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RESEARCH ARTICLE

Correlation of undrained shear strength and CPT resistance

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Abstract

The correlation of CPT resistance and undrained shear strength of soft Holocene clays is discussed in this paper. This soil type, covering significant part of Hungary is frequently involved in different geotechnical engineering problems such as building of highway embankments. Soil samples of eight different sites have been studied, samples were taken at each site and cone penetration tests were performed. The samples were tested by means of unconfined compression and consolidated-undrained triaxial compression tests. The correlation of the determined undrained shear strength and the experienced CPT results was evaluated and the empirical cone factors (N_k, N_{kt}, N_{ke}, $N_{\Delta u}$) were determined for each tests. The back-calculated cone factors have been compared with the values suggested by earlier works in this field. The possible correlations between cone factors and different soil properties (such as index of plasticity, pore pressure coefficient etc.) are also discussed in the paper and recommendations are given for estimation of undrained shear strength of Holocene clays.

Keywords

undrained shear strength · CPTu · empirical correlation

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1 Introduction

Building on soft cohesive soils involves many geotechnical issues. The high compressibility of the soils causes significant settlements which generally develop slowly. As the required construction times are reducing, long term deformation of soils is rarely affordable, therefore different soil improvement techniques are generally used to decrease and accelerate the settlements. Another important issue is the limited strength and bearing capacity of soft soils. The shear strength of soils determines the maximum allowable load which can be applied on it (e.g. maximum footing pressure, embankment height etc.). In the case of cohesive soils the undrained loading condition is the least favorable, so it is the undrained shear strength that governs the bearing capacity. Undrained shear strength (s_u) is a commonly accepted and used soil parameter and there are numerous ways to obtain it. Nevertheless it is not a single soil parameter. The measured undrained shear strength depends on testing method (failure mode), strain rate, stress path and many other factors (Mayne et al., 2009) [12]. Therefore it is important to clearly define which undrained shear the given data refers to.

This paper focuses on correlation of CPT results and undrained shear strength values determined by means of consolidated-undrained triaxial and unconfined compression tests. There are numerous methods available to estimate undrained shear strength of clays of different types, but there is no information about their reliability in case of soft Holocene clays located in the Carpathian Basin. A reliable correlation of the test results could provide more detailed information on the shear strength of such soils at many sites by having CPTu measurements at every two centimeters. The number of data could also enable a statistical analysis of the undrained strength values, thereby could also provide information on the uncertainty of the strength parameter which is essential for failure probability assessment (Nagy, 2008) [13].

Data from 8 different sites are summarized and evaluated in this paper. At each location the upper 5-10 m thick layer was formed by soft, Holocene clays, having a CPT tip resistance (q_c) value less than 2 MPa.

2 Existing correlations, performed tests

Cone penetration testing have been used for a long time in soil exploration, and determining pile bearing capacity (Mahler, 2003) [10] and the undrained shear strength of soft soils is one of the earliest applications.

There are many theoretical solutions based on different considerations such as bearing capacity theory (Terzaghi, 1943 [17]; de Beer, 1977 [2]), cavity expansion theory (Skempton, 1951 [15]; Vesic, 1975 [18]), analytical and numerical approaches (Ladanyi, 1967) [8] or strain path theory (Teh, 1987) [16]. A detailed summary of these methods is given in Lunne et al. (1997) [9]. The undrained shear strength can be derived in a very similar way in each of the theoretical proposals, the general formula can be written as:

$$s_u = (q_c - \sigma_0)/N_c \tag{1}$$

where

s_u is the undrained shear strength,

N_c is the theoretical cone factor,

σ_0 is the total horizontal, vertical or mean stress (depending on the theory considered).

The derived theoretical expressions have pointed out that a reliable correlation can be found between the undrained shear strength and CPT tip resistance, if the in situ stress state is taken into consideration. These expressions became the theoretical basis of later empirical or semi-empirical correlations which are commonly defined by the same equation form, but in order to differentiate distinguish them from the theoretical solutions the empirical cone factor is denoted by N_k.

$$s_u = (q_c - \sigma_{v0})/N_k \tag{2}$$

where

N_k is the empirical cone factor,

σ_{v0} is the total overburden stress.

Many analyses have been conducted to obtain typical cone factor values for different soil types. Lunne and Kleven (1981)[19] have found that N_k varied between 11 and 19 (having an average value of 15) for normally consolidated, Scandinavian marine clays with field vane test as a reference test. Jörss (1998) [7] recommends the use of $N_k = 20$ for marine clays and $N_k = 15$ for boulder clays. Gebreselassie (2003) [5] has summarized the German experiences and has proposed different values ranging from 7.6 to 28.4 for different soil types. Summarizing results of three test sites in Malaysia, Chen (2001) [3] experienced cone factor values varying between 5 and 12.

The wide range of cone factor values implies that care must be taken when using such empirical correlation. They can be used only if there are comparative experiences on similar soil types and geological conditions. The goal of this study is to evaluate the test results of Holocene clays in the Charpatian Basin, thereby to provide a recommendation for choosing appropriate cone factors for this soil type.

The aforementioned formula has been slightly modified and rephrased using the tip resistance values corrected for pore pressure effects (q_t), as the use of CPTu tests became more common worldwide.

$$s_u = (q_t - \sigma_{v0})/N_{kt} \tag{3}$$

where N_{kt} is the empirical cone factor (for the expression using q_t).

The use of pore pressure corrected tip resistance (q_t) is especially important in the case of soft clays, where the measured pore pressure can be nearly as large as the measured tip resistance, thus the difference between q_c and q_t can be significant.

There are a vast number of studies available about values of N_{kt} experienced in different geological conditions. Some of these experiences are summarized in Table 1.

The N_{kt} values, similarly to the N_k values, vary over wide range, between 4 and 20. Some of the cited works have found that the cone factor is a function of certain soil parameters (e.g. plasticity index, overconsolidation ratio, pore pressure parameter), but later works did not confirm the presence of such relationships. Therefore it seems rather complicated to define a single soil property that governs the cone factors, probably because there are more factors affecting the N_{kt} values.

Another possibility to calculate undrained shear strength from CPT tip resistance values is the use of effective cone resistance $q_E = q_t - u_2$.

$$s_u = q_E/N_{ke} = (q_t - u_2)/N_{ke} \tag{4}$$

where N_{ke} is the empirical cone factor (for the expression using q_E).

The effective cone resistance has been successfully used also in other fields of geotechnics, such as soil classification (Fellenius, 1997) [4], pile capacity prediction (Mahler, 2007) [11], so it seems obvious to find a correlation between this value and the undrained shear strength. There are many proposals available for N_{ke} values for different soil types. A brief overview of them is given in Table 2.

In the case of soft clays the measured q_c values are relatively small, so even minor errors can influence the measured values significantly. Therefore for very soft clays the use of excess pore water pressure may be better to find a reliable correlation:

$$s_u = \Delta u/N_{\Delta u} = (u_2 - u_0)/N_{\Delta u} \tag{5}$$

where

$N_{\Delta u}$ is the empirical cone factor (for the expression using Δu),

u_0 is the in-situ pore water pressure.

Lunne et al.[20] have found that the cone factors vary in this case between 4 and 10, Karlsrud et al. [21] experienced $N_{\Delta u}$ values between 6 and 8. Recent experiences show similar values, ratios between 4 and 9 has been found by Hong et al. (2010) [6]. In addition, all author found that $N_{\Delta u}$ correlates well with the pore pressure ratio, B_q. This practically means that the cone

Tab. 1. Recommendations for cone factor N_{kt}

N_{kt} value range	Reference test	Comments	Reference
8-16	triaxial compression, triaxial extension and direct shear	For clays (3% < I_p < 50%) N_{kt} increases with I_p	Aas et al. (1986)
11-18		Found no correlation between N_{kt} and I_p	La Rochelle et al. (1988)
8-29	Triaxial compression	N_{kt} varies with OCR	Rad and Lunne (1988)
10-20	Triaxial compression		Powell and Quarterman (1988)
6-15	Triaxial compression	N_{kt} decreases with B_q	Karlsrud (1996)
7-20	Triaxial compression	Busan clay, Korea 25% < I_p < 40%	Hong et al. (2010)
4-16	Vane shear	High plasticity, soft clay, 42% < I_p < 400%	Almeida et al. (2010)

Tab. 2. Recommendations for cone factor N_{ke}

N_{ke} value range	Reference test	Comments	Reference
6-12		For clays (3% < I_p < 50%)	Senneset et al. (1982)
1-13		N_{ke} varies with B_q	Lunne et al. (1985)
2-10	Triaxial compression	N_{kt} decreases with B_q	Karlsrud (1996)
3-18	Triaxial compression	Busan clay, Korea 25% < I_p < 40%	Hong et al. (2010)

factor can be predicted more accurately, which consequently results in better undrained shear strength prediction.

The soil samples used for this study were taken from 7 different sites along the highway M43 located in southern Hungary and another location in Hajdúszoboszló. At each site CPTu test were carried out in the vicinity of the drillhole. The undrained shear strength of 22 soil samples have been determined by means of consolidated-undrained (CU) triaxial compression tests and unconfined compression tests. The samples have been classified as silt and clay of varying plasticity. The undrained shear strength of the soils varied between 12 and 124 kPa, thus the consistency of the soils could be defined as soft, firm and stiff. However, the characteristic CPT tip resistance values varied between 540 and 1900 kPa, which implies rather soft and firm soil conditions.

3 Empirical cone factor values

The aforementioned empirical cone factors were determined for each tested sample; the characteristic results are summarized in Table 3.

The determined N_k values vary typically between 10.5 and 27.6, having an average of 18.6. The typical values are in good agreement with the literature values, especially close to the German experiences (Gebreselassie, 2003) [5].

The cone factor values N_{kt} and N_{ke} have shown similar trends. The values vary over the same range described previously by other authors, but the mean seems to be slightly higher than experienced by others. This might be caused by the different nature and geological history of soils, but it can partially arise from the sampling quality as well. The scatter of the data is illustrated by Figure 1, in addition to the measured values, the lines representing $N_{kt} = 17$, $N_{kt} = 32$ and the best fitting line are also plotted. The line of best fit has been determined by the method of least squares which minimizes the total deviation between predicted and measured values.

The cone factor values $N_{\Delta u}$ varied in a somewhat wider range than it was observed by other authors, and a more significant scatter can be observed. This is illustrated in Figure 2, here the best fitting line and the $N_{\Delta u} = 17$, $N_{\Delta u} = 32$ lines are also indicated. Nevertheless the mean value shows very good agreement with previously published results, so probably the difference experienced in the case of N_k and N_{kt} values are caused by the different geological formation of the soils rather than by sampling quality differences.

It seems worth to analyze whether there is a reliable correlation between the experienced $N_{\Delta u}$ values and the pore pressure coefficient (B_q), as it was mentioned in previous works.

4 Cone factor correlations

Further investigations have been made in order to analyze if the cone factor could be estimated in a more reliable way as a function of another soil property.

Tab. 3. Experienced cone factors

	N_k	N_{kt}	N_{ke}	$N_{\Delta u}$
minimum value	10.5	11.9	10.9	1.8
arithmetic mean value of the calculated cone factors	18.6	23.3	18.3	6.3
maximum value	27.6	32.1	28.6	13.1

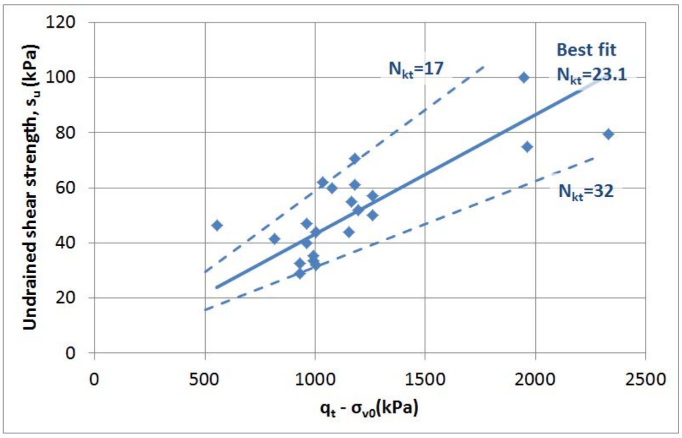

Fig. 1. CPT resistance vs. undrained shear strength

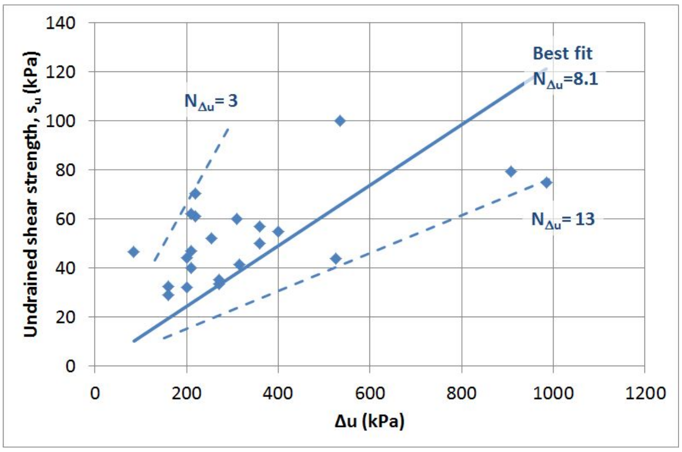

Fig. 2. CPT resistance vs. undrained shear strength

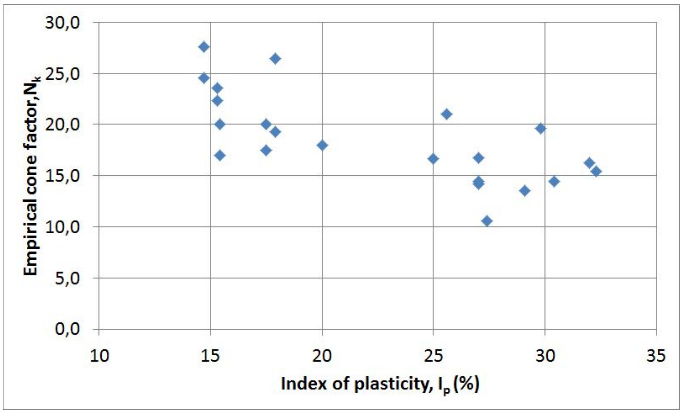

Fig. 3. Index of plasticity vs. Empirical cone factor (N_{kt})

A widely used approach is to use higher cone factors for soils having higher q_c values and lower ones for soils having lower CPT resistance. In our cases no such tendency can be observed, the correlation coefficients of undrained shear strength and the relevant CPT resistance ($q_c - \sigma_0$; $q_t - \sigma_0$; $q_t - u_2$; Δu) values are below 0.1, indicating that not even weak correlation exists between these parameters.

Aas et al. (1986) [22] have found that the empirical cone factor depends on the plasticity index (I_p) of soil, the larger the I_p, the larger the cone factor (N_{kt}), but later works have not confirmed this tendency. The N_{kt} values calculated for our samples have been plotted against the index of plasticity (Figure 3). It seems that, in contrary to the experiences of Aas et al. (1986)[22], N_{kt} slightly decreases with increasing plasticity in the I_p range of 14-33%. It must be also noted that there is no strong correlation between the two parameters, the correlation coefficient is only $R^2 = 0.47$. In addition, N_{kt} values for soils having nearly the same I_p vary over a quite large range, for example they vary between about 20 and 40 in I_p range of 15-20%. This also implies a less reliable correlation.

For cone factors N_k and N_{ke} the trend and the correlation coefficients are very similar, so in contrary to a widely accepted belief, using an I_p dependent empirical cone factor does not improve the reliability of undrained shear strength estimation significantly.

More authors have found that the empirical cone factor $N_{\Delta u}$ correlates well with the pore pressure coefficient B_q. By definition, this coefficient can be calculated by the following formula:

$$B_q = (u_2 - u_0)/(q_t - \sigma_{v0}) \tag{6}$$

where

u_2 is the pore pressure measured just behind the cone tip;

u_0 is the equilibrium pore pressure (consequently $u_2 - u_0$ is the excess pore pressure, Δu);

σ_{v0} is the total overburden stress.

Our calculated cone factor values have been plotted against the pore pressure coefficient (B_q). In the case of N_k, N_{kt} and N_{ke} values no reliable correlation existed, but a better correlation was observed for $N_{\Delta u}$ (Figure 4): the correlation coefficient is $R^2 = 0.81$. The experienced cone factor values plot in a relatively narrow zone which can be defined by the following formula:

$$N_{\Delta u} = (24.3B_q) \pm 2 \tag{7}$$

The best fitting line, giving the most accurate prediction in average, can be expressed by the equation:

$$N_{\Delta u} = 24.3B_q \tag{8}$$

In low pore pressure coefficient range, the ±2 component of the expression (7). causes significant differences (e.g. the cone factor can vary between 2 and 6). This implies that care must be taken if using this correlation when the excess pore pressure is low. In the case of larger excess pore pressure its influence is much smaller, thus the undrained shear strength can be estimated in a more reliable way.

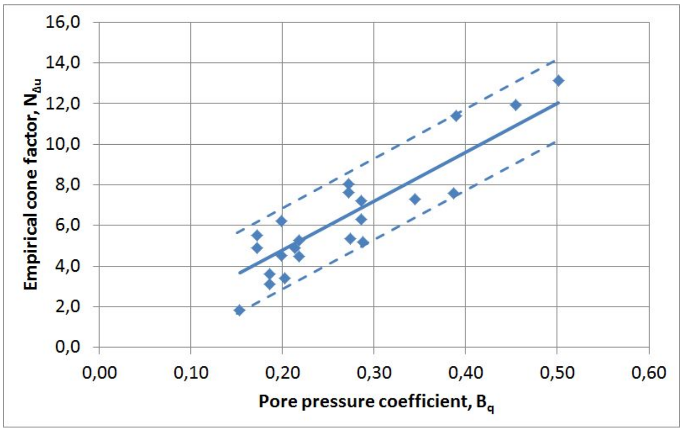

Fig. 4. Pore pressure coefficient (B_q) vs. Empirical cone factor ($N_{\Delta u}$)

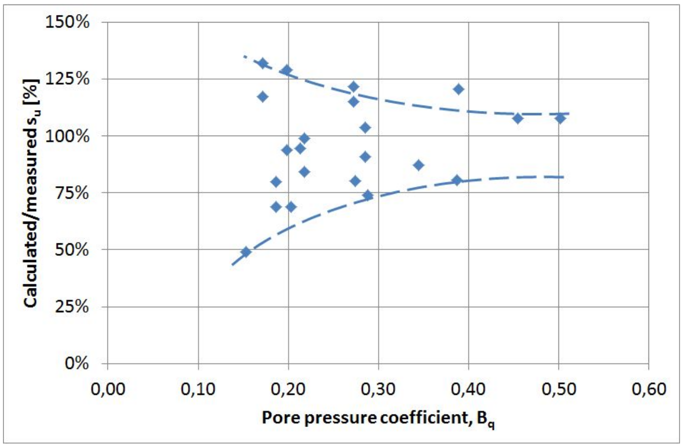

Fig. 5. Calculated/measured undrained shear strength as a function of B_q

This is also illustrated in Figure 5; the undrained shear strength was calculated by expression (8), and the ratio of calculated and measured s_u was plotted against the pore pressure ratio B_q. The calculated undrained shear strength values vary over a range of ±40%, when the pore pressure ratio values are smaller than 0.25. Thus in this case the reliability of the calculations is similar to that of the calculations using N_k, N_{kt} and N_{ke}. Therewith the ratios of calculated and measured shear strength vary over a more narrow range (±25%) in case of $B_q > 0.25$, so the in this case reliability of the calculation are better than that of any other calculation method. Generally, the low B_q values are the characteristic or firm clays, and the increasing pore pressure coefficients implies more soft soil conditions or increasing sensitivity. Thus the proposed relationship provides more reliable results for soft clays.

5 Conclusions

The correlation of cone penetration resistance and undrained shear strength of Holocene clays has been discussed in the paper. There are many published correlations for different type of clays, but there is no experience about their reliability in case of Holocene clays in the Charpatian Basin. Based on CPT and laboratory test results of 22 samples it has been found that existing correlations overestimate the undrained shear strength of this clay, moreover the experienced cone factors (N_k, N_{kt}, N_{ke}, $N_{\Delta u}$) vary over a significant range. The accuracy of the calculation is about ±40%, when cone factors N_k, N_{kt}, or N_{ke}, are used and even higher in case of $N_{\Delta u}$.

There are several studies that propose the use of a soil parameter (e.g. plasticity index, overconsolidation ratio, pore pressure coefficient of CPT) dependent cone factor to improve the accuracy of the calculations. In the case of N_k, N_{kt}, or N_{ke}, factors no such correlation has been observed, but a reliable correlation has been found between the cone factor $N_{\Delta u}$ and the CPTu pore pressure coefficient B_q.

Using a B_q dependent $N_{\Delta u}$ cone factor increases the reliability of the calculation. In low B_q range (i.e. in the case of firm clays) the calculated undrained shear strength values scattered over a range of ±40%, which is similar to the accuracy observed in the case of other cone factors, but in the cases of high B_q values ($B_q > 0.25$, i.e. in the case of softer clays) the accuracy of the calculation is significantly better: about $\pm 20 - 25\%$. So using the proposed formula (equation (8)) enables a more reliable undrained shear strength prediction for typical Holocene clays in the Charpatian Basin.

Such a calculation method provides a helpful guideline when there is no other data available about the undrained shear strength of the soil or when more information is needed to assess the uncertainty of the undrained shear strength of a certain layer. Thus it enables to have more realistic and more detailed information about the soil strength.

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