Estimation method of the bearing capacities of shallow and pile foundations from dynamic probings

Méthode d'estimation de la capacité portante de fondations superficielles et fondations sur pieux à partir de sondages dynamiques

Zadroga Bohdan – *Prof., Geotechnical Department, Technical University of Gdańsk*
Giżyński Tomasz – *M.S.C.E., Geotechnical Department, Technical University of Gdansk. G. Narutowicza St. 11/12, 80-952 Gdańsk, Poland*

ABSTRACT: The purpose of this paper is presentation of calibration results in non-cohesive soils for two new prototypes of dynamic probings. Calibration was performed in accordance with European Standards: Eurocode 7 (Site Investigation) and European experiences. Included are also some practical recommendations to take advantage of the dynamic probings results for determination of the bearing capacities of shallow and pile foundations in non-cohesive soils.

RÉSUMÉ: Le bût de ce papier et la présentation de résultats de calibration pour deux sondes dynamiques. La calibration est effectuée en accord avec Les Normes Européennes: Eurocode 7 (Essais in –situ) et la pratique européenne. Quelques recommandations pratiques concernant la détermination de la capacité portante de fondations superficielles et des fondations sur pieux dans les sols pulverulents à partir des sondages dynamiques sont présentées.

1. INTRODUCTION

In recent years a significant development of various cone penetration techniques can be observed. It has resulted in better constructions of sounding devices and in an improvement of interpretation methods. Simultaneously, in order to enable the comparison of the results obtained in different countries one could also observed the need to standardise the equipment applied.

In Poland, at the beginning of nineties prototypes of two dynamic cone penetrometers have been constructed and calibrated. According to international construction standards which are shown in Table 1 these prototypes can be denoted as medium – SD-30 and heavy - SD – 50 penetrometers.

The new dynamic cone penetrometers have been next calibrated in terms of large number of penetration tests of a subsoil carried out all over the country. The tests were performed mainly in non-cohesive soils of different relative density and gradation. In order to appropriately interpret the test results and obtain reliable calibration of the new dynamic penetrometers the influence of various factors should be considered. Among other the basic factors are:

- friction between a soil and cone rods,
- type and gradation of soil,
- virgin stress,
- localisation of groundwater table,
- the use of hammer fall energy.

Table 1. Classification and parameters of dynamic cone penetrometers according to Polish Standard and EUROCODE-7 (1997)

	Denotation	Hammer's mass [kg]	Lift height [m]	Cone area [cm^2]	Number of blows [N_k]
Light	DPL	10.0	0.50	10.0	N_{10}
Medium	DPM	30.0	0.50	10.0	N_{10}
Heavy	DPH	50.0	0.50	15.0	N_{10}
Super heavy	DPSH	63.5	0.75	20.0	N_{20}

2. CORRELATION OF PENETRATION TEST RESULTS

The results of penetration tests can be compared and correlated analytically by so called energy adequacy coefficient k_a, the value of which can be expressed by the following formula Miura et al. (1997):

$$k_a = \frac{N_{1n}}{N_{2n}} \quad and \quad k_a = \frac{W_{1n}H_{1n}A_{2n}e_{2n}}{W_{2n}H_{2n}A_{1n}e_{1n}}, \tag{1}$$

where: N_n - number of hammer blows [-]; W_n – mass of hammer [kN]; H_n – hammer elevation and fall height [m]; A_n – cross sectional area of cone tip [m^2]; E_n – cone tration due to single blow ($e_n = \frac{h_n}{N_n}$) [m]; H_n – cone penetration for every 10 cm [-].

Calculated theoretical values of energy adequacy coefficient k_a can be compared to those obtained from filed tests assuming that k_a is a ratio of hammer blows count of medium or heavy penetrometer to the equivalent number of any of dynamic penetrometers. In this manner the agreement of the field and analytical results can be assessed.

Additionally, the correctness of cone penetration test results can be verified according to criterion of conformity of dynamic resistances q_d when using both types of penetrometers.

Final relationships between number of hammer blows N_{10} of SD-30 and SD-50 penetrometers and relative density of soil have been determined on the basis of correlation of tests carried out by various penetrometers. Logarithmic relationships for uniformly graded soils (uniformity coefficient $c_u \leq 5.0$) are the following:

Medium dynamic penetrometer SD – 30

$$D_r = 0.368\log(N_{10})+0.223 \qquad (2)$$

Heavy dynamic penetrometer SD-50

$$D_r = 0.347\log(N_{10})+0.293 \qquad (3)$$

3. CALIBRATION OF DYNAMIC CONE PENETROMETERS FROM LABORATORY TESTS

In order to compare and correct typical methodology of calibration of dynamic penetrometers a new direct method has been elaborated by authors. The method can be summarised as follows:

- Within the area that was previously tested by dynamic penetrometers SD-30 and SD-50 the trial pit was made.
- During gradual digging careful sampling of non-cohesive soil was carried out with special attention paid to take undisturbed samples with regard to its structure and moisture content.
- All samples were next tested in the laboratory. During the tests moisture content w, coefficient of uniformity C_u (grain size distribution curve), relative density D_r, angle of internal friction ϕ and bulk density ρ of the soil tested were determined.
- On the basis of known number of hammer blows N_{10} (for both medium and heavy penetrometer) main correlation relationship expressing the dependence of relative density on number of hammer blows was established:

$$D_{r(lab)} = f(N_{10}) \qquad (4)$$

- Using determined values of other geotechnical parameters additional relation was obtained:

$$[\phi, \rho]_{(lab)} = f(N_{10}) \qquad (5)$$

For various types of non-cohesive soils the following particular relations have been found:

1. Soil relative density D_r:

Medium dynamic penetrometer SD – 30

$$D_r = 0.111\log(N_{10})+0.579 \qquad (6)$$

Heavy dynamic penetrometer SD-50

$$D_r = 0.167\log(N_{10})+0.531 \qquad (7)$$

2. Angle of internal friction ϕ [°]

Medium dynamic penetrometer SD – 30
Fine sand

$$\phi = 3.678\log(N_{10})+28.394 \qquad (8)$$

Heavy dynamic penetrometer SD-50
Fine sand

$$\phi = 5.361\log(N_{10})+27.789 \qquad (9)$$

3. Bulk density ρ [g/cm^3]

Medium dynamic penetrometer SD – 30
Coarse and medium sand

$$\rho = 0.111\log(N_{10})+1.806 \qquad (10)$$

Fine sand

$$\rho = 0.045\log(N_{10})+1.817 \qquad (11)$$

Heavy dynamic penetrometer SD-50
Fine sand

$$\rho = 0.069\log(N_{10})+1.799 \qquad (12)$$

Quantitative comparison of particular geotechnical parameters was made for the same number of hammer blows $N_{10} = 10$ for both penetrometers. The analysis was based on the comparison of equivalent values of relative density treated as a basic feature for determination of other geotechnical parameters. The following values have been obtained:

- medium penetrometer SD – 30:

indirect method $N_{10} = 10 \rightarrow D_r = 0.590$ (13)

direct method $N_{10} = 10 \rightarrow D_r = 0.690$ (14)

- heavy penetrometer SD – 50:

indirect method $N_{10} = 10 \rightarrow D_r = 0.640$ (15)

direct method $N_{10} = 10 \rightarrow D_r = 0.698$ (16)

Rough analysis of the values obtained leads to the following conclusions:

- for medium penetrometer the value of relative density determined by the correlation method is approximately 17% lower than corresponding value obtained by direct method. This observation seems to be correct due to more accurate determination of relative density in laboratory conditions.
- for heavy penetrometer the value of relative density determined by the correlation method is lower only 9% from the value determined by direct method.

4. BEARING CAPACITY OF SHALLOW AND DEEP FOUNDATIONS

According to Polish Standard (1981) for strip foundations loaded axially and rested directly on uniform non-cohesive subsoil bearing capacity is verified by the following general relation:

$$q_{rs} \leq m q_f \qquad (17)$$

where q_{rs} – average calculated unit load of a subsoil from strip foundation [kPa]; m – correction coefficient, m = 0.81; q_f – calculated unit resistance of a subsoil under strip foundation [kPa] given by the formula:

$$q_f = N_D D_{\min} \gamma_D^r + N_B B \gamma_B^r , \qquad (18)$$

where D_{min} – minimum depth of strip foundation beneath surface level [m]; $\gamma_D^{(r)}$, $\gamma_B^{(r)}$ – calculated average unit weight of a soil above and below strip foundation base; N_D and N_B – capacity coefficients given as:

$$N_D = \exp(\pi tan\phi^{(r)})tan^2\left(45 + \phi^{(r)}/2\right), \tag{19}$$

$$N_B = 0.75(N_D - 1)tan\phi^{(r)} \tag{20}$$

$\phi^{(r)}$ – calculated values of internal friction angle of a soil under strip foundation.

According to Polish Standard (1983) bearing capacity of a single pile is verified by general formula:

$$Q_f < mN, \tag{21}$$

where: Q_f – calculated vertical load of the pile [kN]; m – correction coefficient depending on a number of piles under foundation.

N – calculated bearing capacity of pushed-in pile given by:

$$N = S_p q^{(r)} A_p + \sum S_{si} t_i^{(r)} A_{si}, \tag{22}$$

where: S_p, S_s – technology factors dependent on type of pile and soil [-]; A_p, A_s – cross-sectional area of pile's base and shaft, respectively [m²]; $q^{(r)}$ – calculated unit strength of soil under pile base [kPa]; $t^{(r)}$ – calculated unit strength along pile shaft [kPa].

General procedure for elaboration and practical application of charts for equations (17)÷(22) is the following:

- on the basis of own correlation formulae derived from the count of hammer blows of the penetrometer the relative density of non-cohesive soil is determined,
- for shallow foundations, know type of non-cohesive soil and its relative density the angle of internal friction can be indirectly determined based on either standard relationship or from own direct relations (see eq. 8 and 9). Subsequently, from standard formula the relations between bearing capacity coefficients N_D and N_B and number of hammer blows N_{10} are evaluated. Next the unit resistance of non-cohesive soil can be calculated and its dependence on number of blows elaborated.
- For deep foundations, know type of non-cohesive soil and its relative density the dependence of unit strength of soil under the base and along the shaft of pile on the number of penetrometer hammer blows is determined. These relations are next used to direct calculations of bearing capacity of single pile.

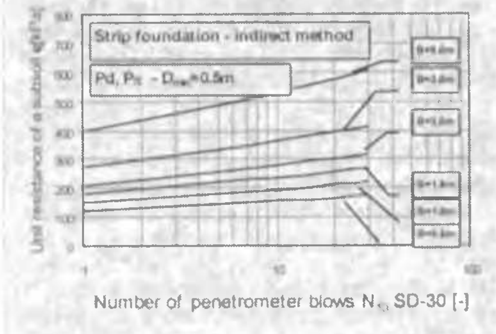

Fig. 1 Exemplary charts for determination of unit strengths of a soil under the base of shallow foundations (q_f)

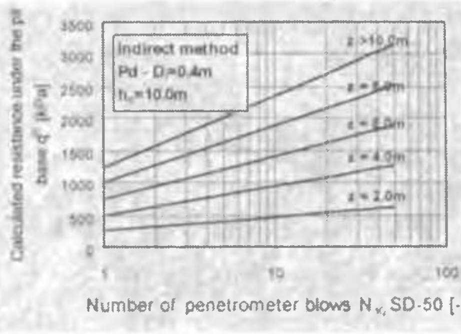

Fig. 2 Exemplary charts for determination of calculated resistance under the pile base ($q^{(r)}$)

Corresponding charts for determination of calculated unit strengths of soil under the base of shallow foundations (q_f) and pile ($q^{(r)}$) are presented in Fig. 1 and 2. Chart serving for determination of calculated unit strengths of a soil under the base and along of pile shaft for injection jet-grouting piles, and CFA piles, not included in the Polish Standard are shown in Figs. 3-5.

with symbols

Ż, P_o Gravel, P_r, P_s - Coarse and medium sand,

P_d, P_π - Fine and silty sand.

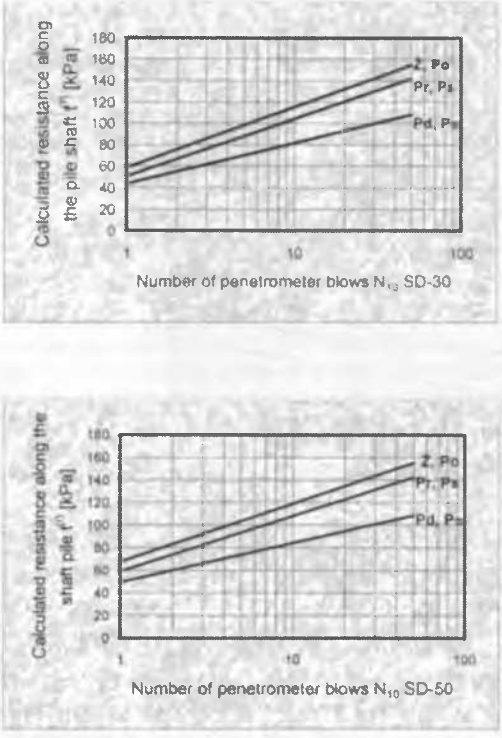

Fig. 3 Medium SD-30 and heavy SD-50 penetrometer. $t^{(r)} = f(N_{10})$ relations for jet-grouting piles and various types of non-cohesive soils

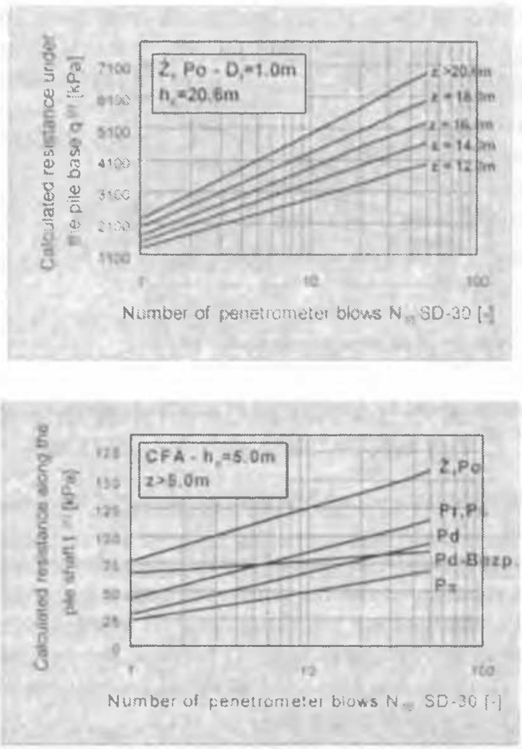

Fig. 4 Medium penetrometer SD-30. $q^{(r)} = f(N_{10})$ relations for CFA piles and various types of non-cohesive soils and $t^{(r)} = f(N_{10})$ relations for various non-cohesive soils and pile depth z>5.0 m.

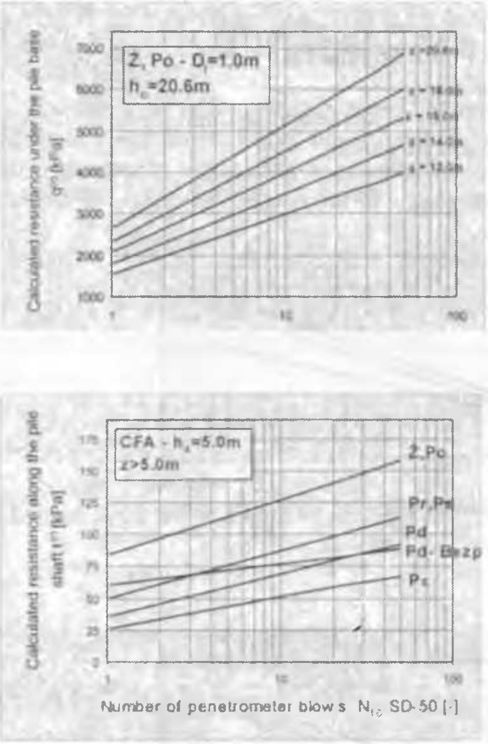

Fig. 5 Heavy penetrometer SD-50. $q^{(r)} = f(N_{10})$ relations for CFA piles and various types of non-cohesive soils and $t^{(r)} = f(N_{10})$ relations for various non-cohesive soils and pile depth z>5.0 m.

5. CONCLUSIONS

Based on experiments made and analyses of the results performed one can conclude that:

1. Geotechnical parameters can be determined with sufficient accuracy from dynamic penetration tests using properly calibrated prototypes of medium and heavy penetrometers both from indirect as well as direct method. Comparison of the two methods presented above shows good agreement between the results obtained.
2. Using the same dynamic penetration test results one can also determine bearing capacity of non-cohesive subsoil under shallow or deep foundations.
3. For in situ determined counts of hammer blows of penetrometers the charts presented in the paper for shallow and deep foundations rested on various types of piles enable quick assessment of bearing capacity of a subsoil tested.

References

EUROCODE-7 Part 1 (1997) Geotechnical Design. General Rules.

Miura K et al. (1997). *Physical characteristics of sands with different primary properties.* Soils and Foundations, Vol. 37, No. 3, pp. 53-54.

Polish Standard PN-81/B-03020 (1981) *Building soils. Foundation bases. Static calculation and design.*

Polish Standard PN-83/B-02482 (1983*) Foundations. Bearing capcity of piles and pile foundation.*