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Research paper

Prediction of CPTu static sounding parameters based on DPH dynamic probing heavy test on the example of "the Praski terrace" sands in Warsaw title

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Abstract: This paper attempts to relate the parameters obtained from CPTu static sounding and DPH dynamic test conducted in non-cohesive alluvial deposits of the Vistula River. The investigation was carried out in eight test stations located on the left bank of the Vistula River in Warsaw. The presented theses were based on the results of static CPTU and dynamic DPH tests obtained at 8 test stations. Additionally, in order to associate the obtained sounding results to the lithological type of the tested medium, drillings and grain size analyses were performed. The correlation of the different test methods stems from the need to identify and explain observed discrepancies against the background of different geological conditions, such as moisture content or grain size distribution. The comparative analysis of the parameters obtained from static and dynamic probing, is relevant to the alluvial sediments formed the lower over-flood terrace (called "the Praski terrace") of Warsaw. Based on the comparison this paper proposes a correlation between the cone penetration resistance the sleeve friction and the number of blows, expressed by the functional relationship. Differences in the matching formulas were shown depending on the saturation of the tested sediments. Correlations were referred to a soil type, which enabled to specify the range of applicability of the proposed relationships. The results of the study were further used to show their diversity using statistical methods. This made it possible to assess the variability of the parameters of the non-cohesive soil, which forms a single lithogenetic unit.

Keywords: alluvial sands, dynamic probing DPH, static sounding CPT

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1. Introduction

CPTu static sounding and DPH dynamic probing are widely used to assess the geotechnical parameters of the subsoil [1–11]. These two methods differ significantly in the way of penetration of the cone, the required equipment, measured parameters and interpretation possibilities [12–14]. DPH test is a simpler method and therefore carries less chance in terms of potential technical failures and operator errors. The dimensions of the drive for this probe are small, which facilitates its relocation and stabilization in the field. The execution of the DPH test is relatively fast and the interpretation of the results is simple. CPTu static sounding requires a more sophisticated (usually heavier and larger than the DPH drive) penetrometer and its anchoring, which is very difficult in many places. The testing procedure involves extensive verification of the accompanying apparatus (equipment) and measuring tools (electric cones). The interpretative possibilities of static sounding CPTu are much greater but at the same time require a lot of experience and knowledge of local correlative conditions. The authors attempted to compare these methods based on the studies of alluvial sediments of "the Praski terrace" in Warsaw. Relating (assigning) the obtained relationships to the lithogenic type of sediment is, in the authors' opinion, extremely important in terms of their proper application.

2. Materials and method

This analysis is based on investigations carried out in eight test stations. At each station, one CPTu static sounding, one DPH dynamic test and one geological drilling were carried out in order to determine the soil type and origin, measure the depth to the ground water level and collect soil samples for further laboratory tests. The profile covered by the detailed studies averaged between 2 and 11 meters in depth. The total length of the profiles included in the comparative analysis was approximately 71 m.

The dynamic probing rig UMSD (Polish manufactured) was used for dynamic probing tests, the characteristics of which were in accordance with the requirements of the relevant standards [14–16]. A cone of a diameter $D = 43.7$ mm, hammer mass $m = 50$ kg, height of fall $h = 50$ cm, and 1-meter rods with diameter $d_r = 32$ mm was used.

A CPTu static penetrometer equipped with a data logger and a wireless electric cone with pore water pressure measurement (piezocone) from Geotech AB was applied. The Gouda hydraulic drive with a maximum 200 kN thrust capacity was used to push the measurement devices into the soil. The measurement points within the stations were at the distances of approximately 2−3 m.

The following parameters were measured during the tests:

– CPTu static sounding – cone resistance q_c, sleeve friction f_s, pore pressure u, measured behind the cone u_2, with a resolution of 2 cm.
– DPH dynamic probing heavy: blow counts $N_{10\,\mathrm{DPH}}$ recorded every 10 cm in vertical profile.

The testing procedures and geometry of the cone tips were in accordance with the requirements of the international standards [17, 18].

Based on the parameters registered in the field, the following values were calculated:

$$q_t = q_c + u_2 \cdot (1 - a) \ \text{[MPa]} \tag{2.1}$$

q_c – measured cone resistance, u_2 – excess of pore pressure measured during the test, q_t – cone resistance corrected with regard to the influence of pore pressure, a – area ratio of the cone ($a = 0.58$)

$$R_f = \frac{f_s}{q_t} \cdot 100 \ [\%] \tag{2.2}$$

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} \ [-] \tag{2.3}$$

where: B_q – pore pressure parameter, u_o – in situ equilibrium pore water pressure, σ_{vo} – in situ total vertical stress

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \ [-] \tag{2.4}$$

where: Q_t – normalized cone resistance, σ'_{vo} – effective overburden stress

$$F_r = \frac{f_s}{q_t - \sigma_{v0}} \cdot 100; \ [\%] \tag{2.5}$$

where: F_r – normalized friction ratio

Dynamic heavy probing (DPH) and cone penetration test (CPTu) with an electric cone differ in the quantity of readings per 1 m (sampling intervals). In the case of DPH probing, the number of blows N_{10} represent a zone of 10 cm thick, and the results are collected in such intervals. During static sounding with an electric cone, data was collected every 2 cm. In the first step, the penetration resistances were compiled. Then each N_{10} value from DPH test was compared with the corresponding averaged value from static sounding (q_t or f_s) for a specific 10 cm section. In this way, sounding parameters were compared for the same sections of the profile.

The drillings were carried out with a Wamet MWG-6 caterpillar drilling rig, equipped with spiral augers with a diameter of $f = 120$ mm. During drillings, 78 samples were collected at approximately 0.5–1.0 m intervals, which were tested by sieve analyses.

It is crucial to relate the results of the analyses to the grain-size distribution parameters and geological history of the studied soils. The authors consider that the results obtained should be related to the local genetic-structural factors of the analysed sediments. Therefore, a lot of attention was paid to sieve analyses and the preparation of a sufficiently large set of grain size analyses.

3. Geological conditions

The analysed site is located in Warsaw in a dense residential area. In terms of geomorphological conditions, the area is located within the lower overflood terrace called "the Praski terrace” [19]. The size of this terrace is approximately 23% of the city’s area. The terrace surface is located at an elevation of 82.5–87.5 m above sea level (5–10 m above the level of the Vistula river). The Praski overflood terrace is 2–3 m higher than the floodplain terrace (Fig. 1).

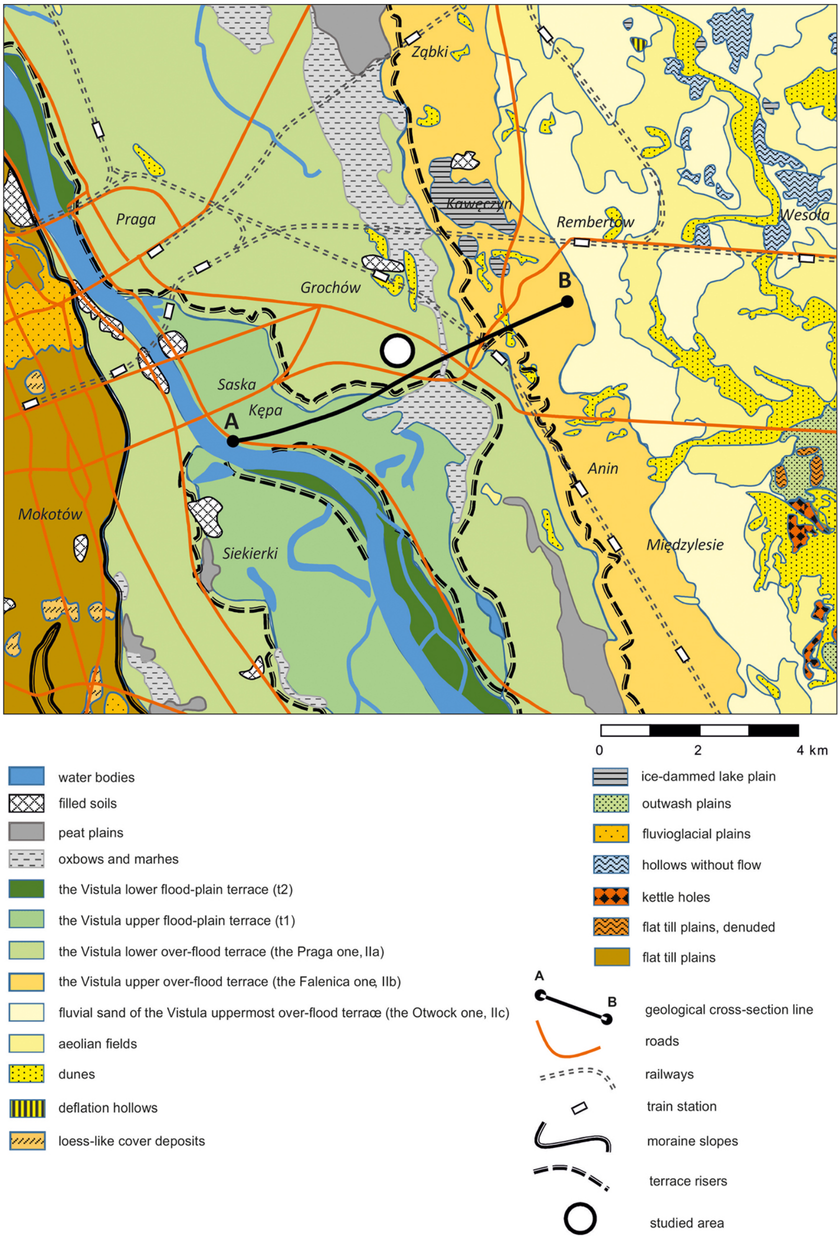

Fig. 1. Geomorphological units in the investigated area (after Sarnacka [20], modified)

The geological profile is formed by fluvial deposits of the North-Polish glaciation (the Bölling interphase, [18]) mainly represented by medium and coarse sands, locally fine sands. Grain size increases gradually with depth. The thickness of fluvial sands reaches approx. 8–12 m [18]. Underneath, there are sandy and gravelly deposits of the Eemian interglacial of similar thickness. Neogene clay (greywacke clays) (Fig. 2) underlies the Eemian interglacial sediments.

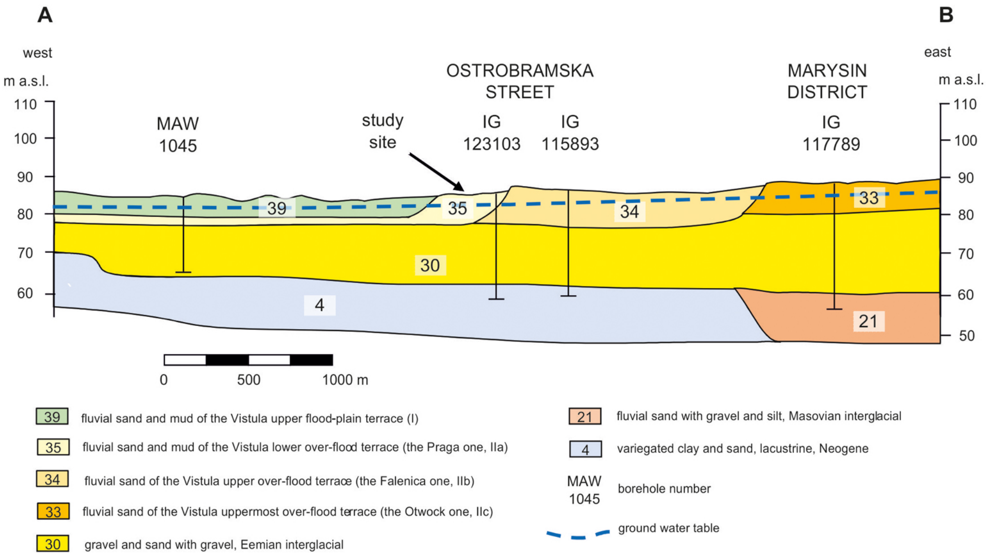

Fig. 2. Schematic geological cross-section of the studied area (after Sarnacka [19], modified)

4. Results & discussion

The synthetic lithological cross-section created as a result of the analysis of the geological drillings and sieve analysis is presented in the Fig. 3. It schematically shows the distribution of soils within the 8 analyzed testing stations and the position of the groundwater table. It also indicates the extent of the zones (a section of the profile) where the comparative analysis was carried out. Groundwater table stabilises at the depth of approximately 4.0 m below ground level (Fig. 3).

Generally, fillings formed of medium sands mixed with humus, locally with fragments of rubble were observed to a depth of 2–3 m. Underlying the fill material is medium to course sands and gravel. In the upper and middle parts, medium sands predominate with the proportion of course grains increasing in the lower parts to predominantly medium to course sands with gravel. Detailed results of grain size changes in the vertical profile are shown in Fig. 4.

The evaluation of soil type for 78 samples is presented according to [21–23]. Its results are shown in Fig. 5.

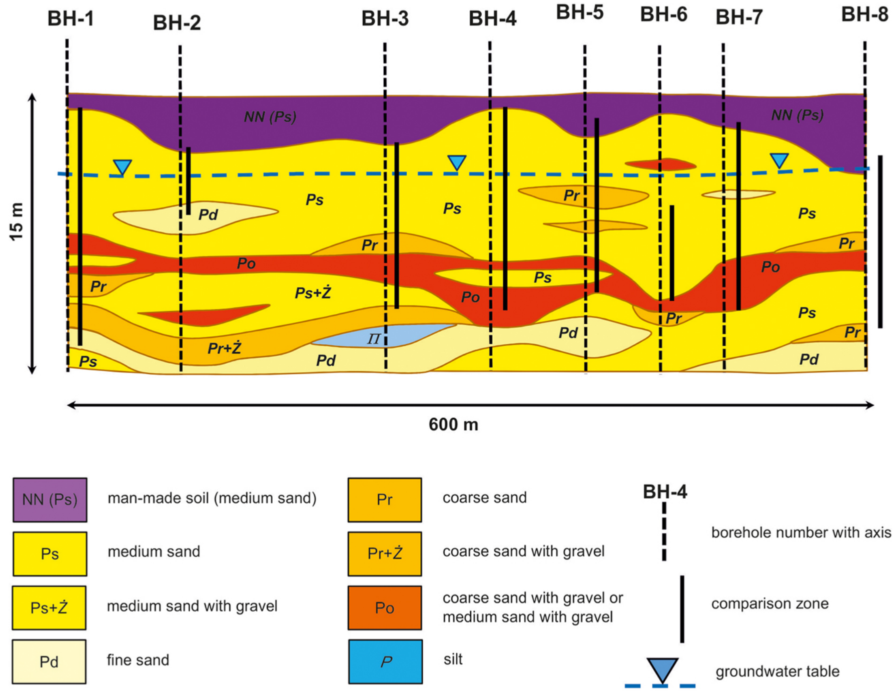

Fig. 3. Schematic lithological cross-section within the analysed site. Soil symbols according to the PN-B-02480:1986 [21]

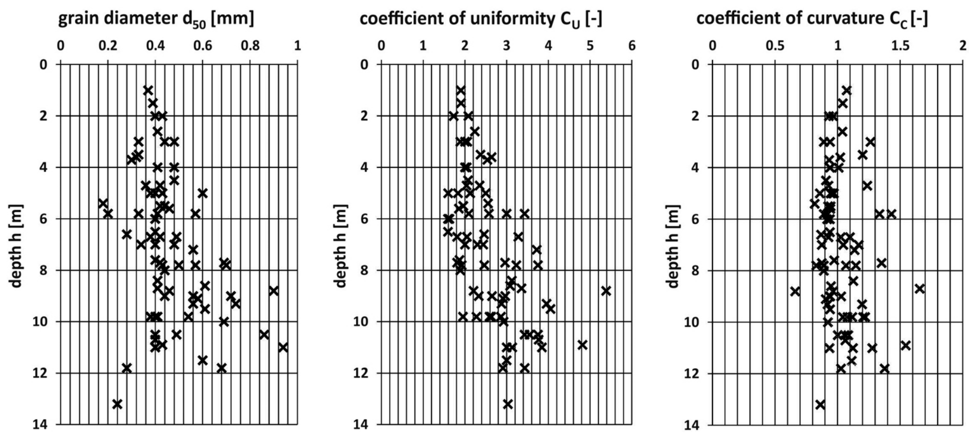

Fig. 4. The variability of grain-size distribution features in the vertical profile

Most of the tested soils are medium sands (about 60%) both according to the Polish and the EN ISO standard. If medium sands with gravel are also included, the total percentage of these soils varies between 69–87% according to the standard.

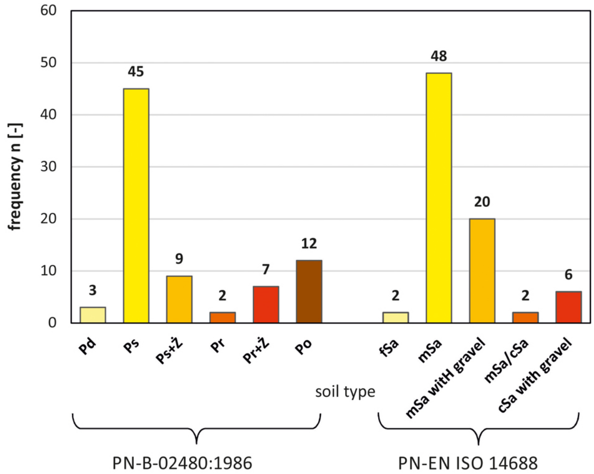

Fig. 5. Results of soil type evaluation according to the relevant standards

A lower percentage is represented by coarse sands, coarse sands with gravels and sand gravel mixes (a total of 27% according to PN-B-02480:1986 [21]. If the assessment is made according to EN ISO-14688 [22, 23], coarse sands and soils that are on the borderline between medium sands and coarse sands are a minority (about 10% in total). Fine sands represent only about 2–5% against all the samples examined.

Through sieve analyses, additional numerical ratios describing grain-size distribution were determined. These are expressed as follows:

– grain diameter D_{50} – particle size at which 50% of the particles are finer by weight
– coefficient of uniformity C_U according to formula [23]:

$$C_U = \frac{D_{60}}{D_{10}} \, [-] \tag{4.1}$$

where: D_{60} – size of the particle corresponding to 60% finer, D_{10} – size of the particle corresponding to 10% finer

– coefficient of uniformity C_C according to formula [23]:

$$C_C = \frac{D_{30}^2}{D_{10} \cdot D_{60}} \, [-] \tag{4.2}$$

where: D_{30} – size of the particle corresponding to 30% finer

The distribution of the above parameters based on 78 samples is shown in the histograms below (Figs. 6–8).

The results of the C_U ratio test indicate that 75% of the tested samples are uniformly (uniform grain sizes) graded soils with $C_U < 3$ (according to PN-EN ISO-14688-2:2018 [23]). From a geological point of view, these are well sorted sediments that have been subject to relatively long periods of river transport. The remainder are poorly graded soils, i.e. with C_U from 3 to 6.

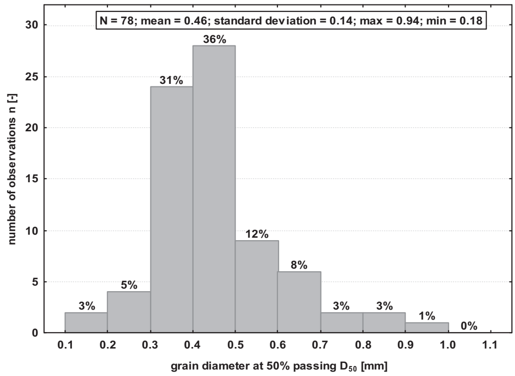

Fig. 6. Frequency and percentage of grain diameter D_{50} of studied sands

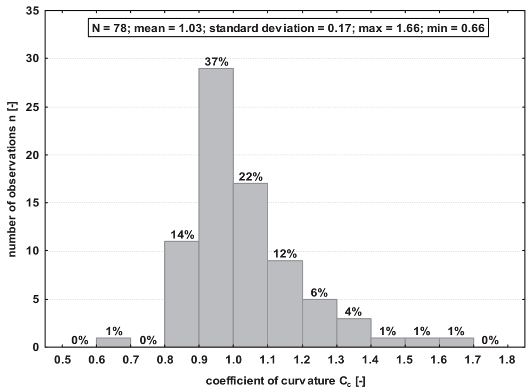

Fig. 7. Frequency and percentage of coefficient of curvature C_C of studied sands

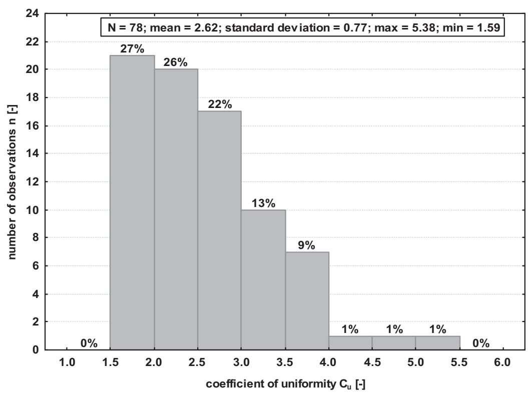

Fig. 8. Frequency and percentage of coefficient of uniformity C_U of studied sands

Analysis of the above charts indicates that:

– the grain diameter of D_{50} mostly varies in the range of 0.3–0.5 mm (about 67% of the data, according to the Fig. 6);
– with depth, the average grain size gradually increases;
– the coefficient of uniformity increases with depth, indicating increasingly poor sorting. The studied sediments are characterized by good sorting (according to the Fig. 8);
– coefficient of curvature most often fluctuates between 0.8 and 1.1 (about 73% of the data, according to Fig. 7). No evident changes are observed with the depth.

Corrected cone resistance q_t of static soundings with the corresponding number of blows N_{10} of dynamic soundings versus depth is shown in Fig. 9.

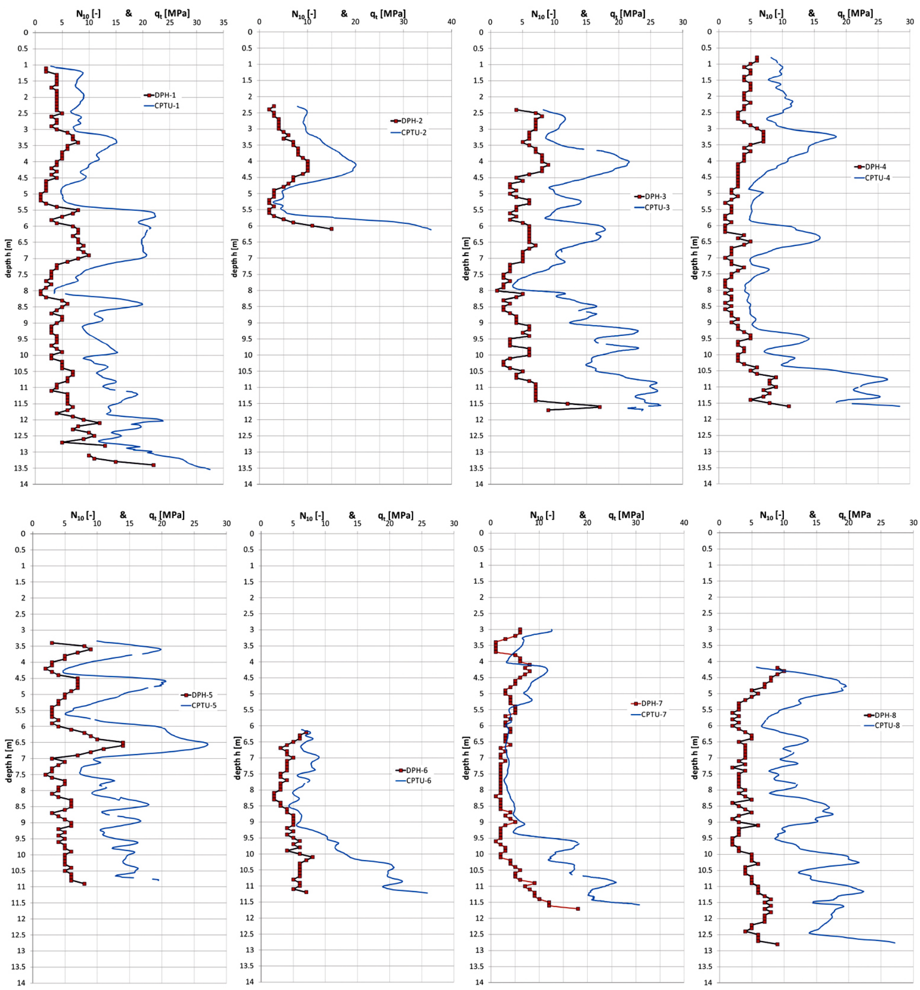

Fig. 9. Corrected cone resistance q_t with the corresponding number of blows N_{10} versus depth

The depth of soundings was variable and depended on penetration resistance. CPTu probing was most often discontinued if the resistance threatened to damage the tip. The total thickness of the comparative zone was 66 m. Thus, at each test station, the comparison zone had an average thickness of about 8.3 meters.

Moreover, the carried out tests enabled the collection of a large and representative dataset, which was compiled in the histograms (Figs. 10–13). They represent the characteristic values of penetration resistance of soundings for the Praski terrace sands. The variability of the data was reported by minimum, maximum, mean and standard deviation values.

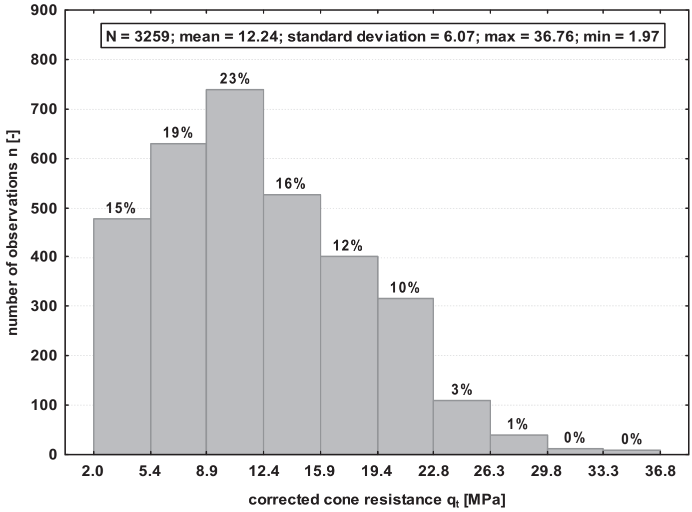

Fig. 10. Frequency and percentage of corrected cone resistance q_t of studied sands

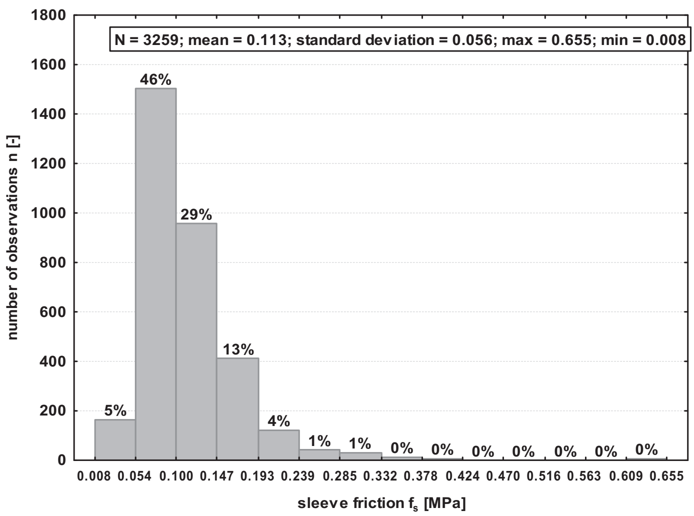

Fig. 11. Frequency and percentage of sleeve friction f_s of studied sands

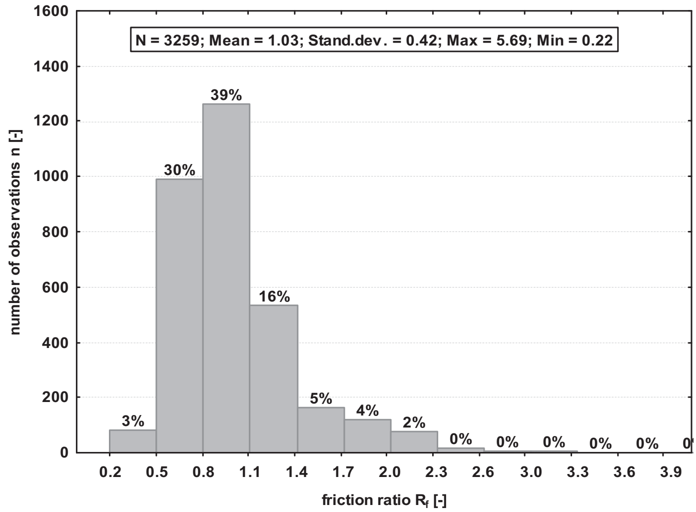

Fig. 12. Frequency and percentage of friction ratio R_f of studied sands

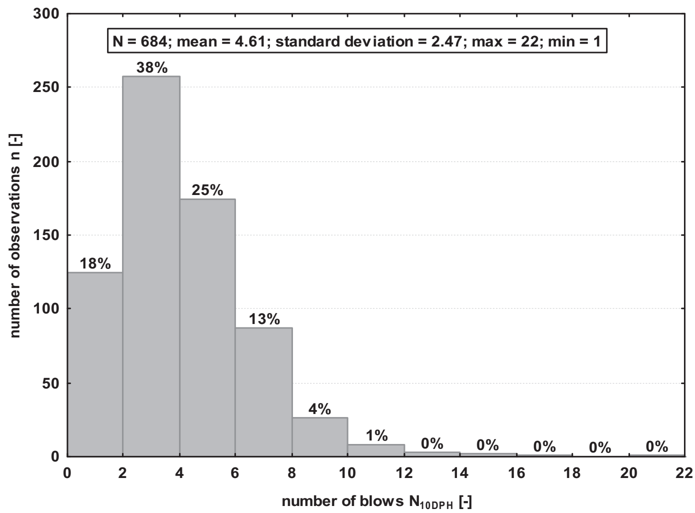

Fig. 13. Frequency and percentage of blows $N_{10\,\mathrm{DPH}}$ of studied sands

The results of CPTu static soundings allow, based on the charts developed by Lunne et al. [13] (Figs. 14–16), for the estimation of soil types. For this purpose the obtained sounding results were superimposed on the above mentioned charts and additionally compared with direct laboratory sieve analyses. That comparison allowed for the validation of the charts in terms of predicting the lithological type of Praski terrace sands.

In Fig. 16, due to the lack of generation of excess pore water pressure u_2, pore pressure parameter values are concentrated near $B_q = 0$. The studied sediments do not contain fine fractions that could generate an excess u_2. It is close to the value of natural pore pressure u_0 and therefore the result of subtracting $u_2 - u_0$ in the formula for B_q gives values close to zero.

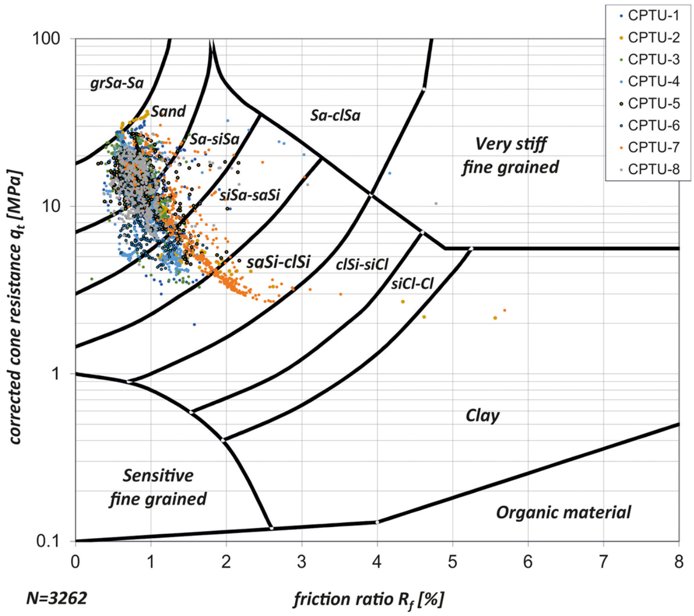

Fig. 14. Robertson's et al. [24] chart with the results of CPTu tests for the studied sands

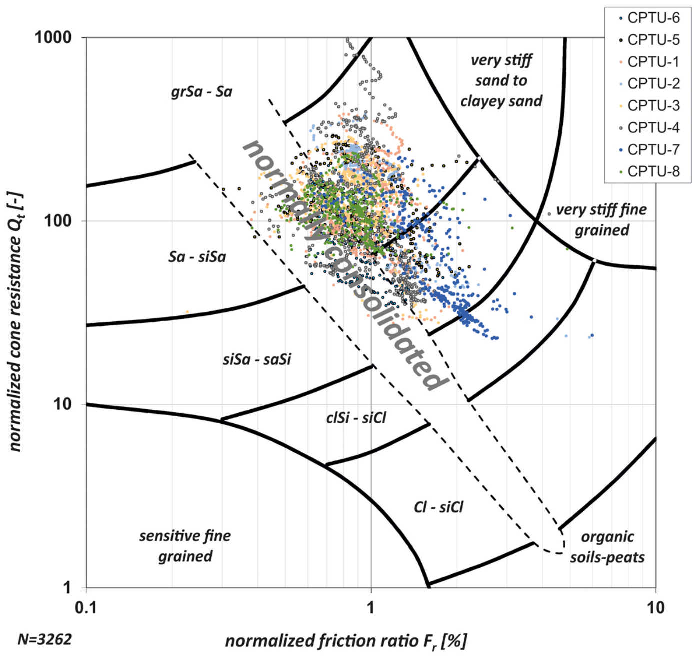

Fig. 15. Robertson's et al. [25] chart with the results of CPTu tests for the studied sands

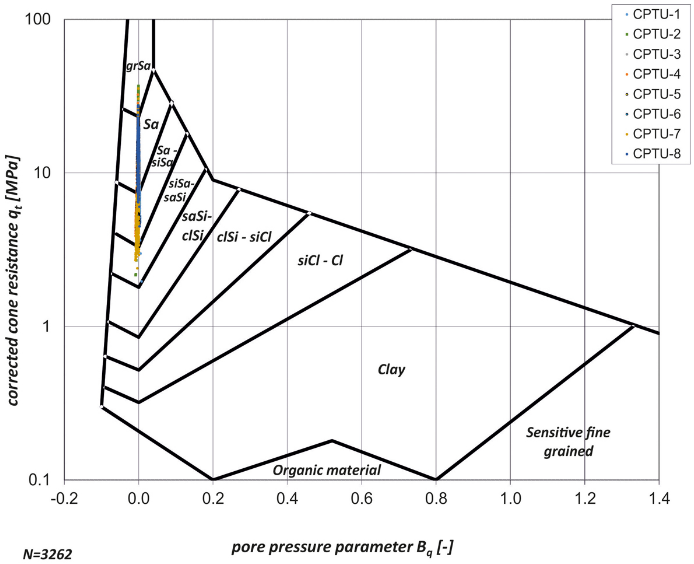

Fig. 16. Robertson's et al. [25] chart with the results of CPTu tests for the studied sands

Analysis the above charts, shows that most of the obtained data are located in the correct zones (described as Sand). However, some of the points especially for poorly compacted sands (e.g., for which q_t is below 7 MPa) are located in the siSa – saSi zone. Some of the data even goes to zones characteristic of clayey silt. This is not confirmed by sieve analyses, in which medium sands and medium sands with gravel clearly predominate, with no significant admixture of fine fractions. No silty sands or sandy silts were found in sieve analyses.

The Praski terrace sands are often characterized by low compaction and low values of resistance q_t, which locates some of the results in areas typical of silty soils. These observations confirm the thesis that these charts can only indicate the soil behavior type and cannot with certainty decide which soils are present.

In the next stage of analysis, the penetration resistance of the medium dynamic probe DPH represented by the number of blows $N_{10\,\mathrm{DPH}}$ and the penetration resistances of the static probe CPTu represented by the corrected cone resistance q_t and sleeve friction f_s were compared with each other (Figs. 17, 18). These comparisons were made separately for the vadose and phreatic zones.

In order to find the best fit between the data, the highest R^2 coefficient values were obtained for linear relationships. Between $N_{10\,\mathrm{DPH}}$ and q_t, the coefficients of determination obtained were about $R^2 \approx 0.60$. When $N_{10\,\mathrm{DPH}}$ and f_s were compared the coefficients of determination obtained were lower, i.e. about $R^2 \approx 0.45$. Nonetheless, it was possible to estimate sleeve friction based on DPH probe measurements. The coefficients of determination for the q_t prediction seem satisfactory, considering the structural variability of the studied sediments.

Due to the variability of the grain size of the studied sediments, its effect on the character of the correlation between N_{10} and q_t was also analysed. An assessment could only be made for the saturation zone since in the aeration zone the data only represented medium sands. For

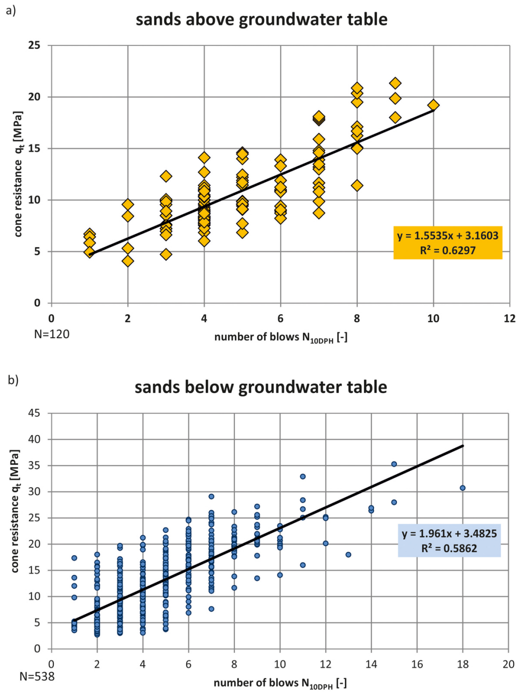

Fig. 17. Prediction of q_t based on $N_{10\,\mathrm{DPH}}$ in vadose (a) and phreatic (b) zone (best fit)

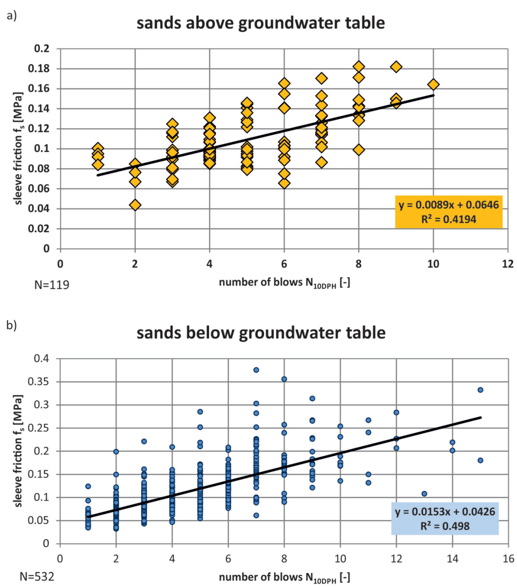

Fig. 18. Prediction of f_s based on $N_{10\,\mathrm{DPH}}$ in vadose (a) and phreatic (b) zone (best fit)

the assessment purpose, blows and cone resistance were compared separately for different soil types. Three groups of soils were established, i.e. fine sands, medium sands (which includes medium sands and medium sands with gravel), and coarse sands (which includes coarse sands, coarse sands with gravel, and sand gravel mixtures). For each group, the relationship between the penetration resistances of the dynamic and the static probe was analysed. The results of this comparison are shown in the chart below (Fig. 19).

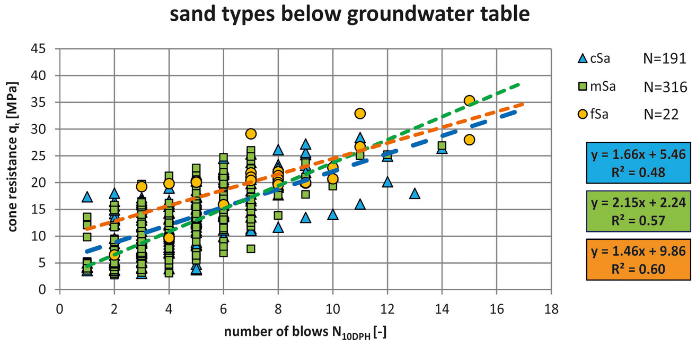

Fig. 19. Prediction of q_t based on $N_{10\,\mathrm{DPH}}$ in phreatic zone for different sand types

The above chart shows that there is no clear relationship between the soil type and the correlation formula. Although different linear correlations were obtained they do not show significant differences or clear trends between one another. In addition, the small data set representing fine sands reduces the strength of correlations. It can be concluded that the search for general correlations for existing, correctly identified lithostratigraphic units (in this case, alluvial sands of the Praski terrace) is adequate. On the other hand, attempts to further differentiate this data set or distinguish smaller ones, in this case, do not lead to new, constructive solutions.

The functional relationships obtained are significantly different for the vadose and phreatic zones (Fig. 20).

Various formulas (different trend line parameters) of the functional relationships between DPH and CPTu sounding parameters in the vadose zone and in the phreatic zone are related to the different probing methodology.

Dynamic penetration of the DPH cone in the saturation (phreatic) zone causes a rapid, temporary increase in pore water pressure and a decrease in effective stress. Consequently, the penetration rate increases (penetration is facilitated) while the number of blows in the saturation zone decreases. During static CPTu probing, such an effect is not observed due to the good permeability of the tested soils and the steady, slow pushing of the cone. By comparing these two test methods, the effect of facilitated penetration of the DPH probe in the saturation zone became evident and can be quantified. The amount of the reduction in dynamic versus static penetration resistance is shown by the following formula (according to the diagram in Fig. 20):

$$R = \frac{\Delta N_{10\,\mathrm{DPH}}}{\Delta N_{10\,\mathrm{DPH\_}V}}\ [\%] \tag{4.3}$$

where: R – blows reduction, $\Delta N_{10\,\mathrm{DPH}} = N_{10\,\mathrm{DPH\_}V} - N_{10\,\mathrm{DPH\_}P}$, $N_{10\,\mathrm{DPH\_}V}$ – blows in vadose zone for a corresponding q_t, $N_{10\,\mathrm{DPH\_}P}$ – blows in phreatic zone for corresponding q_t of the particle corresponding to 10% finer

According to the graph above (Fig. 21), the saturation zone shows a reduction in penetration resistance (blows) of about 25% on average in comparison with the vadose zone, with the same q_t.

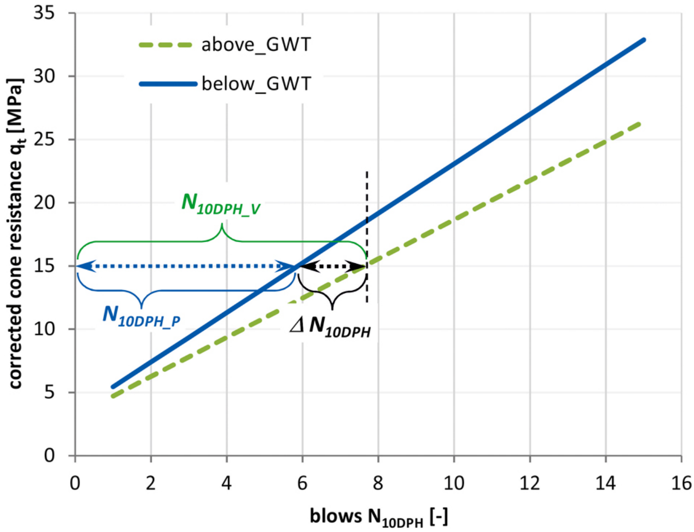

Fig. 20. Trends lines in vadose zone (green dashed line) and phreatic zone (blue line); GWT – groundwater table

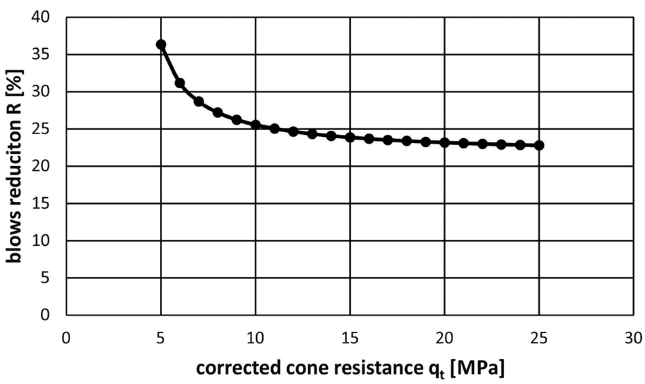

Fig. 21. Blows reduction in phreatic zone versus corrected cone resistance q_t

For example, where the corrected cone resistance q_t (in static conditions) is 15 MPa and the number of blows $N_{10\,\mathrm{DPH}}$ in the vadose zone is about 8 then in the saturation zone the number of blows $N_{10\,\mathrm{DPH}}$ is about 6.

5. Conclusions

The tests carried out have enabled the collection and statistical analysis of the characteristic parameters of the CPTu static and DPH dynamic soundings, as well as the grain-size distribution features of the non-cohesive soils of "the Praski terrace". Correlation formulas were proposed for prediction of corrected cone resistance q_t and sleeve friction f_s based on the number of blows of $N_{10\,\mathrm{DPH}}$. These proposals were developed separately for the vadose and phreatic zones. An attempt to assess the effect of grain size on the form of correlations did not provide satisfactory results. Structural variability (grain size variation) present in the studied sediments is not a sufficient criterion for differentiating its influence on the form of correlations between the analyzed research tools. The main factor that determines the presented relationships is the origin and geological history of the alluvial sediment of the Praski terrace. The analysis of penetration resistance has shown that performing the evaluation of compaction below the ground water table, the number of blows should be corrected, by increasing it by about 25% to take into account the influence of the saturated zone on the results of the tests. In addition, thanks to this comparison, it is possible to explain the discrepancies that appear when assessing the compaction state of soils below the groundwater table using the CPTu static method and the DPH dynamic method. Thanks to the presented correlations, there is a possibility of wider application of the DPH probe.

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Prognoza parametrów sondowania statycznego CPTu w oparciu o sondowanie dynamiczne DPH na przykładzie piasków tarasu praskiego w Warszawie

Słowa kluczowe: osady rzeczne, sondowanie dynamiczne DPH, sondowanie statyczne CPT

Streszczenie:

W artykule powiązano parametry sondowania statycznego CPTu i sondowania dynamicznego DPH w środowisku niespoistych aluwiów rzeki Wisły. Poligon badawczy zlokalizowany zostałw obrębie lewobrzeżnej Warszawy w rejonie osiedla Ostrobramska. Przedstawione badania reprezentowane są przez wyniki testów CPTu oraz DPH uzyskanych w 8 węzłach badawczych. Potrzeba korelowania różnych metod badawczych wynika z dążenia do ich wzajemnej walidacji, wyjaśnienia obserwowanych odstępstw na tle innych uwarunkowań, np. nawodnienia lub uziarnienia. Prezentowana analiza porównawcza parametrów sondowań statycznych i dynamicznych, odnosi się do osadów rzecznych tworzących taras nadzalewowy (tzw. praski) w Warszawie. Utwory stanowiące ośrodek badawczy zostały zakumulowane u schyłku plejstocenu. W artykule porównano dwie metody badawcze oraz przedstawiono propozycje korelacji między oporem wciskania stożka q_t tarciem na tulei f_s oraz liczbą uderzeń młota $N_{10\,\mathrm{DPH}}$, wyrażone zależnością

funkcyjną. Wykazano różnice w formułach dopasowania w zależności od nawodnienia badanych osadów. Dodatkowo dzięki temu zestawieniu można wyjaśnić rozbieżności, które pojawiają się przy ocenie stanu zagęszczenia gruntów poniżej lustra wody podziemnej metodą statyczną CPTu i dynamiczną DPH. Dzięki przedstawionym zależnością jest możliwość szerszego stosowania sondy DPH. Korelacjami nawiązano do uziarnienia, co pozwoliło uściślić zakres stosowalności zaproponowanych zależności. Wyniki badań posłużyły dodatkowo do przedstawienia ich zróżnicowania metodami statystycznymi. Umożliwiło to ocenę zmienności parametrów niespoistego ośrodka gruntowego, stanowiącego jedno wydzielenie litogenetyczne. Zaproponowano formuły korelacyjne do prognozowania skorygowanego oporu stożka q_t oraz tarcia na tulei f_s na podstawie liczby uderzeń $N_{10\,\mathrm{DPH}}$. Propozycje te opracowano oddzielnie dla strefy aeracji i saturacji. Analiza oporów wbijania wykazała, że prowadząc ocenę zagęszczenia poniżej lustra wody powinno się korygować liczbę uderzeń, poprzez jej zwiększenie o ok. 25% aby uwzględnić wpływ strefy nasyconej na wyniki badań. Próba oceny wpływu uziarnienia na charakter korelacji nie dała zadowalających wyników. Zróżnicowanie strukturalne (zmienność uziarnienia) obecne w badanych osadach nie jest wystarczającym kryterium do różnicowania jego wpływu na postać zależności między analizowanymi narzędziami badawczymi. Dominującą rolę, która determinuje przedstawione zależności, odgrywa geneza i historia geologiczna osadów aluwialnych tarasu praskiego.

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