Correlations to estimate engineering properties from dynamic penetration test

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ABSTRACT: Dynamic penetration test is one of the most frequent field tests used during ground investigation, therefore it is important to correctly define the correlations used for determining of various geotechnical parameters. According to correlations between the test results and soil properties, it is possible to define characteristic values of geotechnical parameters required for geotechnical design. Characteristic values of geotechnical parameters should come from the results and derived values of the considered field test and moreover, it should be complemented by verifiable comparable experience. This article presents and compares correlations from Slovakia and other countries, which are used for specification of following geotechnical parameters: relative density I_D, angle of internal friction φ_{ef}. Mentioned geotechnical parameters directly affect the geotechnical design and are used in everyday practice.

Keywords: dynamic penetration test, coarse-grained soil, relative density, angle of shear strength

1. Introduction

Field testing is one of the methods used for design of geotechnical structures. Results of various field tests can be used for determining of the characteristic values of geotechnical parameters, which directly used in the design. The most commonly used in situ tests are standard penetration test, cone penetration test, vane test, pressuremeter test and dilatometer test [13]. The most frequent field test used in ground investigation in Slovakia in addition to dilatometers, pressuremeters and static penetration is the dynamic penetration.

The Dynamic Penetration Test (DP) is a field test that is used particularly for coarse grained soil and soft rock resistance testing. The resistance of soil and soft rock is tested against the dynamic penetration of the rod ended with a conical tip. A hammer of different weights and with different drop height is used for rod penetration [1]. Considering hammer parameters, Eurocode 7-2 [1] divides DP into four categories: DPL (light), DPM (medium), DPH (heavy) and DPSH (super heavy). During the test, the number of blows N_{10}, N_{20}, required for rod to penetrate specific depth, is recorded. Dynamic penetration resistance q_{dyn}, representing soil resistance, can be estimated from the measured N_{10}, N_{20} values. Eurocode 7-2 [1] also states that these results should be mainly used for profile analysis, which should be accompanied by borehole sampling. Selected geotechnical parameters of soils can be determined from the results of DP as well. For determination of geotechnical parameters, it is necessary to know the correlations between the results of DP and the required soil parameter. Following geotechnical parameters can be derived for coarse-graind soil: the relative density I_D, deformation modulus E_{def}, E_{oed}, dry density ρ and angle of shear strength φ_{ef}.

Foreign and Slovak scientific literature mention several correlations between various types of DP and specific geotechnical paramaters. According to Hawrysz, M. and Strózyk, J [9], due to inaccuraces, additional difficulties are often introduced into the interpretation of existing correlations. Therefore, the existing correlations should be tested and adjusted for application in local geological conditions.

Researches concerning the applicability of the DP correlations were provided for example in the UK by Langton et al. [11] or in Germany by Vrettos and Papamichael [8]. Langton et al. [11] used the lightweight dynamic penetrometer to clarify the usefulness and reliability of the selected correlations in their research. Vrettos and Papamichael [8] compared correlations for various penetration tests without considering overburden stress for the interpretation of the test. Vrettos and Papamichael suggested that the applicable correlations from standards should be homogenized with regard to the level of detail in the evaluation and adjusted to the international state of knowledge [8].

In some european countries, the correlations for DP are given in national standards (e.g. DIN 4094-3 [2], EN 1997-2 [1], PN-B-04552 [5]). In Slovakia, various correlations published by Švasta [4], Obert [4] and recommended in the Slovak standard STN 72 1032 [3] are used to derive various geotechnical parameters from the results of DP.

The empirical formula given in EN 1997-2 [1] and PN-B-04552 [5] specifies relative density of sand and gravel from the results of N_{10}. The correlations coefficients in the formula are determined separately for DPL and DPH (according to EN 1997-2) and DPL, DPM and DPSH (according to PN-B-04552). These correlations distinguish the following types of soil: sand above GWL with $Cu \leq 3$, sand below GWL with $Cu \leq 3$, sand-gravel over HPV with $Cu \geq 6$).

On the other hand, STN 72 1032 [3] and Obert [4] suggest presumed values for a certain range of N_{10} or q_{dyn}, based on which the relative density can be determined. Švasta [4] derived an empirical formula for relative density and the angle of shear strength φ_{ef} from the results of dynamic penetration resistance q_{dyn}, which considers different types of sand and gravel.

The Slovak standard STN 72 1032 [3] published the derivation of angle of the shear strength from the results of the N_{10}. Eurocode 7-2 [1], Mohammadi et al. [15], Meyerhof [in 15] and the US Navy [in 16] derive φ_{ef} from relative density. Eurocode 7-2 [1] presents the determination of φ_{ef} for coarse-grained soils from the specific range of relative density. Meyerhof [15] introduced the correlation for φ_{ef} of normally consolidated sand. Mohammadi et al. [15] suggested similar correlation for sands during the research of DP use for estimating engineering properties of sandy soils. The US Navy suggested correlations between the φ_{ef} and relative density for sands considering the particle size and genesis of the soil [16].Another relation between the relative density and the angle of shear strength is suggested in British standard BS 8002 [7], also interpreted in [6], which expresses the determination of peak and the critical angle of shear resistance for siliceous sands and gravels.

The main aim of this study is to summarize and analyze correlations for selected geotechnical parameters of coarse-grained soils derived from DP results. The evaluation of I_D, φ_{ef} for gravel soil, using selected correlations, is presented in the article. The DP results, from which the soil parameters were derived, were measured during the experimental project focused on soil-structure interaction. Part of this task was to build an experimental field with gravelly soil. During the experiment, the soil was tested by DPM. Geotechnical parameters I_D and φ_{ef} were analyzed from measured results.

2. Test and soil description

Correlations described in this paper were used to evaluate I_D and φ_{ef} of coarse-grained soil from the results of DPM. Derived parameters of I_D and φ_{ef} were compared with laboratory test results.

Dimensions of the experimental field, where the DPM test was executed, were 0.9 m × 8.0 m × 1.8 m. The soil in the field was compacted in 0.3m layers by the vibration plate.

Tested soil was classified as well-graded gravel (class G1, symbol GW). The fluvial soil comes from the locality of Danube river basin and the diameter of the biggest grains does not exceed 30 mm.

Characteristics of well graded gravel were tested by medium dynamic penetration test with the following parameters:

- Tip diameter 43,7 mm
- Angle of conical tip 90 °
- Cross-sectional area 15 cm^2
- Rod diameter 32 mm
- Rod length 1 m
- Hammer weight 0,3 kN
- Hammer drop height 50 cm
- Number of blows 30 / min

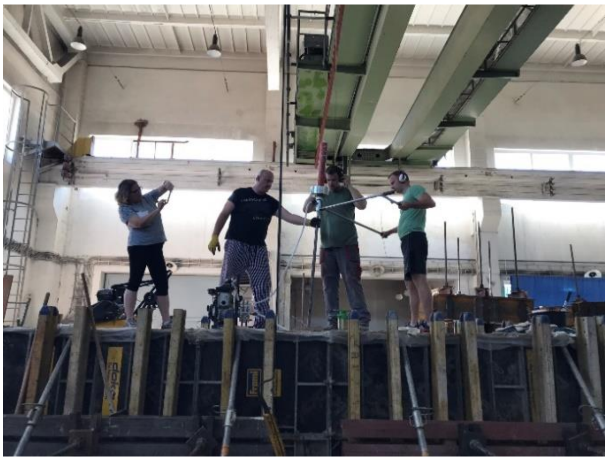

Figure 1. Dynamic penetration test execution

The results of number of blows N_{10} and dynamic penetration resistance q_{dyn} (Table 1) were taken in the consideration during the evaluation process of soil geotechnical parameters. Dynamic penetration resistance was calculated from the N_{10} results as shown in equation 1.

Determination of dynamic penetration resistance:

$$q_{dyn} = \frac{M^2 * H * N}{A * e * (M + P)} \qquad (1)$$

where
q_{dyn} dynamic penetration resistance (MPa);
M hammer weight (kN);
H hammer drop height (m);
P penetrometer weight (kN), /tip, rods, anvil/;
A cross-sectional area of the tip (m^2);
N number of blows necessary for penetration e;
e tip penetration of 0.10 or 0.20 m.

In laboratory a large scale shear box was used to evaluate angle of shear strength φ_{ef} of tested soil. Large scale shear box device has dimensions 300 × 300 mm, therefore it is suitable for testing the soil containing larger particles. The recommended size of the soil particles, appropriate for large scale shear box, is up to 30 mm. Since the dimensions of the box are much larger than the biggest soil particle of tested soil, it provides more reliable results even for gravelly soils than the standard shear box test.

3. Analysis of selected soil geotechnical parameter from results of DPM testing

Two dynamic penetration tests (DPM 1 and DPM 2) were carried out during the experiment. Each test was executed in different area of the experimental field. The average results of both DPM tests are shown in Table 1.

No skin friction and no underground water was measured during the dynamic penetration, so the results of N_{10} were put into analysis without any further modification. If the friction is measured, there are some correlations suggested in DIN 4094-3 [2], which need to be considered for modification of N. Beside the correlations, there is also an alternative way of reducing the skin friction on the rod, which is described by Abuel-Naga at al. [14]. The influence of the underground water can be taken into account by applying the formulas described in the standard EN ISO 22476-2 [12].

Table 1. Results of DPM

Test	N_{10} (-)	q_{dyn} (MPa)
DPM 1	5.4	3.8
DPM 2	5.6	4.2

3.1. Relative density

Relative density of tested soil was derived from presumed values published by Obert [4] and STN 72 1032 [3] and by applying empirical formulas recommended by Švasta [4] and standard EN 1997-2 [1].

3.1.1. Presumed values

Table 2 summarizes relations between dynamic penetration resistance and relative density for sands and gravels described by Obert [4] and Slovak standard STN 72 1032 [3].

Table 2. Relative density I_D of coarse-grained soils

Relative density I_D		Range of validity	
		Poorly graded gravel (Obert)	Sands STN 72 1032
Loose	< 0.33	q_{dyn} (<4.0)	q_{dyn} (<2.8)
Medium dense	0.33 – 0.66	q_d (4.0 – 14.0)	q_d (2.8 – 10.0)
Dense	> 0.66	q_d (> 14.0)	q_d (> 10.0)

Standard STN 72 1032 [3] points out relative density for alluvial gravels (Table 3) based on the results of dynamic penetration resistance.

Table 3. Relative density of alluvial gravels (STN 72 1032)

Relative density I_D	q_{dyn} (MPa)
Loose	≤ 8.5
Medium dense	8.5 to 21.5
Dense	≥ 21.5

Table 4 shows relative density of coarse-grained soils derived from number of blows N_{10}. This table describes general classification specified by Obert [4].

Table 4. I_D of coarse-grained soils published by Obert [4]

Relative density I_D	Soil type and validity range for N_{10}	
	Sands	Gravels
Loose	$N_{10} \leq 3{,}0$	$N_{10} \leq 4{,}0$
Medium dense	$3 \leq N_{10} < 15$	$4 \leq N_{10} < 15$
Dense	$N_{10} \geq 15$	

3.1.2. Empirical formulas

Another way to determine relative density is to calculate I_D from empirical formula. The following formulas, published by Švasta, EN 1997-2 [1] and PN-B-04552: 2002 [5], were used for the calculation.

The empirical relation (equation 2) described by Švasta [4] takes into account the composition of soil types through dimensionless parameters a, b. The values of dimensionless parameters a, b for individual types of coarse-grained soils are given in Table 5.

$$I_D = a * (q_d)^b \tag{2}$$

Table 5. Dimensionless parameters a, b entering equation (2)

Soil type		a	b
Sand	Silty, clayey	0,16	0,7
	fine	0,15	0,67
	Medium and coarse-grained	0,14	0,63
Gravelly soils, Sandy gravels		0,13	0,6

The second empirical relation for I_D (equation 3) is given in EN 1997-2 [1]. This relation is derived directly from number of blows N_{10}. As can be seen in Table 6, in addition to the soil type, the groundwater level and the type of penetration test are taken into consideration. Based on these considerations, parameters C_1 and C_2 are subsequently derived. The range of validity for the equation 3 is $3 \leq N_{10} \leq 50$.

$$I_D = C_1 + C_2 * \log N \tag{3}$$

Table 6. Dimensionless parameters C_1, C_2 entering equation 3 (EN 1997-2)

DPT type	Sands above GWL (Cu ≤ 3)		Sands below GWL (Cu ≤ 3)		Sands – gravels above GWL (Cu ≥ 6)	
	C_1	C_2	C_1	C_2	C_1	C_2
DPL	0,15	0,26	0,21	0,23		
DPH	0,10	0,435	0,23	0,38	-0,14	0,55

Poland standard PN-B-04452:2002 [5] suggests, in principle, the same correlation (equation 3) like EN 1997-2 [1]. The difference between the Eurocode 7-2 and Poland correlation is the type of dynamic penetrometer for which the correlation was derived. Poland correlation takes into account the number of blows N_{10} of DPL, DPM and DPSH, therefore the correlations coefficients (Table 7) are different. Poland correlation is determined for the sand above and below ground water with validity range $3 \leq N_{10} \leq 60$.

Table 7. Dimensionless parameters C_1, C_2 entering equation 3 (PN-B-04452:2002)

DPT type	Sands above GWL (Cu ≤ 3)		Sands below GWL (Cu ≤ 3)	
	C_1	C_2	C_1	C_2
DPL	0,15	0,26	0,21	0,23
DPM	0,176	0,431	-	-
DPSH	0,196	0,441	-	-

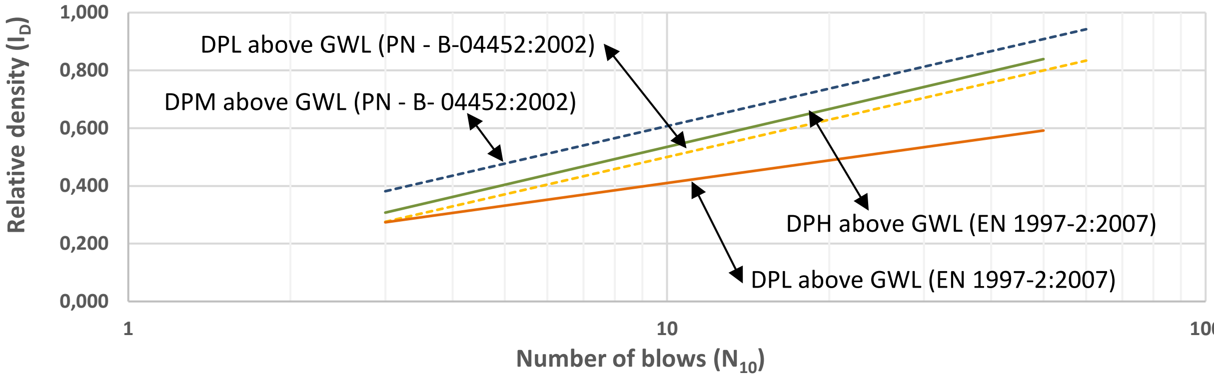

Figure 2. Correlations between N_{10} and I_D published in EN 1997-2:2007 and PN–B–04452:2002

Figure 2 reviews the correlations for I_D derived from (DPL, DPM, DPH) that are mentioned in both EN 1997-2 [1] and PN-B-04452: 2002 [5].

3.1.3. Derived values of relative density

In Table 8, the results of N_{10} (Table 1) are compared with the presumed values evaluated by Obert (Table 4). Based on this comparison, the tested soil can be classified as medium dense.

Table 8. Relative density derived from presumed values for N_{10}

Correlation (Obert)		Test results		Conclusion
		Test	N_{10}	I_D
$N_{10} \leq 4,0$	**Loose**			
$4 \leq N_{10} < 15$	**Medium dense**	DPM 1	***5.4***	***Medium dense***
$N_{10} \geq 15$	**Dense**	DPM 2	***5.6***	

Table 9 relates the results of dynamic penetration resistance (showed in Table 1) with presumed values for I_D, published in STN 72 1032 (Table 3). The comparison shows that the soil should be rather loose than medium dense.

Table 9. Relative density derived from presumed values for q_{dyn}

Correlation (Obert)		Test results		Conclusion
		Test	q_{dyn}	I_D
≤ 8.5	**Loose**			
8.5 to 21.5	**Medium dense**	DPM 1	***3.8***	***Loose***
≥ 21.5	**Dense**	DPM 2	***4.2***	

The results of the relative density calculated by the equation 2 and equation 3 are shown in Table 10. Based on the values derived from equation 2 and equation 3, the soil can be classified as loose. Applying the equation 3 determined directly for DPM, from the Poland standard, the soil can be classified as medium dense.

Table 10. Relative density derived from empirical formulas

Correlations		I_D results		*Relative density*
		DPM 1	**DPM 2**	
Švasta	$I_D = a * (q_d)^b$	*0.29*	*0.31*	***Loose***
EN 1997-2:2007	$I_D = C_1 + C_2 * \log N$	*0.23*	*0.27*	***Loose***
PN–B–04452:2002		*0.47*	*0.49*	***Medium dense***

3.1.4. Results discussion

According to the correlations based on N_{10} used in Slovakia (see Table 8), the tested soil is characterized as medium dense. If we use the results of q_{dyn} [3,4] (see Table 9,10) to evaluate the I_D, the soil is characterized as loose.

Based on the correlations given in the European standard, which are based on N_{10} (see table 9), the soil is classified as loose. Using a Poland standard, which takes into account the DPM results (see Table 9), soil can be described as medium dense.

Slovak and EU correlations were derived for DPH test. Only Obert [4] and STN [3] take into account the type of penetration test when calculating q_{dyn} (see equation 1). The correlations for I_D in the Poland standard were derived directly for DPM.

As can be deduced from the comparison in figure 2 as well as from the results of our experiments (see Table 10), for the same number of blows for DPT, the I_D is significantly higher when using correlations from the Poland standard [5] than in the informative annex G of EN 1997-2 [1].

3.2. Angle of shear strength

Angle of shear strength φ_{ef} was derived from DPM test by using presumed values and empirical formulas. Coarse-grained soil was simultaneously tested in large scale direct shear box test.

3.2.1. Presumed values

STN 72 1032 [3] presents recommended values of angle of shear strength for gravels (Table 11), determined for the specific ranges of N_{10} results from heavy dynamic penetration (DPH). The intermediate values can be specified by simple interpolation.

Table 11. Angle of shear strength for gravels [3]

N_{10}	Angle of shear strength φ_{ef} (°)
< 3	< 30
3 - 6	30 - 35
6 - 17	35 - 40
17 - 30	40 - 45
> 30	> 40

Eurocode 7-2 [1] presents an example of deriving the angle of shear strength for coarse-grained soils (Table 12) directly from the values of relative density I_D.

Table 12. Effective angle of shear strength (φ_{ef}) of coarse soil derived from density index (I_D) and the uniformity coefficient (C_u) [1]

Soil type - Grading	I_D (%)		φ_{ef} (°)
Slightly fine-grained sand, sand, sand gravels Poorly graded (C_u <6)	15 – 35	loose	30
	35 – 65	medium dense	32,5
	> 65	dense	35
Sand, sand gravel, gravel Well-graded (6 < CU < 15)	15 – 35	loose	30
	35 – 65	medium dense	34
	> 65	dense	38

3.2.2. Empirical formulas

Švasta's empirical formula [4] (equation 4), which was derived from q_{dyn} results, was used to calculate the angle of shear strength φ_{ef}. The parameters p and r, whose values for coarse-grained soils are given in Table 13, enter this relation.

$$\varphi_{ef} = p * (q_d)^r \quad (4)$$

Table 13. Parameters p,r entering equation 4

Soil	p	r
Fine-grained sand	24	0.16
Gravels		

According to British standard BS 8002 [7], the angle of shear strength can be derived indirectly from the results of in situ dynamic penetration test. The standard suggests two formulas (equations 4 and 5) to conservatively estimate the peak and critical angle of shear strength for siliceous sands and gravels.

The peak effective angle of shear strength φ'_{max} is expressed as

$$\varphi'_{max} = 30° + A + B + C \quad (5)$$

The critical effective angle of shear resistance is given by

$$\varphi'_{crit} = 30° + A + B \quad (6)$$

The values A, B and C and are described in Table 14. A stands for angularity, B for grading of the soil and C for results N (number of blows) of dynamic penetration tests. Angularity is determined by visual test and grading of soil is suggested to be determined from the grading curve, according to uniformity coefficient $C_u = D_{60}/D_{10}$ [7].

Table 14. Parameters A, B and C entering equation 5,6 to estimate angle of shear strength for siliceous sands and gravels (BS 8002)

Angularity	A (°)	Grading of soil	B (°)	Number of blows (N)	C (°)
Rounded	0	Uniform	0	< 10	0
Sub-angular	2	Moderate	2	20	2
Angular	4	Well graded	4	40	6
				60	9

3.2.3. Determination and comparison of φ_{ef} from laboratory and field test

The angle of shear strength results derived for the gravelly soil, tested in a large-scale shear box apparatus, are shown in Figure 3. The shear strength angle is 42.8 °. The relative density is I_D = 0.60.

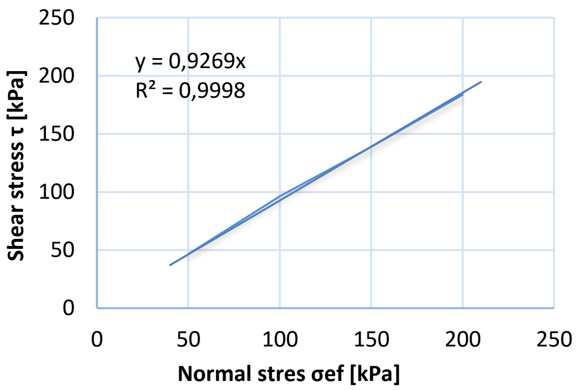

Figure 3. Correlations between N_{10} and I_D published in EN 1997-2:2007 and PN – B – 04452:2002

Table 15 shows the results of φ_{ef} determined by Švasta's empirical formula (equation 4) from the values of dynamic penetration resistance.

Table 15. Angle of shear strength derived from q_{dyn}

Test results		Correlation	φ_{ef} (°)
Test	q_{dyn} **(MPa)**	**Švasta**	
DPM 1	*3.8*	$\varphi_{ef} = p * (q_d)^r$	***28.4***
DPM 2	*4.2*		***30.1***

Table 16 presents the results N_{10}, which were used for determinating φ_{ef}, based on the correlation recommended by Slovak standard STN 72 1032. The results of angle of shear strength were obtained from the interpolation of the values listed in Table 11.

Table 16. Angle of shear strength derived from N_{10}

Test results		Correlations (STN 72 1032)		φ_{ef} (°)
Test	N_{10}	N_{10}	φ_{ef} (°)	
DPM 1	*5.4*	3 - 6	30 - 35	***33.9***
DPM 2	*5.6*			***34.4***

Table 17 shows derivation of φ_{ef} directly from soil relative density. In this case results of relative density, listed in Table 10, were compared with presumed values of φ_{ef} recommended by Eurocode 7-2 (Table 12).

Table 17. Angle of shear strength derived from I_D

Correlation (EN 1997-2:2007) for well – graded gravel			I_D results		Angle of shear strength
I_D (%)		φ_{ef}	DPM 1	DPM 1	
15 – 35	loose	**30**	*0.29*	*0.31*	***30***
35 – 65	medium dense	**34**	*0.23*	*0.27*	***30***
> 65	dense	**38**	*0.47*	*0.49*	***34***

According to BS 8002 [6], the angle of shear resistance is 34° for rounded, well graded soil where N_{10} from DPT is less than 10 (see Table 1).

The angle of shear strength, determined by various correlations, ranges from 28.4° to 34.4° (see Table 15,16). The laboratory value is 42.8°. However, this value is set for a higher I_D than that for field tests. In general, the laboratory determined values for geotechnical parameters of soils and rocks are higher than field values.

Values according to STN, EN and empirical formula used in the UK give the same result, i. e. $\varphi_{ef} = 34$ °.

4. Conclusion

DP is one of the most frequent field tests used in engineering geological investigation. Therefore, it is important to correctly define the correlations used for determining various geotechnical parameters. According to correlations between the test results and soil properties it is possible to define characteristic values of geotechnical parameters required for geotechnical design.

Our analysis was focused on the correlation comparison between soil properties and different types of dynamic penetration test (DPL, DPM and DPH).

Despite the fact that there exist various types of dynamic penetration, most of the correlations were derived for DPH. There exists some correlations for DPM, but they are limited. Only available source that mentions correlation between I_D and DPM is Poland standard.

As DPM test is more and more used it is necessary to analyze correlations between the soil geotechnical parameters and medium dynamic penetration test.

Based on derived values of I_D from our experiments and from analysis of accessible correlations presented in European, Slovak and Poland standard, it is clear that I_D determined by correlation from Poland standard is notably higher than that derived from European or Slovak standard.

Comparison of angle of shear strength φ_{ef} confirms, that laboratory and field test results do not differ so much as the results for I_D.

Acknowledgements

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5. References

[1] EN 1997-2:2007: Eurocode 7. Geotechnical design. Part 2: Ground investigation and testing.

[2] DIN 4094-3:2002: Subsoil. Field testing. Part – 3: Dynamic probing.

[3] STN 72 1032:1997: Dynamic penetration test (in [Slovak]).

[4] Matys, M., Ťavoda, O., Cuninka, M. "Poľné skúšky zemín" (Soil field tests), Alfa, Bratislava, Slovakia, 1990, pp. (in [Slovak]).

[5] PN-B-04552:2002: Geotechnika - Badania polowe. (Geotechnics. Field investigation.) (in [Polish])

[6] Bond, A., Harris, A. "Decoding Eurocode 7". 1st ed. Taylor & Francis. London. England. 2008.

[7] BS 8002:1994: Code of practice for earth retaining structures

[8] Vrettos, C., Papamichael, S.: Relative density of cohesionless soils from dynamic probe and cone penetration test. An update assessment of empirical relationships. *Geotechnik* 41 (2018). pp. 186-196

[9] Hawrysz, M., Strózyk, J.: Kontrowersyjna interpretacja wyników sondowań dynamicznych w praktyce inżynierskiej. 2015. Inżynieria morska i Geotechnika

[10] Spagnoli, G., An empirical correlations between different dynamic penetrometers, 2007 Electron J Geotech Eng 12 (Bundle C)

[11] Langton, D.: The Panda lightweight penetrometer for soil investigation and monitoring material compaction. 1999. Ground Engineering. pp. 33– 37

[12] EN ISO 22476-2: Geotechnical investigation and testing - Field testing - Part 2: Dynamic probing

[13] Schnaid, F.: In Situ Testing in Geomechanics, The main tests. London, New York: Taylor & Francis. 2009. 328 p. ISBN 0-203-93133-5

[14] Abuel-Naga, H.M., Holtrige, M., Pender, M. J.: Simple method for correcting dynamic cone penetration test results for rod friction. 2011. Geotéchnique Letters 1. pp. 37-40

[15] Mohammadi, S.D., Nikoudel, M.R., Rahimi, H., Khamehchiyan, M.: Application of the dynamic cone penetrometer (DCP) for determination of the engineering parameters of sandy soils. 2008. Engineering Geology 101 (2008). pp.195-203

[16] Bentley, S.P., Carter, M. Soil Properties and their correlations. 2nd ed. John Wiley & Sons, Ltd. Chichester. United Kingdom. 2016