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*Bartłomiej Czado *, Jan S. Pietras **

COMPARISON OF THE CONE PENETRATION RESISTANCE OBTAINED IN STATIC AND DYNAMIC FIELD TESTS

1. Introduction

Soil field testing performed with the static method of CPT/CPTU is increasingly being used in Poland to examine the ground for the purposes of foundation design. The results of this test may be used directly in the calculations of foundation piles, but also of spread foundations. The use of a static test becomes problematic when coarse soils (sandy gravels, gravels) or composite soils with coarse fractions (clayey gravels, weathered clays) are found in the subsoil. In some cases performing the CTP to a designed depth becomes impossible in such conditions as the risk of damage of the cone is relatively high. The possibility of supplementing the results of CPT with the results of dynamic probings (DP), in the soil strata where the CPT examination is impossible, seems to be very important for practical reasons. This requires the development of the appropriate correlation between the soil parameters obtained in static and dynamic tests. Examples of such correlations, originally published by Stenzel and Melzer, 1978 [6], can be found in Part 2 of the Eurocode 7 [EC7-2] and DIN 4094 [9]. However, these correlations reflect the German experience, while the Eurocode 7 clearly indicates the need for a development of local correlations.

This paper presents an analysis of the results of field tests conducted in Kraków, Poland. Results were obtained in the test nodes, which included: cone penetration test (CPT), dynamic probing (DPH) and a soil identification in a borehole.

2. Characteristics of the test field

In terms of geomorphology the test field is located in a high river terrace of the Vistula River [7]. It is located approximately 1.0–1.5 km south of the river. The subsoil is composed of

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* Cracow University of Technology, Faculty of Civil Engineering, Institute of Structural Mechanics, Kraków

Tertiary and Quaternary deposits. The sequence of soil strata in the subsoil is shown in Figure 1. In the following description soil symbols in accordance to ISO classification [11] were noted in italics, while the symbols of Polish soil classification [15] were placed in brackets.

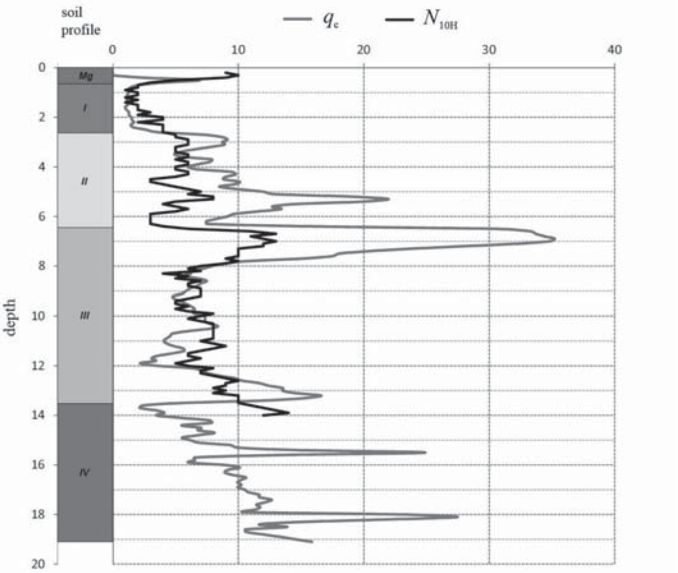

Fig. 1. Example of the results of CPT and DPH with a corresponding soil profile

Beneath the 0.5–1.2 m thick layer of made ground Quaternary alluvial soils of the high river terrace are deposited in about 13,0–14,0 m in thicknesses. These deposits, to a depth of 2.5–3.5 m are represented by fine-grained (cohesive) soils: silty clays *siCl*, clayey silts *clSi* to sandy silts *saSi* (Gz, G, Π, Πp, Pg). These soils were separated as stratum I.

Underneath a stratum of coarse (non-cohesive) soils occures, formed generally as as uniform (even-graded [12]) medium sands *MSa* (Ps), locally as silty sands *siMSa* (Pπ). These soils were separated as stratum II — with a thickness of about 3.5–4.0 m.

Coarse soils with an irregular occurrence of gravel and cobble fraction are deposited below: gravely sands *grSa* also with cobbles *cogrSa*, gravels *Gr* and sandy gravels *saGr* (Ps+Ż, Ps+K, Po, Ż, Ż+K), forming a stratum of about 8.0–9.0 m in thickness. These soils, separated as a stratum III, occur as even-, medium- and multi-graded (both well- and gap-graded).

Quaternary deposits are underbedded with a layer of Miocene clays, separated as a stratum IV. Sediments of this stratum are clays *Cl*, silty clays *siCl* and fine-sandy clays *fsaCl* (I, Iπ, Ip). In the roof area they are in a plastic consistency, becoming more and more firm with increasing depth, up to a stiff and very stiff consistency.

In the considered area there is one Quaternary aquifer associated with the sandy and gravely deposits of river accumulation (strata II and III). Ground water table is stabilized at a depth of 3.5-4.0 m in the sandy stratum II.

3. Research methodology

The study analyzes the results of field tests conducted in five research nodes located within an area of a building plot of approximately 80×120 m. In each of the nodes a cone penetration test (CPT), dynamic probing (DPH) and a borehole were made. Individual tests have been performed maintaining the recommended minimum distances from each other.

The CPT and DPH tests conducted by the authors were related to the drillings previously made. Those were made with a rotary-percussive system, using a mechanical rotary drilling rig, in steel casing tubes of 245 mm diameter.

The interpretation of the soil profile — the separation of the fine-grained (cohesive) and coarse-grained (non-cohesive) soils — was performed on the basis of the borehole profiles, particle size distribution tests and the results of CPT with use of Robertson's chart [3].

Laboratory tests were carried out in accordance with the procedures described in the CEN ISO/TS 17892 [8] technical specifications.

Dynamic probings (DPH) were performed to a depth of 14.0 m below ground level, i.e. the roof of clayey stratum IV. The tests were conducted using a universal mechanical probing device UMSD–SPT. The test procedure and the equipment comply with the guidelines of the standards [13, 16, 17]. The interpretation of the results was performed in accordance with ISO standard [13]. The influence of groundwater on the registered values of N_{10H} was taken into account. Then the dynamic soil resistance qd was calculated.

Cone penetration tests (CPT) were conducted to depths of about 19.0–20.0 m below ground level. Self-propelled device PAGANI TG 63–150 was used, which provides a maximum pressure of 150 kN, equipped with a standard electrical probe of 10 cm^2 cone tip surface. A wired, electronic data acquisition system was used. The tests were performed in in accordance with the procedures of ISSMFE guidelines [18] and the appropriate standards [14, 16, 17]. The results were interpreted in accordance with the standards and recomentdations of Lunne et al. [3].

An example of the registered results of both CPT and DPH tests for one of the nodes is shown in figure 1.

4. Correlations between static cone resistance and a number of blows in dynamic probing

Studies on the correlations between the results of static and dynamic penetration tests conducted in Germany [1] led to the formulation of linear dependence between the value of q_c, and the number of blows N_X for different probing methods. Table 1 contains a summary of developed coefficients.

Attempts to verify these correlations for ground conditions in Hungary are described in the study by Makler and Szendefy, 2009 [4]. The relationship between the calculated, and registered values of q_c for different soil types are shown in figure 2.

A similar dependence, determined for the results of the tests conducted by the authors, is shown in Figure 3. Of all the results obtained in tests only the data for the stratum II of

TABLE 1

Correlation ratios for cohesionless soils by Biedermann, 1978 [5]

Soil classification*	SPT q_c/N_{30}	DPH q_c/N_{30}	DPL q_c/N_{30}
SE	0.5	0.7	0.25
SW, SI	0.7	1.0	0.35
GE, GW, GI	1.1	1.5	—

* S — sand, G — sand and gravel, E — poorly graded (even-graded), W — well graded (multi-graded), I — poorly graded with some grain diameter missing (gap-graded)

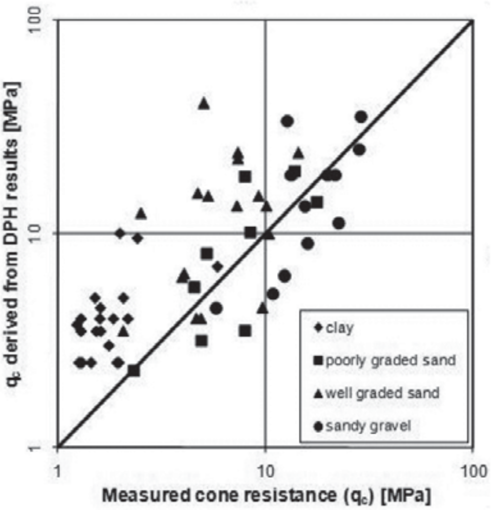

Fig. 2. The results of the studies by Makler and Szendefy [4]

medium sands (Fig. 3a) and stratum III of sandy gravels (Fig. 3b) were presented. Linear correlation slope values of 0.7 and 1.5 were used, respectively.

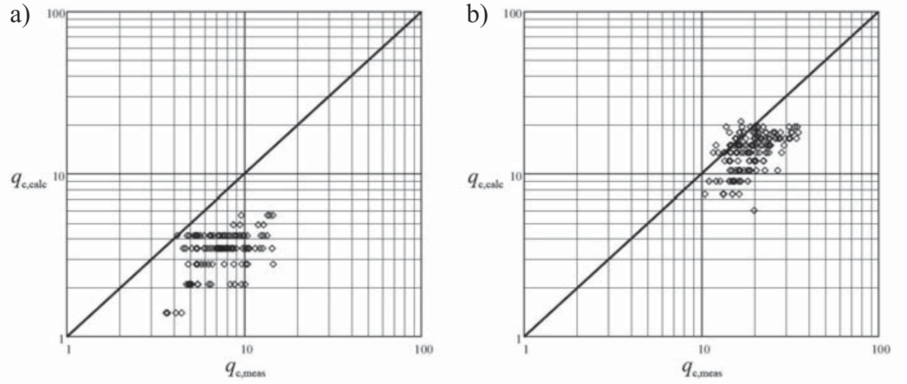

Fig. 3. The correlation of the values calculated with use of Biedermann's ratios $q_{c,calc}$ with the measured values $q_{c,meas}$: a) for medium sands, b) sands with gravels

To make the direct comparison of the static cone penetration resistance with the results of the dynamic probing possible, a proper averaging of the q_c values was necessary. It was made at intervals corresponding to the values of N_{10H}, i.e. for every 10 cm.

Analysis of the plots presented in figure 3 shows that for the saturated coarse-grained soils (strata II and III) from the area of Krakow, the use of coefficients by Biedermann [1] for heavy dynamic probing (DPH) leads to a safe estimation of the value of q_c resistance.

In the Eurocode 7 (Part 2, Annex G) examples of correlations between cone penetration resistance qc and the results of dynamic probing N_{10H} are presented (see Figure 4). It should be noted that these correlations, originally proposed by Stenzel and Melzer, 1978 [6], are based on the test results of tests performed with use of a mechanical probe.

Four different correlation curves are presented, which have been developed for two groups of soils (poorly-graded sands and well-graded gravely sands) in both unsaturated and saturated conditions. As the authors collected the data for saturated soils, only curves no. 2 and no. 4 (according to Fig. 4) are analyzed in this study.

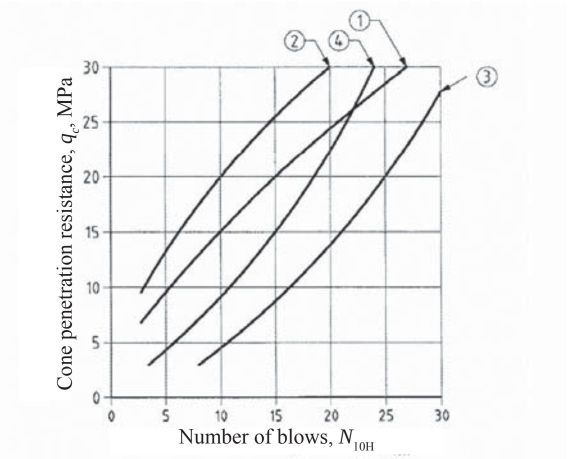

Fig. 4. Example of correlations between cone penetration resistance and number of blows in dynamic probing [EC7-2]
1 — poorly-graded sand above groundwater, 2 — poorly-graded sand below groundwater, 3 — well-graded sand and gravel above groundwater, 4 — well-graded sand and gravel below groundwater

Due to the fact that in some soils the values of the cone penetration resistance obtained by means of mechanical and electrical probes are significantly different [17], the q_c values measured by authors (with electrical probe) were recalculated for the purpose of comparison, according to the following formula:

$$q_{c(m)} = \beta \cdot q_{c(e)} \tag{1}$$

where the value of $\beta = 1.3$ was used for even-graded, saturated sandy soils of stratum II.

The number of blows N_{10H} registered in the dynamic probing (for soil stratum II) was varying between 2 and 8 blows per 10 cm. The corresponding resistances of static cone penetration q_c, are within the range of 3–15 MPa. The results of measurements in comparison to the correlation curve no. 2 are shown in figure 5.

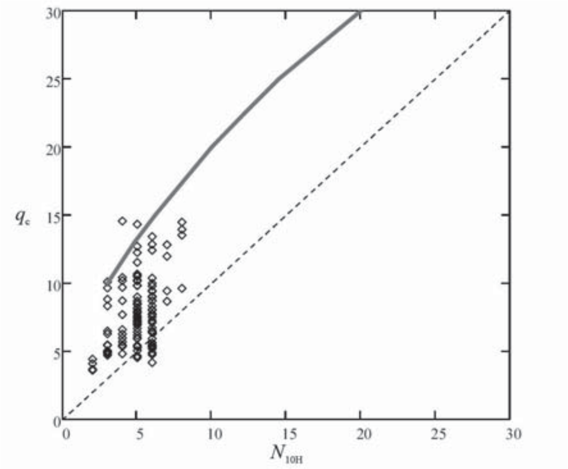

Fig. 5. The results of measurements for stratum II in comparison tothe correlation curve no. 2

The analysis of the plot leads to a conclusion that the use of the correlation proposed by Eurocode 7 for saturated sands (curve 2 on Fig. 4) may result in an overestimation of $q_c$values, and therefore it should be used with caution.

In the soil stratum III (mixtures of sands and gravels, saturated) the number of blows N_{10H} registered in the dynamic probing was varying in the range of 4 to 14. The corresponding resistances of static cone penetration q_c, were in the range of 10–36 MPa. The results of measurements in comparison to the correlation curve no. 4 are shown in figure 6.

Analysis of this data indicates that the use of a correlation curve no. 4 (Fig. 4) results in a safe estimation of the qc values — none of the points obtained in measurements are found on the lower side of the curve.

It should be noted that correlated value of N_{10H} registered in the dynamic probing does not include the influence of the weight of a set of rods (depending on the depth of the penetration) on the actual energy applied of the probe tip at a single blow. Therefore, in the next part of this study authors attempted to analyze the values of the dynamic cone resistance q_d (which takes into account this influence) instead of number of blows N_{10H}.

5. Comparison of static and dynamic cone resistance

In this part of the study, where authors attempted to improve the correlations between the results of static and dynamic cone penetration tests, the following assumptions have been made:

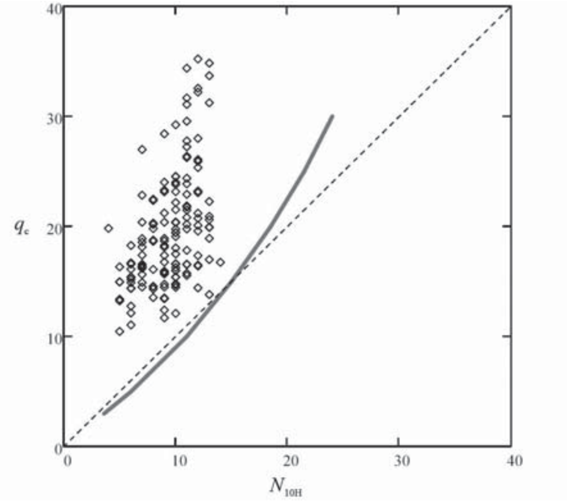

Fig. 6. The results of measurements for stratum III in comparison to the correlation curve no. 4

- the results of the cone penetration tests performed with the use of an electrical probe are analyzed,
- an influence of effective stresses in the soil at a depth of penetration on the cone penetration resistance measured with CPT and DPH are similar, therefore they are neglected,
- an influence of groundwater on the registered number of blows N_{10H} in the DPH test is significant, therefore a proper correction is made in accordance with ISO standard [13],
- the corrected value of N_{10H} is the basis for the calculation of the value of dynamic resistance q_d, which includes the influence of mass of the set of rods on the actual energy of the blow,

The correlation between values of static cone penetration resistance q_c and dynamic resistance q_d have been expressed in the coefficient, defined as:

$$\alpha = \frac{q_c}{q_d} \tag{2}$$

following the notation proposed by Gadeikis et al. [2]. This made it possible to directly compare of the results described in the study carried out for Lithuanian soil conditions with the results of own research.

The relation between static resistance q_c and dynamic resistance q_d in the stratum II of medium sands is shown in Figure 7a. The values of the coefficient α for this stratum are varying in the wide range of 0.5 to 2.3. An approximation with a linear function performed with the use of least squares approach resulted in the value of $\alpha = 1.15$.

Similar analysis, conducted for the results of super-heavy dynamic probing (DPSH) in medium sands [2], resulted in an average value of $\alpha = 2.3$. The dispersion of the results of that study was also high (regression coefficient $R = 0,60$).

Such a significant difference in the values of the α coefficient is probably caused by the omission of the influence of groundwater on the registered number of blows N_{20} in the study of Gadeikis et al. [2].The fact that a DPSH (super-heavy) method was used in place of DPH, should not be relevant as the normalized value of q_d was used in the analysis.

The results of the Lithuanian studies [2] suggest that the value of α coefficient increases with an increase of index of density of sands — in the study carried out by authors such relationship was not confirmed. It was noted instead, that the value of α coefficient increases with the depth of penetration (Fig. 7b). However, due to the small thickness of the sand layer that has been considered, it was not possible to formulate a precise conclusion on this issue, especially since there was no similar trend observed for the stratum III of sands and gravels (Fig. 8b).

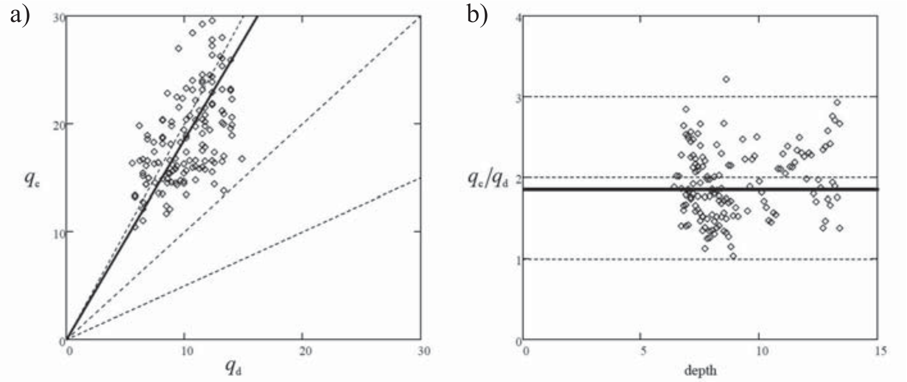

Fig. 8. Results in the stratum III of sands with gravels: a) relation between static resistance q_c and dynamic resistance q_d, b) values of □ coefficient vs. depth of penetration

Figure 8a shows the relation between static cone resistance q_c and dynamic resistance q_d in the stratum III of sands and gravels. Values of α coefficient in this stratum is varying in the range of 1,0–3,2. The value of the coefficient determined in linear approximation is $\alpha = 1.85$. A simple correlation of $q_c = q_d$ (corresponding with the value of $\alpha = 1$) can be regarded as a safe estimation of the calculated value of q_c.

6. Summary

The analysis of the correlations between static cone resistance qc and a number of blows NX of dynamic probing proposed by Eurocode 7, which have been applied to the results of field tests obtained by authors, leads to the conclusion, that the use of these correlations in some cases (i.e. for saturated sands) may result in overestimation of q_c values, while in others (i.e. saturated sands with gravels) results in a safe estimation. Therefore, those correlations should be used with caution.

Value of N_X registered in the dynamic probing does not include the influence of the weight of a set of rods (depending on the depth of the penetration) on the actual energy applied of the probe tip at a single blow. Therefore, an analysis of the values of the dynamic cone resistance q_d (which takes into account this influence) instead of number of blows N_X is required.

The differences in the values of the α coefficient obtained by the authors in comparison to the studies of Gadeikis et al. [2] shows, that the influence of groundwater on the registered number of blows N_X of dynamic probing is very significant. Relation of α coefficient with other factors, i.e. soil density (compaction), depth of penetration (overburden stress) is not easily definable.

Formulation of reliable correlations between static and dynamic cone resistance is difficult and requires further studies.

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