Comparative Analysis of Cone Resistances in Cone Penetration Test (CPTu) and Dynamic Probe Heavy Test (DPH)

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Abstract This paper presents a comparison of geotechnical soil testing with the use of Piezocone Penetration Test (CPTu) and Dynamic Probing Heavy (DPH) in a uniform coarse-grained medium located in southwest part of Poland. The soil medium was identified in detail. The interpretation of results included both grain-size analysis of samples from drillholes and soil behavior type results obtained from the Robertson nomograph (Soil behaviour type from the CPT: an update. In: 2nd international symposium on cone penetration testing, USA, 2010). Cone penetration resistances \( q_c \) obtained in the static CPTu tests were compared with the results of dynamic probing \( N_{10H} \) and of dynamic point resistance \( q_d \) obtained in the dynamic DPH tests. The evaluation of soil density index was based on both dynamic DPH and static CPTu probing. The obtained results were analyzed and plotted in a form of graphs corresponding to the Eurocode 7 and other works describing coarse-grained soils.

Keywords Static cone penetration test CPTu · Dynamic probing DPH · Cone resistance \( q_c \) · Dynamic point resistance \( q_d \) · Soil density index \( I_D \)

1 Introduction

Static CPTu (Piezocone Penetration Test) probing and dynamic DPH (Dynamic Probing Heavy) tests have been extensively used to evaluate geotechnical soil parameters. Both techniques allow determination of density index \( I_D \), but typically they are not performed simultaneously, as they are assumed to provide comparable data on the compaction degree of non-cohesive soils. Also, the DPH tests are believed to be unnecessary if the CPTu tests have been performed. This paper focuses on the presentation and comparison of both probing techniques, inter alia by identifying soil density index, which is the basic parameter measured in-situ for coarse soils during any construction project. This value may be determined with several dynamic probing techniques and with static probing. In the case of dynamic probing, the measurement and its interpretation is discrete, i.e. at every 10 cm or 20 cm, while in the case of static probing with the use of an electrical cone, the measurement and its interpretation is almost continuous at every 2 cm. This paper compares the interpretative results of...
soil density index obtained from DPH dynamic test with the results obtained from CPTu probing.

Additionally, the paper presents a comparative analysis of both the measured values ($q_c$ for CPTu with $N10_H$ for DPH) and the derivative values from both tests, with the aim to verify a thesis that correlation between the results from both tests is possible, safe and harmonized with the $q_c$ nomograph of the relationship between the $q_c$ values from CPTu and the $N10_H$ measurements from DPH included in EN 1997-2:2007 Eurocode 7 Annex G.4 (after Stenzel and Melzer 1978).

Such investigations are of special importance for verifying local applicability of cone penetration resistance ($q_c$) estimations in sands and sand-gravels on the basis of DPH, as represented in EN 1997-2:2007 Eurocode 7, Annex G.4. The resulting $q_c$ vs depth pattern may serve to establish the load-bearing capacity limits of piles on the basis of the correlations established from the test results of static load-bearing capacity of piles as per EN 1997-2:2007 Eurocode 7.

The Eurocode 7 is not the only source allowing direct correlation of the measurement values obtained from dynamic and static probing. Already in 1968, Melzer (1968) presented a correlation between DPH and CPT tests performed with a mechanical cone. Currently, an increasingly popular solution has become to perform penetration tests with the use of electrical cones (piezocones), whose $q_c$ measurement values are lower than in the case of mechanical cones (Bustamante and Gianeselli 1993). Therefore, it seems important to search for new correlations established for various local conditions and various non-cohesive soils (Czado and Pietras 2012; Lingwanda et al. 2015; Kodicherla and Nandyala 2016; dos Santos and Bicalho 2017). Research should also include finding the relationship between CPTu measurements and various dynamic probing techniques (Dynamic Penetrometer Light, Medium, super Heavy), as well as SPT (Standard Penetration Test) results, as indicated by Gadeikis et al. (2010); Pinheiro et al. (2018) and Ampadu et al. (2018) for non-cohesion soils and by Mahler & Szendefy (2009) for cohesive soils.

The tests presented in this paper have been performed with electrical CPTu piezocone having an area of 10 cm$^2$, as per EN ISO 22476-1:2012, while the DPH tests were performed with a heavy probe (50 kg) as per EN ISO 22476-2:2005. The influence of soil friction on the side surface of rods used in CPTu and DPH measurements was ignored in this work. The obtained results were analyzed and plotted in this paper in a form of graphs corresponding to Eurocode 7 and other, not only Polish, works in the field (Gadeikis et al. 2010; Czado and Pietras 2012).

The basic statistical measures used in this paper include:

- Mean value of parameter $\mu = \frac{1}{k} \sum_{i=1}^{k} X_i$;
- Standard deviation (SD) $\sigma^2 = \frac{1}{k-1} \sum_{i=1}^{k} (X_i - \mu)^2$;
- Coefficient of variation (CV) $c_V = \frac{\sigma}{\mu}$, where $X_i$ = the measured value of parameter; $k$ = the number of observations.

## 2 Test site and results

Morphologically, the test site is a part of the Central Polish Lowland. More specifically, it is located at the southwest border of the Dałków Hills being part of the Polkowice Hills. The shallowest formations are represented by sand-gravel deposits, clays and dusts classified as South-Polish, Central-Polish and North-Polish Glaciations.

The tests covered an area of approx. 50 m$^2$ and were conducted in an industrial space, which prevented a very large number of tests at regular distances. The tests included one static CPTu probing (Fig. 1), four dynamic PDH probings (Fig. 3) and four drillings in the DPH test axis in order to verify the type of soil and to collect soil samples for grain-size analysis. The test points were located at greater distances than the minima required in industry standards due to the disruptive influence of one test on another ($> 2$ m as per EN ISO 22476-2:2005). The DPH probings were spaced at approx. 5 m. The minimum distance between the DPH test points in relation to CPTu tests was approx. 3 m, and the maximum distance—10 m.

The test site was located near a very large industrial object with spread foundations at 3.5 m b.g.l. Based on archived information, the foundations were identified to be located in a wide excavation, which was later filled with local soil. Therefore, the grain-size analysis was performed for 3 samples collected above and 7 samples collected below 3.5 m b.g.l. The grain-size distribution was measured with the use of the
Fig. 1 Measurement of cone resistance $q_c$, local friction $f_s$ and pore-water pressure $u_2$ from CPTu.
The samples showed the dominance of sand gravel (grSa), and medium sand (MSa) at lower depths, as per EN ISO 14688-2:2018. Mean value of uniformity coefficient $C_u$ was 3.29, and of grain size distribution curve $C_c = 1.15$ ($C_u = \frac{d_{60}}{d_{10}}$ and $C_c = \frac{d_{2}_{30}}{d_{10}}$, calculated in accordance with EN ISO 14688-1:2018). Based on the obtained results, the soil was classified as poorly-graded sand (SP as per ISO 22476-2:2005). The drilling operations revealed a free groundwater table at 4.7 m b.g.l., which was allowed for in the interpretations of both CPTu and DPH tests.

As shown in Fig. 2, the evaluation of the soil type based on CPTu was made on the basis of the SBT (Soil Behavior Type) soil classification, Robertson (2010), as SBT6 (Sands: clean sand to silty sands). Each of the points indicated in the nomograph corresponds to mean current values measured per each 10 cm in the quasi continuous CPTu measurement every 2 cm, from 2.5 to 15.0 m b.g.l. The majority of the measurement points forms a dense group, indicating a significant uniformity of the tested soil medium.

Figure 3a presents the recorded $N'10_H$ for all four DPH tests versus depth without consideration to increased number of blows below the groundwater table, while Fig. 3b shows the $N'10_{Hmean}$ pattern before and the $N10_{Hmean}$ pattern after allowing for the influence of groundwater per each 10 cm of the DPH test penetration. The influence of water on the measurement was allowed for in accordance with the recommendations of EN ISO 22476-2:2005, i.e. in accordance with relationship (1) below 4.7 m b.g.l.

$$N10_H = a_1 N'10_H + a_2$$

Values $a_1$ and $a_2$ in (1) have been assumed equal to 1.3 and 2.0, respectively, as is the case for poorly graded sands (SP) having $C_u \leq 3$, as mean $C_u$ is 3.29 and is significantly smaller than 6.

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**Fig. 2** Identification of soil type according to the Robertson (2010) classification, where $p_a$—atmospheric pressure ($\sim$ 100 kPa), $R_f$—friction ratio $R_f = \frac{f_s}{q_c} \times 100\%$
The evaluation of soil density index was based on both dynamic DPH and static CPTu probing. Calculations of the density index based on the DPH test were based on the most commonly employed Eurocode 7 formula for poorly graded sands (SP) (2).

\[ ID_{DPH} = 0.38 \cdot \log N_{10H_{mean}} + 0.23 \]  

(2)

In (2) \( N_{10H_{mean}} \) is the number of free hammer falls per each 10 cm of the DPH probe head penetration, with allowance for an increased number of falls below the groundwater table level, in accordance with relationship (1) (Fig. 3b).

In the case when ID (soil density index) is identified from the CPTu test, a number of correlations can be used, which should be verified (Bałachowski 2006; Jamiolkowski et al. 2003). In this work, two such correlations were used, in accordance with Lunne et al. (1997) Lancellotta expression (3) and in accordance with Jamiolkowski et al. (2003) (4).

\[ ID_{CPTu} = -98 + 66 \cdot \log \left( \frac{q_c}{\sigma'_{vo}} \right) \% \]  

(3)

\[ ID_{CPTu} = -1.292 + 0.268 \cdot \ln \left( \frac{q_c}{\sigma'_{vo}} \right) [-] \]  

(4)

where: \( q_c \)—cone resistance [MPa], \( \sigma'_{vo} \)—vertical component of effective stress [MPa].

Figure 4 shows the values of the ID soil density index, calculated against depth in accordance with Eqs. (2), (3) and (4). Down to 4.7 m b.g.l., the density increases with depth. Below 4.7 m b.g.l., the density becomes stable in the range from 0.65 to 0.85, allowing the classification of soil as dense (look at Fig. 4). Coarse-grained soil grSa/FSa may be eventually classified to be dense soil, and locally to be between dense and very dense (EN/ISO 14688-2:2018). Table 1 shows the calculated ID.
values for all depth ranges, where the greatest $I_D$ value was obtained from Eq. (3) based on the CPTu measurement. Very consistent results were also obtained for depths below 4.7 m, from Eqs. (2) and (3) (Fig. 4, Table 1).

Direct comparison of the values recorded in DPH and CPTu tests required using Eq. (5) to find dynamic point resistance $q_d$ in the DPH tests, as defined in EN ISO 22467-2.

$$q_d = \left( \frac{m}{m + m'} \right) \cdot r_d$$

(5)

where $m$—hammer mass (for DPH: 50 kg); $m'$—total mass of the anvil, hammer guide and rod whose length increases with depth; $r_d$—unit dynamic cone resistance.

Unit dynamic cone resistance $r_d$, as defined in (7) is determined on the basis of the energy of the hammer blow ($E_{theor}$) in relation to cone area ($A$) and pile penetration depth per one blow $e$ in (6).

$$e = \frac{0.1}{N10_H}$$

(6)

$$r_d = \frac{E_{theor}}{A \cdot e} = \frac{m \cdot g \cdot h}{A \cdot e}$$

(7)

where $g$—gravitational acceleration; $h$—hammer free falling height.

Figure 5 shows the relationship between depth and the defined values: $e$—pile penetration depth per one blow (Eq. (6)), $r_d$—unit dynamic cone resistance (Eq. (7)) and $q_d$—dynamic point resistance (Eq. (5)) for $N10_{H\text{mean}}$ values determined on the basis of four DPH measurements.

### 3 Comparative Analysis of Resistances in DPH and CPTu

This paper focuses on finding $q_d$ and $r_d$ for coarse-grained soils in order to relate them to static measurements of $q_c$ from CPTu.

The results are shown in Fig. 6. Best correlation between $q_c$ and $q_d$ and between $q_c$ and $r_d$ is described by the exponential functions provided in the graphs, together with the coefficient of determination ($R^2$) at about 0.8, which allows a satisfactory match between the exponential function and the measurement points.

### Table 1  Calculated soil density index values

| Depth            | $I_D$ DPH Eq. (2) [-] | $I_D$ CPTu Eq. (3) [-] | $I_D$ CPTu Eq. (4) [-] |
|------------------|-----------------------|------------------------|------------------------|
|                  | Mean | SD | Mean | SD | Mean | SD |
| 1.5–3.5 m        | 0.44 | 0.08 | 0.73 | 0.15 | 0.59 | 0.14 |
| 3.5–4.7 m        | 0.60 | 0.01 | 0.81 | 0.04 | 0.67 | 0.04 |
| 4.7–15.0 m       | 0.69 | 0.04 | 0.86 | 0.04 | 0.71 | 0.03 |
The Pearson linear correlation coefficient was 0.82 between \( q_c \) and \( q_d \) and 0.86 between \( q_c \) and \( r_d \). This fact indicates a high positive correlation between the compared values and implies that if for example \( q_d \) and \( r_d \) rise, \( q_c \) should rise as well. In addition, values \( q_d \) and \( r_d \) from the DPH test may serve to estimate the \( q_c \) value (instead of the direct measurement of \( q_c \) from CPTu), with the use not only of the exponential function (blue continuous line), but also of linear regression functions (black dashed line) provided in Fig. 6a and b.

Fig. 5  a Pile penetration depth per one blow (e) Eq. (6); b Unit dynamic cone resistance \( (r_d) \) Eq. (7); c Dynamic point resistance \( (q_d) \) Eq. (5)

Fig. 6 Results of measured relationships between: a cone resistance \( q_c \) and dynamic \( q_d \); b cone resistance \( q_c \) and unit dynamic resistance \( r_d \)
Comparison of resistances between static and dynamic cones may be represented with quotients $q_c/q_d$ and $q_c/r_d$ depending on the measurement depth (Fig. 7). In a lithologically uniform soil, DPH and CPTu tests must overcome resistances related to effective stress which increases with depth. This effect can be seen more clearly in the $q_d$ and $r_d$ graph (Fig. 5 b, c) than in the $q_c$ graph (Fig. 1). In this case (Fig. 7), an observation can be made that below 3.5 m b.g.l., where the soil is much more uniform, the quotient values have lower variability than above 3.5 m b.g.l. Mean value of $q_c/q_d$ below 3.5 m b.g.l. becomes stable at 2.10 with standard deviation SD = 0.39 and coefficient of variability CV = 18.6%, while $q_c/r_d$ is 0.88 as SD = 0.16 and CV = 18.2%. The results here presented correspond to the results presented in other works, in which $q_c/q_d$ for coarse-grained soils was obtained at 2.3 (Gadeikis et al. 2010) and 1.85 (Czado and Pietras 2012).

4 Discussion of Results

Eurocode 7 allows the possibility of estimating $q_c$ on the basis of DPH tests. The standard includes a nomograph which proves very helpful in estimating $q_c$ on the basis of $N_{10H}$, as presented in Fig. 8.

Figure 8 shows curves 1, 2, 3 and 4 which represent proposals taken from Eurocode 7 for water-saturated and water-unsaturated soils, well and poorly graded.
sands and sand/gravels. The original results show measurement points from mean \( q_c \) values read every 10 cm (CPTu) and the corresponding mean measurement values \( N10_{Hmean} \) read from the four DPH tests at the same depth. The curve No 5 is a representation of an exponential function which best describes the correlation between the considered values of \( q_c \) and \( N10_{Hmean} \). The curve obtained in this research is similar to curves 1 and 3 which describe poorly graded soils being sands below and above the groundwater table.

In order to emphasize the correlation between \( q_c \) and \( N10_{Hmean} \), the Pearson linear correlation coefficient was determined, which in this case was 0.86 for linear regression function having the form of Eq. (8). This function is represented with the dashed line in Fig. 8.

\[
\hat{q}_c = 6.70 + 0.96 \cdot N10_H
\]

(8)

5 Conclusions

The test results presented in this work are in accordance with the nomograph of Eurocode 7 (Fig. 8), which is suggested for estimating cone penetration (\( \hat{q}_c \)) in sands and sand-gravels on the basis of the DPH dynamic tests.

A positive verification, as presented in the nomograph (Fig. 8), allows (in the discussed area) using the proposed empirical correlations between \( N10_H \) and \( \hat{q}_c \) (Fig. 8). The \( \hat{q}_c \) values calculated directly from the DPH tests may be used to find pile capacity base (Ćosić et al. 2016; Wyjadłowski et al. 2018; Baca et al. 2016). In other geotechnical conditions, the method should be used with precautions. The correlation which allows estimating cone resistances \( \hat{q}_c \) was determined for poorly graded, coarse-grained soils (SBT6, sand-gravels (grSa)/medium sands (MSa)) below groundwater table, based on four DPH tests and one CPTu test. Such approach is occasionally necessary when direct CPTu probing is rendered difficult or impossible by e.g. insufficient test site area, no possibility to anchor the CPTu probe or significant resistances \( q_c > 25 \) MPa.

The obtained correlations between \( q_c \) and \( q_d \) as well as between \( q_c \) and \( r_d \) were determined on a limited base of tests (Fig. 6). However, the calculated functions have the coefficient of determination \( R^2 \) at a level of approx. 0.8, showing a satisfactory match level between the functions and the measured values. The Pearson linear correlation coefficient at 0.8 also indicates a high positive correlation between the compared values and implies that if for example \( q_d \) and \( r_d \) rise, \( q_c \) should rise as well. The calculated quotient of \( q_c \) over \( q_d \) at 2.10 with SD = 0.39 (Fig. 7) correspond to the results presented in other works, in which \( qc/qd \) for coarse-grained soils was obtained at 2.3 (Gadeikis et al. 2010) and 1.85 (Czado and Pietras 2012). This fact confirms that it is possible to estimate the \( \hat{q}_c \) values on the basis of \( q_d \) from the DPH test.

The results of correlations between values measured in DPH and CPTu tests, as presented in this work, allow considering the possibility to use the DPH tests as an alternative to the CPTu tests, especially in the case of coarse-grained soils in which static probing is hindered by great penetration resistance.

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