



PROBLEMS OF CORRELATION BETWEEN DYNAMIC PROBING TEST (DPSH) AND CONE PENETRATION TEST (CPT) FOR COHESIVE SOILS OF LITHUANIA

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Abstract. The paper analyses problems of correlation between the results of dynamic probing (DPSH – Super heavy dynamic probing) and cone penetration test. According to investigations of geological cross-sections of cohesive soils of the territory of Lithuania correlation dependencies are evaluated. Reliability of dynamic probing and modern methods of results correction are discussed. Effect of DPSH rods and lateral stress of soils to the results of probing is evaluated. Correlation dependencies between blow count N and depth of probing and cone resistance q_c for various cohesive soils found in the territory of Lithuania.

Keywords: dynamic probing test (DPT), super heavy dynamic probing (DPSH), cone penetration test (CPT), correlation, cohesive soils.

1. Introduction

For construction of bridges, overhead roads, overpasses, because of the specific nature of these buildings and because of uneven load and dynamic impact, foundations need to be supported to deeper soils that are stiff enough. In such cases, deep pile foundations (8.0–12.0 m) are used. Depth of geotechnical investigations under foundation must be at least 5.0–10.0 m (Look 2007).

Geological conditions in Lithuania determine the fact that in such depth often very stiff and small compressibility cohesive clay soils – sandy silty clays and other cohesive soils – are detected, CPT of which becomes technically impossible (Amšiejus *et al.* 2009). In such cases, the only proper method of field investigation is dynamic probing using super heavy standard equipment (DPSH). Using this method in Lithuanian conditions, it is possible to evaluate soil features until the depth of 25.0–30.0 m. Unfortunately, the results of DPSH tests are not used directly in design of pile foundations on cohesive soils. On the other hand, it must be noted, that data of CPT according to currently valid normative documents *EN 1997-2:2007 Eurocode 7: Geotechnical Design. Ground Investigation and Testing* is the main calculation method for pile bearing capacity. Therefore, in cases when investigation data is derived from DPSH tests and when design of foundations must be carried out according to the results of CPT, the prerequisite is recalculation of data achieved using these different methods.

For this purpose, based on data of CPT and DPSH their correlations are analyzed, problems of reliability and correction of data of DPT are discussed. Received data allowed providing correlation dependencies between DPSH and CPT for cohesive soils of Lithuania.

2. Differences between methods of cone penetration test and dynamic probing

In geotechnical investigations of construction sites using in-situ tests two main methods exist: cone penetration test and dynamic probing. In both methods of soil investigation soil resistance to cone penetration at any depth interval is measured (Bell 2007). Probing results provide information to designers about soil at any investigated depth interval. It is very difficult and expensive to get continuous information regarding physical and mechanical properties of soil strata using other investigation methods applied in engineering geology.

Field probing methods have many advantages comparing to other field and laboratory methods of investigation. However, there are many disadvantages related to variety of probing equipment. Both CPT and DPT penetrometers of different modifications give different results. The smallest difference of results is observed when investigating soils using electric and piezocone tests. A slightly larger difference is observed using mechanical cone tests, and the largest – using various dynamic penetrometers (DPT) (Look 2007).

CPT is the main method of soil investigation in Lithuania. During penetration soil resistance to cone penetration (q_c , MPa, MN/m²) and local soil friction with friction sleeve (f_s , kPa, kN/m²) is measured.

CPT equipment and testing procedure is standardized by technical committee at an international level (ISSMFE, 1989). Separate countries have prepared their recommendations and norms conforming to proposals of the mentioned committee (Schnaid 2009).

A large theoretic base has been created for CPT data interpretation (Lunne *et al.* 1997; Robertson 2006). This demonstrates popularity of the method and its applicability towards solving various geotechnical issues. In Lithuania, in addition to formulas that are proposed in European standards and norms, equations established by local scientists are used for CPT data interpretation. In Lithuania, this issue has been widely analyzed by A. S. Brilingas, H. Valiulis and others (Dundulis, Žaržojus 2008).

In engineering geological surveys of transport buildings DPT needs to be employed. According to the methods of works fulfillment, dynamic probing test may be divided into two parts: using sampling tube (standard penetration test SPT) and probing using cone (DPT). According to many authors, blow count of SPT (N_{SPT}) is similar to blow count (N_{DPSH}) of DPT. Regression Eq (1) between these parameters is linear, conversion factor (n) varies from 0.5 to 1.5 (Spagnoli 2007; Cabrera, Carcole 2007; Tomlinson, Woodward 2008).

$$N_{SPT} = n \times N_{DPSH}. \quad (1)$$

In this article super heavy dynamic probing (DPSH) is discussed. During DPSH, blow count (N) necessary for a probe to penetrate an established depth interval (usually 20.0 cm), is calculated. The received data may be expressed also in indirect index – dynamic unite point resistance (r_d , MPa) or in dynamic point resistance (q_d , MPa). These indexes are calculated using various driving formulas.

Among the scientists of the field of geotechnics, contradictory opinions regarding correctness of calculation of dynamic unite point resistance according to driving formulas exist. Scientists from Western countries have been insisting for a long time that use of driving formulas to process data of geotechnical “dynamic systems” (calculation of driving pile bearing capacity (R_d , kN), dynamic unite point resistance (r_d , MPa) from DPT and SPT data) is contradictory and inaccurate due to a number of reasons related to accuracy and correctness of the formulas themselves, to particularities of “dynamic systems” and due to soil properties (Poulos, Davis 1980; Peck *et al.* 1974; Terzaghi *et al.* 1996; Tomlinson, Woodward 2008).

Scientists from the former Eastern block (Russia, Belarus) propose to consider dynamic unite point resistance as the main index of data of DPT. Here an opinion prevails that dynamic unite point resistance is invariant and allows comparing data received by different types of probes (Пубинштейн, Кулачкин 1984).

Advantage of DPSH is that it is possible to reach the necessary depth for investigations and to achieve solid information regarding investigated geological strata notwithstanding inter-layers of stiff soil or small boulders, pebble or other hindrances. However, large disadvantages persist – reliability of data of DPSH depends on the quantity of energy transferred to rods and then to a cone by a falling hammer (E , J). At the time of probing, due to influence of various factors, energy loss appears. It determines reliability of probing data. Factors of energy loss may be divided into two groups: quantity of energy, determined by properties of probing equipment; and quantity of energy, determined by physical and mechanical properties of soil. Quantity of transferred energy also effects the values of dynamic unite point resistance (r_d).

When evaluating data of DPT and while employing them to calculate various soil properties, it is necessary to consider the type of used probing equipment (Smolczyk 2002).

3. Analysis of factors that influence data of DPSH

3.1. Efficiency analysis of DPSH energy transfer

In dynamic probing of soils, it is essential to know the quantity of energy, transferred to rods for data analysis. Real establishment of quantity of energy is a complicated and expensive process. Many authors limit themselves to theoretic calculation of energy quantity or gravity (Newton Law of Impact) and simplify it to elementary formulas for potential and kinetic energy by adding additional coefficients of energy loss. This principle of calculation is applied in all driving formulas. For recalculation of direct data of dynamic probing (Blow count – N_x) to dynamic unite point resistance (r_d or q_d , MPa), “Dutch” driving formula was chosen Eqs (2) and (3) (Stefanoff *et al.* 1988).

$$r_d = \frac{E}{A \times e}, \quad (2)$$

$$q_d = r_d \times \left(\frac{m}{m + m'} \right), \quad (3)$$

where r_d – dynamic unite point resistance, MPa; E – hammer transferred energy, J; A – nominal base area of cone, m²; e – cone penetration per blow, m; q_d – dynamic unite point resistance, MPa; m – mass of hammer, kg; m' – mass of anvil and rods, kg.

In Russia according to GOST 19912-2001 and Belarus according to STB 1377-2003 for calculations of dynamic unite point resistance (r_d) a slightly different expression was chosen Eq (4). Its author – A. J. Rubinstein. He also based his calculations on canonical Newton formulas (Пубинштейн, Кулачкин 1984).

$$r_d = \frac{A \times K_1 \times K_2 \times n}{h}, \quad (4)$$

where A – ultimate probing energy, N/m; K_1 and K_2 – coefficients of energy loss; n – blow count per series; h – probe penetration per blow series, m.

Analysis of mentioned Eqs (3) and (4) demonstrates that loss of energy at blow or blow efficiency (η) is the following Eqs (5), (6):

$$\eta = \frac{m}{m + m'}, \quad (5)$$

$$\eta = K_1 = \frac{m + n \times m'}{m + m'}. \quad (6)$$

Expression (5) shows that blow is analyzed as plastic and the basis is Carnot's theorem. This theorem describes change of kinetic energy of plastic body after a blow (Syrus *et al.* 2008). Expression (6) shows that blow is analyzed as elastoplastic (Poulos, Davis 1980; Рубинштейн, Кулачкин 1984).

Calculation of losses of energy transferred by hammer according to the mentioned Eqs (5) and (6) makes it impossible to describe many influencing factors that depend on particularities of probing equipment. To calculate efficiency of energy transfer, it is possible to base calculations on one dimensional wave equation in elastic body. For the first time this theory was applied in SPT by the following scientists: C. Fairhurst, A. Palacios, J. H. Schmertmann, F. Y. Yokel (Odebrecht 2003; Savidis, Müller 2007).

In the work Savidis and Müller (2007) took formulas of the mentioned scientists, intended for SPT equipment, and applied them to DPL and DPH probes. He also checked their efficiency in practice.

Authors of this article calculated blow efficiency for DPSH-A probe type based on formulas of mentioned scientists Eqs (7) and (8) (Fig. 1).

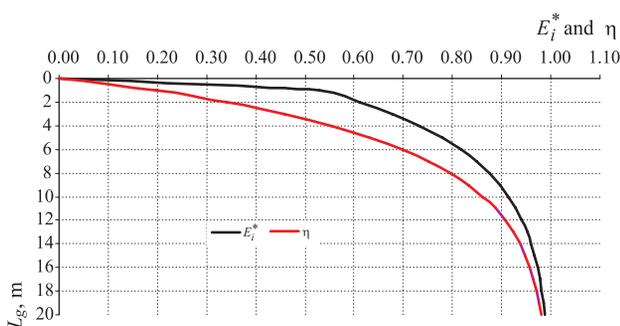


Fig. 1. Efficiency of hammer impact versus rod length of DPSH-A type probe: E_i^* – Yokel solution; η – Schmertmann, Palacios and Fairhurst solution

Eq (7) of blow efficiency (η) provided by C. Fairhurst, A. Palacios and J. H. Schmertmann and Eq (8) is a remake of S. Tymoshenko solution made by F. Y. Yokel (Odebrecht 2003; Savidis, Müller 2007):

$$\eta = (1 - K^n) + \left(\frac{L_g}{L_h} - n \right) \times \frac{4 \times r \times K^n}{(1 + r)^2}, \quad (7)$$

$$\eta = E_i^*(t) = 1 - e^{-\frac{2 \times m_g}{M}}, \quad (8)$$

where K – coefficient of energy loss due to equipment elasticity features; n – positive integer $\left(\frac{L_g}{L_h} \geq n > \left(\frac{L_g}{L_h} - 1 \right) \right)$; L_g – length of rods, m; L_h – length of hammer, m; r – ratio of impedance of hammer and rods; $E_i^*(t)$ – energy used for probing; m_g – mass of rods, kg; M – mass of hammer, kg.

Calculation of hammer blow efficiency provided here is theoretical. It may be applied only if lateral friction of rods with soils and if lateral stress of soils to rods is eliminated at the time of probing. Provided calculations (Fig. 1) demonstrate that the longer the rods (higher probing depth), the larger blow efficiency (E_i^* and η), i.e., the larger quantity of energy reaches the rods. Blow count at initial depth interval (to 3.0–4.0 m), will be higher than soil of the same features in deeper layers.

3.2. Influence of soil lateral friction with rods for the blow count

In DPSH soil rubs into rods. Here, in order to overcome the friction, energy is needed. This energy is provided by hammer and it is necessary to eliminate soil resistance. Blow count (N_x) is an index of DPSH. It is dependent on soil resistance to penetration at cone tip and at the side of probe. In evaluation of probing data, it is often assumed that blow count depends solely on soil resistance at tip; lateral friction is not considered. To establish the impact of lateral friction of clay soils, an experiment was carried out: a special bore mud designed to cause an effect of a lubricant was used (Fig. 2a). Probing was carried out through the strata of fine sand and sandy clay and sandy silty clay till (from depth of 5.0 m) (Fig. 2a).

Analysis of data of investigations demonstrates that friction of rods with soil has an effect on DPSH test data. However, this influence is slight. If you put a probe to 5.0 m depth influence of lateral friction is not observed, blow count is very similar. If probing is carried out in higher depth the difference between blow counts ($N_{20} - N_{20}^*$) varies from 1 to 5. However, average number of blows was 2 (Fig. 2b). Fig. 2c shows that the use of drill mud for the depth lower than 5.0 m had no effect, and in deeper probing blow count decreased by approx 10–15%.

3.3. Soil horizontal geostatical stress influence on probing data

In DPSH of clay soils it has been noticed that in existence of indiscrete soil strata blow count rises together with the depth. Particularly it can be observed from depth of 6.0–7.0 m. When probing deeper, lateral geostatical stress of soil increases. It presses the rods. To overcome this stress, energy is needed. Therefore, the smaller and smaller quantity of energy is transferred to a cone, which determines the increase of blow count.

Tests have been carried out seeking to examine the impact of lateral geostatical stress. In these tests one probe

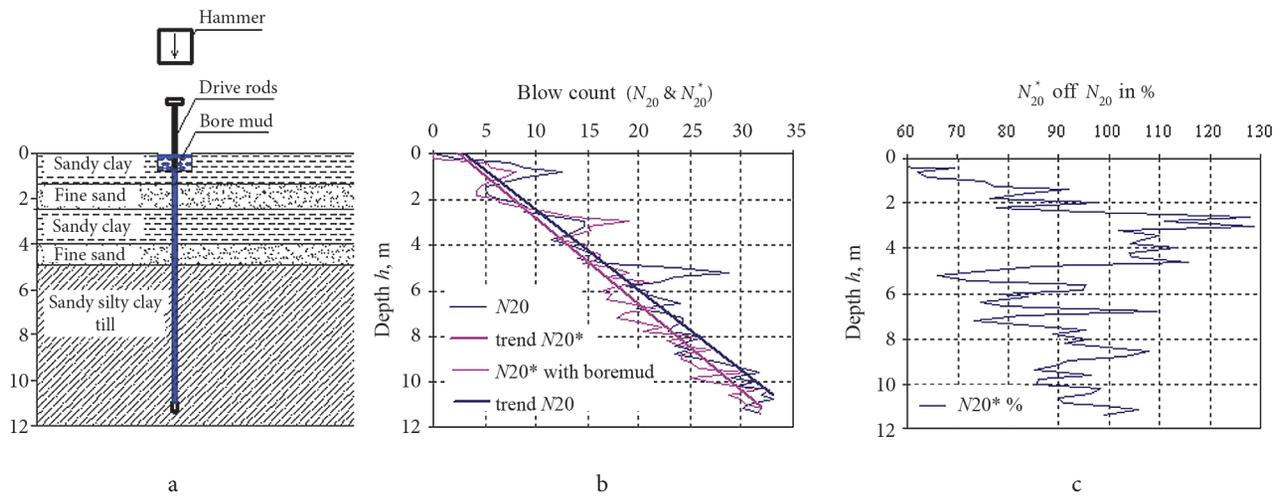


Fig. 2. Results of research of friction influence in to DPSH data (blow count N_x)

was driven from the ground surface, the other – by disrupting the soil at certain intervals (probing with predrilling). Also, to establish indiscreteness of soil, CPT test was carried out. Investigations of clay soil were conducted at depth interval of 13.0–16.0 m by probing silty sandy clay till.

These investigations have demonstrated that in probing of clayey soils, lateral geostatical stress has a large influence upon data (Fig. 3). Ratio (β) of blow count without predrilling and with predrilling Eq (9) varies in interval: 4.3 (13.0 m) \rightarrow 6.3 (16.2 m). Meanwhile, data of CPT (q_c) remain even ~ 6.2 MN/m².

$$\beta = \frac{N_{20}}{N_{20}^*}, \quad (9)$$

where β – ratio revealing the impact of lateral stress on data of DPSH test; N_{20} – blow count when probing without predrilling; N_{20}^* – blow count when probing with predrilling.

Ratio (β) to the depth varies within the limits of logarithmic curve, i.e., at initial depth interval it is close to 1. It increases significantly when the depth increases (Fig. 4). These investigations allowed to provide regression equation (correlation coefficient $R = 0.86$). This equation enables the establishment of blow count (N_{20}^*)

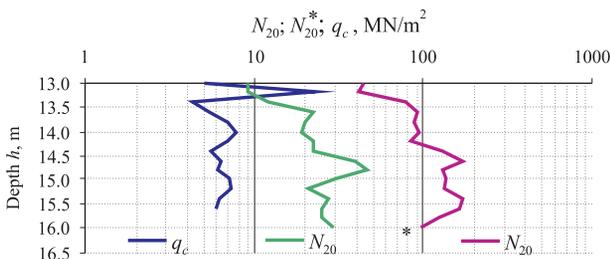


Fig. 3. Data of blow count with predrilling (N_{20}^*) without predrilling (N_{20}) and cone resistance (q_c) from CPT test

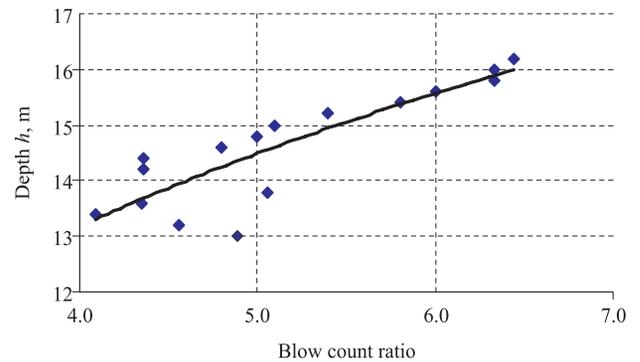


Fig. 4. Relation between penetrating depths (h) and blow count ratio (β) is described of Logarithmic regression curve

Eq (10) when it is not influenced by lateral geostatical soil stress by probing silty sandy clay till. This N_{20}^* blow count reflects a real soil resistance to cone penetration and it is to be used at future calculations of physical and mechanical properties of soil:

$$N_{20}^* = 0.8311 \times N_{20} \times e^{0.1243 \times h}. \quad (10)$$

4. Correlation between indexes of dynamic probing (DPSH-A) and cone penetration test (CPT)

4.1. Reasoning of correlation search between DPT and CPT

In Lithuania for calculation of foundation bearing capacity (R_u) of transport and civil buildings, CPT data is used. Utilization of data of DPT test with cone for foundation design is not popular as no reliable methods of calculation exist. In USA and some European countries, methods based on data of SPT test are used for foundation design. Many correlation equations are proposed to evaluate physical and mechanical properties of soils according to CPT and SPT probing data (Dundulis, Žaržojus 2008; Lunne *et al.* 1997; Schnaid 2009). According to data of DPT test,

only soil density index (I_D) and soil relative density index (D_r), oedometer deformation modulus (E_{oed}) can be approx evaluated.

If one wishes to evaluate properties of site soils investigated by a method of DPT in more detail, one needs reliable correlation equations between data of DPT test and various indexes of soil properties, or correlations showing relations between indexes of other types of geotechnical probing (q_c , N_{SPT} , etc.).

Correlation relation between different types of dynamic probing equipment (DPL and DPH) is provided in European standard *EN 1997-2:2007*. Graphs are provided here showing correlations between N_{10H} (DPH) and q_c (CPT). DPSH and SPT have been analyzed by many scientists; the received results are similar (Cabrera, Carcole 2007; Spagnoli 2007; Tomlinson, Woodward 2008). One of the first scientists to have examined the relation between SPT and CPT was R. G. Campanella (1979), other authors followed him later (Campanella, Berzins, Shields 1979; Chin, Duann, Kao 1988; Robertson *et al.* 1983; Sharma, Ilamparuthi 2005).

Many equations designed to convert data of DPT, SPT to that of CPT are applied to coarse uncohesive soils of various granular composition. Due to complex behavior of cohesive soils in effect of dynamic load, little investigations are carried out in these soils.

Correlations between DPT and CPT for cohesive clay soils were analyzed Butcher *et al.* (1996).

Until now, in Lithuania no attempts to find correlations between DPT and CPT are known. Separate engineering geologists have tried to correlate the values of dynamic point resistance (q_d) and cone resistance (q_c). Another way to convert the values of DPT indexes to CPT is through intermediate indexes:

$$N_{20(DPSH)} \rightarrow I_D \text{ or } D_r \rightarrow q_c,$$

$$DPSH \rightarrow SPT \rightarrow CPT,$$

$$DPSH \rightarrow DPH \text{ or } DPL \rightarrow CPT.$$

Conversion of data of DPT to CPT through intermediate indexes is incorrect and results in large bias. Reliable equations enabling to convert DPSH directly to CPT are needed.

4.2. Selection of correlation indexes

Data of DPT test can be expressed in direct indexes (N_x), as well as in indirect, recalculated indexes (r_d and q_d). This has already been discussed above, in chapter 2.3. In CPT, cone penetration (q_c) is measured. In DPT and CPT there is another very important index – depth (h). In order to find correlations between DPT and CPT there are several variants for correlation of indexes:

$$N_x \rightarrow q_c \text{ i.e., direct DPT with direct CPT;}$$

$$r_d \text{ or } q_d \rightarrow q_c \text{ i.e., indirect DPT with direct CPT;}$$

$$(N_x \rightarrow q_c) + h, \text{ i.e. direct DPT with direct CPT, considering impact of depth;}$$

$$(r_d \text{ or } q_d \rightarrow q_c) + h, \text{ i.e., indirect DPT with direct CPT, considering impact of depth.}$$

Two first variants of correlation which do not consider the effect of depth, could be in part correct, if in probing, dispersion of energy, friction and lateral press were considered (Butcher *et al.* 1996). Without consideration of the mentioned factors the received results are unreliable (Fig. 5), where correlation coefficient R varies from 0.44 to 0.81, on average – 0.61. It is assumed that impact of depth and of loss of energy is included in q_d calculation (Livneh *et al.* 2000). However, investigations conducted by various authors show that this is inaccurate and unreliable (Poulos, Davis 1980; Terzaghi *et al.* 1996).

Other two variants of correlation reflect a more realistic probing situation, because the effect of depth to DPT data is huge (Chapter 3). In Lithuania, for DPT, predrilling or other technological solutions that reduce the impact of lateral friction and soil geostatical stress are not used. Also, the real quantity of energy for cone is not measured.

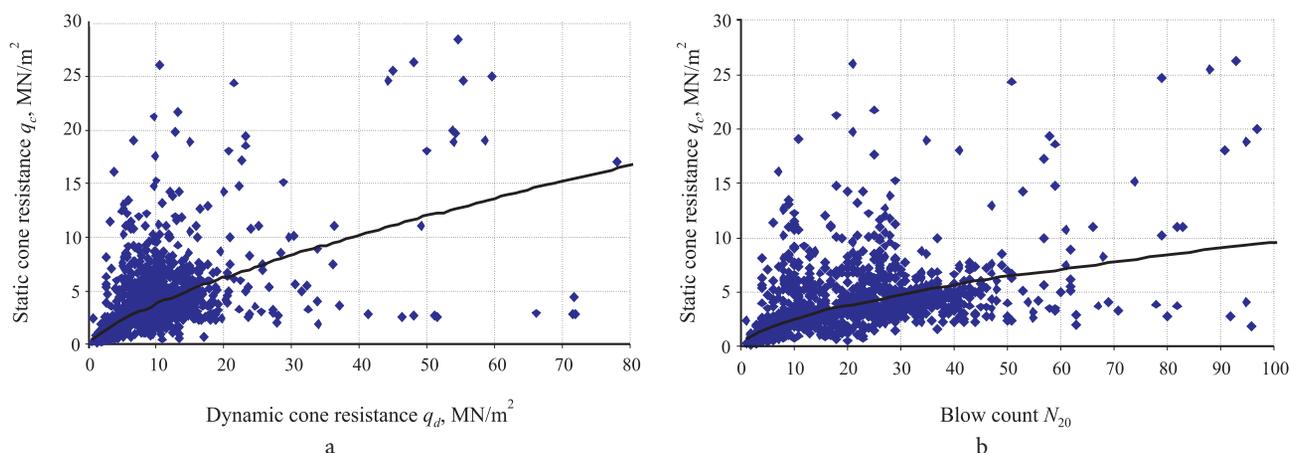


Fig. 5. Correlation results then underestimating probing depth: a – static cone resistance (q_c) versus dynamic cone resistance (q_d); b – static cone resistance (q_c) versus blow count (N_{20})

Table 1. Cone resistance calculated from blow count (DPSH-A) in different cohesion soils

Soil type	q_c MN/m ²	R
Clay	$(0.3324 - 0.0141 \times h) \times N_{20}$	0.87
Various granular composition till	$(0.4686 - 0.1231 \times \ln(h)) \times N_{20}$	0.97
Sandy silty clay	$(0.7622 - 0.2124 \times \ln(h)) \times N_{20}$	0.85

The correlation variant with direct DPT and CPT measurement indexes (N_{20} ir q_c) which take into consideration the impact of probing depth (h) have been chosen.

4.3. Correlation between DPSH-A and CPT indexes for cohesive soils

In Lithuania the most popular type of dynamic probing equipment is DPSH (A and B). The difference of specific work per blow between A and B probes is 20%. In this article, for search of correlations, DPSH-A was chosen. Correlation between three indexes (N_{20} , q_c , h) was analyzed. For simplification of regression equations, ratio index (α) between cone resistance and blow count was added. The results are specified in Table 1.

5. Conclusions

In Lithuania for investigation of transport and civil buildings by methods of field investigation CPT and DPT probing methods are employed. Much scientific material exists to analyze and interpret CPT data. However, investigations using CPT alone are not possible in every place. Often, if complex geological conditions exist, DPT is used. Interpretation of DPT test data is complicated, reliability of received results is low (especially for cohesive soils). It is impossible to reject this method, as sometimes it is the only method allowing receiving data on soils by in-situ. Therefore, it is necessary to create scientific base for data analysis and interpretation.

In analysis of DPT data, it is necessary to consider blow efficiency. Blow efficiency described in valid European and Russian standards is very simplified and it misses a number of important factors depending on particularities of probing equipment. It is better to evaluate blow efficiency using one dimensional wave equation.

Reliability of DPT data depends on lateral friction of soil and rods. Analysis of cohesive soils has shown that lateral friction increases blow count (N_x) to 10%.

Researches on effect of lateral geostatical stress on rods have demonstrated that this factor exercises large influence upon data reliability. Ratio β varies within the following interval: 4.3 (13.0 m) \rightarrow 6.3 (16.2 m). In evaluation of physical and mechanical properties of soil according to DPT results, it is necessary to use a corrected blow count (N_{20}^*).

Use of DPT data in foundation design and in a broader evaluation of soil properties is complicated, as theoretical basis is not extensive enough. Often, DPT data are converted to CPT data using correlations of indexes (N_x or q_d

with q_c) or through intermediate indexes (DPT \rightarrow SPT \rightarrow CPT). Such method of conversion is not accurate enough and may distort final data. Seeking to convert DPT data to CPT, one needs to correlate only direct indexes (N_x ir q_c) considering probing depth (h).

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