correlations are not suitable for ALL soil types.

In addition, the following points can be made:

- Correct γ and GWL can improve the results of many derived geotechnical parameters;
- Derived parameters obtained based on other previously derived parameters should be avoided;
- Different correlations can give very different derived parameters for the same soil type;
- Sometimes agreements between measured and derived parameters have been found to be purely fortuitous. Two incorrectly derived parameters appearing to give a correct answer, this is worrying!

Correlations used in similar soil types are valuable, as are site specific ones. Parameter profile shape is often promising, but the absolute values between correlation vary wildly.

Can we find correlations that use soil type in terms of I_c as input parameter? It looks unlikely.

Why derive parameters that can be easily measured, like V_{vh}. However, site specific correlation can be useful for example, between q_t and measured V_{vh} from SCPTU, when used with other CPTUs on a site.

The importance of linking CPTU parameters with results from quality laboratory tests cannot be overstressed if efficiency in design is to be achieved. Correlations can be very useful but should only be used when all influences in their derivation are understood.

Finally, always revisit processing when site specific information becomes available and site-specific correlations are established. They are far from foolproof. Soils properties should be treated with caution if they are derived without basic input information.

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