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THE ANGLE OF THE SHEAR RESISTANCE OF DANUBE GRAVEL DERIVED FROM THE DYNAMIC PENETRATION TEST

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Abstract

The dynamic penetration test was used to investigate the angle of shear strength of Danube gravel. The correlations for its determination are available in the standards and literature. From the data set of the results, the characteristic value of the angles of shear strength was derived according to the recommended statistical procedure from the second generation of Eurocode 7. The characteristic values of the angle of shear strength were evaluated for well-graded gravels, poor-graded gravels, and gravels with fine-grained particles of the Danube. The correlations, which were based on field tests and considered the genesis of the soil, were compared with laboratory test results and a table of the values from the Slovak standard, which are used for purposes of comparison.

In our research we compared the characteristic field values of the angle of shear strength obtained in the laboratory to observe the effect of their genesis on the appropriateness of the correlations used. We conclude with recommendations for the regional correlations and suggest values of the angle of shear strength for the classes of gravels tested.

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Key words

- Characteristic value,
- Angle of shear strength,
- Danube gravel,
- Dynamic penetration test.

1 INTRODUCTION

Dynamic penetration (DP) belongs among widely used in situ soil tests in geotechnical engineering. Together with the standard penetration test (SPT), it belongs to the category of penetration tests that are driven into the soil by dynamic force. The two tests, along with the cone penetration test (CPT), measure the resistance of soil against the penetration of a rod. In Slovak geotechnical practice, heavy dynamic penetration is widely used in engineering-geological surveys of coarse-grained soils.

It is possible to derive specific geotechnical parameters of coarse-grained soils using the appropriate correlations for test results. These correlations have international and local (Slovak) significance. Correlations applicable internationally are published in various standards (STN EN 1997-2:2008, DIN 4094-3:2002, EN ISO 22476-2, PN-B-04552:2002, STN 72 1032: 1997), which mainly focus on correlations for relative density (I_D). These correlations are direct, which means that they express a direct relation between the results of DP and the relative density of coarse-grained soil. The applicability of these correlations was studied by Vrettos and Papamichael (2018), who concluded that correlations are most reliable when evaluating the relative density of medium-dense soils.

The standards also mention an indirect correlation for the angle of shear strength, which is specifically based on the relative density of the soil, but not directly based on the DP results. Vrettos and Papamichael (2018) have stated that the use of this

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correlation brings about uncertainties and instead recommend the use of direct correlations.

The correlations between the relative density and angle of shear strength of coarse-grained soils have also been described by other authors (Schnaid, 2009; Carter, Bentley, 2016; Sanglerat, 1972, Bolton, 1979; Robertson, and Hughes 1986). These correlations were derived from the number of N_{SPT} blows of the Standard Penetration Test. Lobo et al. (2009) expressed the relationship between SPT and φ_{ef} as dependent on the soil's stiffness, which is thus applicable in a constant N profile and has yet to be verified for a general procedure. Hatanaka and Uchida (1997) investigated the φ_{ef} of sands using laboratory tests, which were compared with the results of SPT tests. They derived a correlation from the comparison between N_{SPT} and φ_{ef} of sands with a validity range of 3.5–30 N_{SPT}.

Other direct correlations between the results of the DP test and selected soil parameters are used in Slovakia (Matys et al., 1990). These correlations are derived from the results of dynamic penetration resistance – q_{dyn} [MPa], which considers the effect of the groundwater level, friction on the rod, and the increasing weight of the probe with increasing depth. Most of the published correlations state a limitation of applicability based on the soil class. However, a few correlations also specify the genesis of the soil.

From the results of the geotechnical parameters, it is necessary to derive the representative value that is essential for the design of geotechnical structures. According to the second generation of Eurocode 7 (EN 1997-1:2024), the representa-tive value can be represented by the nominal or characteristic value. The procedure for the determination of the characteristic value was mentioned in the previous generation of EC 7 (EN 1997-1:2005), which has been discussed by various authors. Orr (2019) stated that in addition to a statistical evaluation, previous comparable experiences should also be considered in an evaluation of the characteristic value. Prästings et al. (2019) said that the classical statistical procedure of confidence intervals does not consider the uncertainties of geotechnical properties. Schneider (2010) and Frankovská (2016) investigated the applicability of the determination procedure of the characteristic value published in Eurocode 7 (EN 1997-1:2005). The authors pointed out that rock and soil properties are quantitatively described by one parameter, i.e., the characteristic value, the definition of which was not clear in EC 7. They stated that it is not possible to follow the same statistical rules as for man-made materials, and it is necessary to know the basic statistical characteristics of the data set.

The new generation of EC 7 (EN 1997-1:2024) describes the procedure for an evaluation of the characteristic value considering the basic statistical characteristics such as the mean, standard deviation, or coefficient of variation. In this article, the method from the second generation of EC 7 has been applied to derive the characteristic value of the angle of shear strength for Danube gravel, which was derived from the results of dynamic penetration tests.

To study the appropriateness of the correlations used with respect to genesis, the results of the angle of shear strength were compared with the laboratory results, other correlations, and the table (nominal) values from canceled Slovak standard (STN 73 1001:1987), which are still used as a comparable experience.

2 MATERIALS AND METHODOLOGY

The Dynamic Penetration Test was used for the examination of Danube gravels as a part of engineering-geological investigations conducted in various parts of Bratislava. The locality belongs to a geotectonic unit that is mostly formed by Neogene and Quaternary soils. Quaternary soils are present in the form of the sand-gravel sediments of the Danube River.

In this region, the river has predominantly accumulative and sedimentary activity, which has affected the shape and properties of river gravels and sands. Due to the river's activity, the gravels are characterized by their smooth and fine particles (Fig. 1), which are well-rounded and 1 – 5 centimeters in size.

In our research we focused on analyzing the angle of shear strength of the Danube gravels G1/GW, G2/GP, and G3/GW, which are the most representative gravel classes in the area. The well-graded G1/GW gravels contain 63 – 76 % of gravel particles and grading of the particles at d_{50} varies from 5 to 10 millimeters (Fig. 2).



Fig. 1 *Samples of Danube gravels*

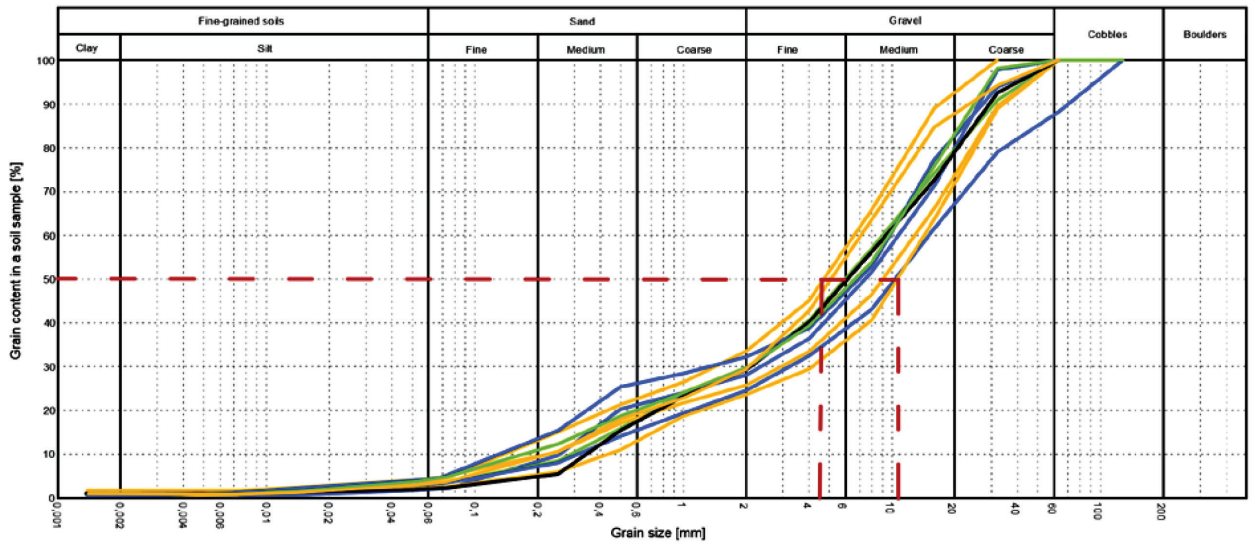


Fig. 2 *Grain size distribution of well-graded gravels (G1/GW)*

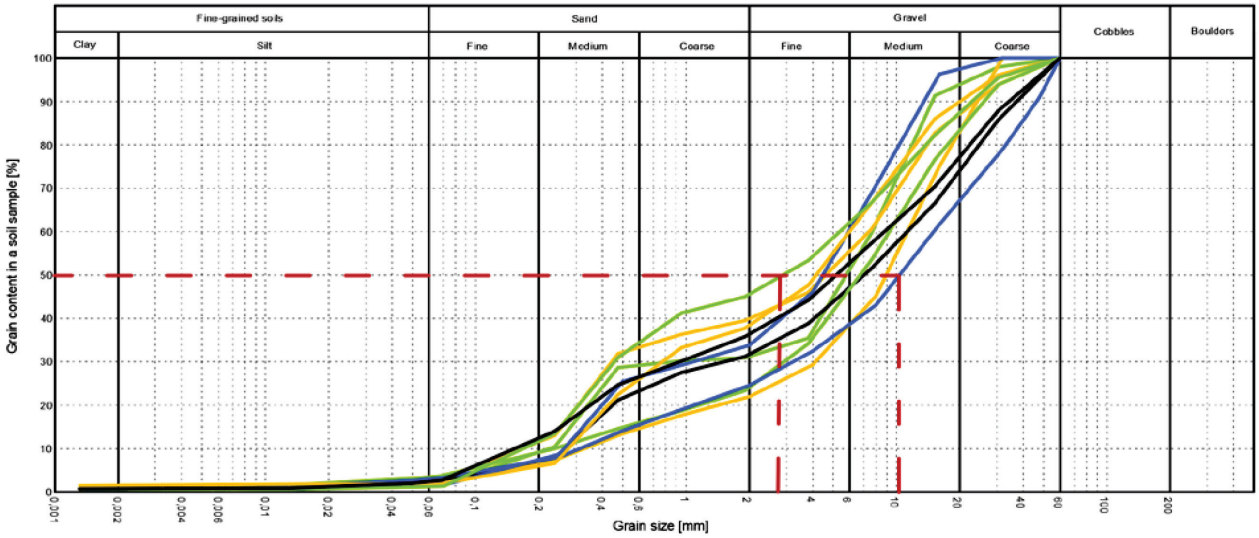


Fig. 3 *Grain size distribution of poorly-graded gravels (G2/GP)*

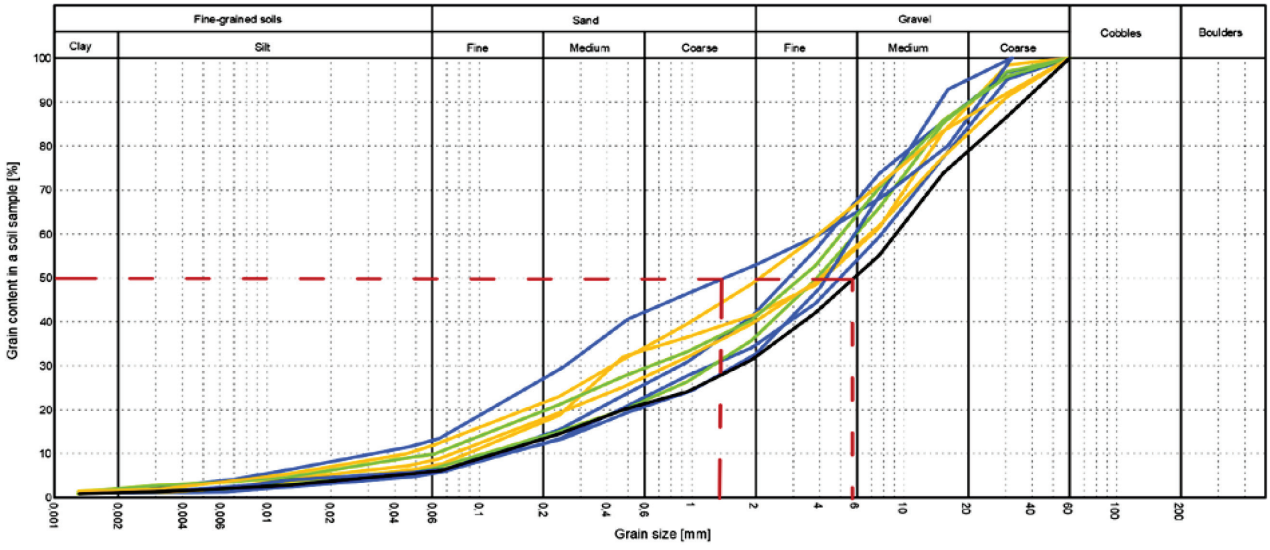


Fig. 4 *Grain size distribution of gravels with fine-grained soil (G3/G-F)*

Poorly-graded gravels contain about 54 – 77% of gravel fractions, and the grading of the particles at d_{50} is from 3 to 10 millimeters (Fig. 3). The content of the gravel fraction in gravels with fine-grained particles (G3/G-F) varies from 45 – 70%. The grading of the particles at d_{50} is 1.5 – 6 millimeters (Fig. 4).

2.1 Determination of the angle of shear strength from field tests

The angle of the shear strength of the Danube gravels was derived using various correlations (Tab. 1, eq. 1). According to Švasta and Obert (Matys et al., 1990), the correlations express a direct relation between the soil property and the results of the dynamic penetration test (N, q_{dyn}). Other correlations published in standards (EN 1997-2:2008) and non-Slovak literature (Bolton, 1979; Robertson and Hughes, 1986) estimate the angle of shear strength based on the relative density of the coarse-grained soils. Eurocode 7 (EN 1997-2:2008) presents correlations that are directly applicable to the dynamic penetration test results. Bolton (1979) and Robertson and Hughes (1986) describe the correlation valid for the Standard Penetration Test (SPT). Using the relation between SPT and DPT published by Carter and Bentley (2016), the correlation for SPT can be applied to the DPT as well. Carter and Bentley determined that N_{SPT} (blows/ 300 mm) is approximately equal to 2× N_{DPH} (blows/ 100 mm). However, the correlation can be used for all the variations of the DPT test as the authors expressed the general formula for recalculating N_{SPT} to N_{DPT}, considering the parameters and depth of penetration of the probe.

The British standard (BS 8002:1994) describes the correlation that expresses the relation between the angle of shear strength and the results of blows – N, taking into consideration the shape of the particles and grading of the coarse-grained soils. In general, the correlation is applicable to all classes of gravels or sands and was established based on a comparison.

$$\varphi = 30° + \begin{Bmatrix} 0 - \mathrm{R} \\ 2 - \mathrm{SA} \\ 4 - \mathrm{A} \end{Bmatrix} + \begin{Bmatrix} 0 - \mathrm{U} \\ 2 - \mathrm{MG} \\ 4 - \mathrm{WG} \end{Bmatrix} + \begin{Bmatrix} 0 - \mathrm{N} < 10 \\ 2 - \mathrm{N} = 20 \\ 6 - \mathrm{N} = 40 \\ 9 - \mathrm{N} = 60 \end{Bmatrix} \quad (1)$$

Key:

R – round
SA – sub-angular
A – angular
U – uniformly graded.
MG – moderately graded.
WG – well graded.

2.2 Laboratory determination of the angle of shear strength

The large-scale shear box test was used to verify the shear parameters (φ_{ef}) of the gravel samples, i.e., dense gravels of class G1, G2, and G3. A series of tests on a large-scale Shearmatic 300 shear box test was carried out in the laboratory of the Department of Geotechnics. Due to the dimensions of the shear plane, i.e., 300x300 mm, it is suitable for testing coarse-grained soils with grains up to 15 mm in size. The tests were performed in accordance with STN EN ISO 17892-10:2018.

Each test consisted of a series of 3 to 4 shearings, each performed with a different effective normal stress σ_{eff}. The velocity of the shearing was set up at 1 mm/min.

Tab. 1 *Correlations between the DPT and angle of shear strength of coarse-grained soils*

Author	**Soil**	φ_{ef} **derived from** N_{10}	
		N_{10}	φ_{ef} (°)
STN 72 1032	Gravels	< 3	< 30
		3 – 6	30 – 35
		6 – 17	35 – 40
		17 – 30	40 – 45
		> 30	> 45
Švasta	**Correlation**	**Coefficients**	
	[°]	*p*	24
		r	0,16
EN 1997-2:2008	**Soil**	φ_{ef} (°) derived from I_D	
		Loose	***Medium dense***	***Dense***
	Fine-grained sand/ sand, and gravel (C_u <6)	30	32.5	35
	Sand and gravel (6 < *C*U < 15)	30	34	38
Bolton (1979)	Well-graded sand or gravel	-	-	55[1]/35[2]
Robertson and Hughes (1986)		-	-	40

Note: [1] Peak angle of shear strength [2] Angle of shear strength at critical state

2.3 Representative value of the geotechnical parameters

The determination of the representative value of geotechnical parameters is an important step in the design of geotechnical parameters. According to the new generation of Eurocode 7 (EN 1997-1:2024), the representative value can be expressed as a nominal, conservative estimate of the value affecting the limit state or characteristic value. In our research, we used the characteristic value of the angle of shear strength of the Danube gravels as a representative value.

The characteristic value (X_k) is defined as a value affecting the limit states that corresponds to a specific quartile of the assumed statistical distribution of a specific soil property. In the second generation of Eurocode 7, there is a given formula (eq. 2) for the calculation of the characteristic value:

$$X_k = X_{mean}[1 \mp k_n V_x] = X_{mean}\left[\frac{1 \mp k_n \sigma_x}{X_{mean}}\right] \quad (2)$$

where

- X_{mean} average of the measured values of the soil property.
- V_x coefficient of the variation of the measured values of the soil property.
- k_n coefficient depending on the frequency of the measured values (n) of the soil property.
- σ_x standard deviation of the measured values of the soil property.

The procedure for the evaluation of the characteristic value is suitable for known/ assumed and unknown coefficients of the variation. According to the case of V_x, there are formulas given for the evaluation of coefficient k_n (Tab. 2), which depend on two distribution functions – normal and Student´s t distribution function.

Coefficient N_{95} (in Tab. 2) stands for a 95% confidence level and infinite degrees of freedom regarding the normal distribution. Coefficient $t_{95,n-1}$ is evaluated for a 95% confidence level and n-1 degrees of freedom regarding the Student´s t distribution, n being the number of samples used for an evaluation of X_{mean}.

Tab. 2 *Determination of coefficient k_n with respect to the type of the coefficient of the variation*

Cases	Known & assumed V_x	Unknown V_x
Estimate of the mean value	$k_n = N_{95}\sqrt{\frac{1}{n}}$	$k_n = t_{95,n-1}\sqrt{\frac{1}{n}}$
Estimate of the inferior or superior value (5 or 95% quartile)	$k_n = N_{95}\sqrt{1+\frac{1}{n}}$	$k_n = t_{95,n-1}\sqrt{1+\frac{1}{n}}$

The aim of our research was to determine the critical value of the selected soil properties. Therefore, we evaluated the characteristic value as the lower quartile of the corresponding statistical distribution. The coefficient of variation was not previously specified. It was evaluated during the statistical analysis, and the equation for the evaluation of coefficient k_n was chosen accordingly, based on the Student´s t distributional function.

3 RESULTS

An analytical determination of the angle of shear strength for the Danube gravels G1, G2, and G3 was done using correlations according to Švasta and STN 72 1032 (Tab. 1), which are widely used in Slovakia. The angle of shear strength was determined from the results of N_{10} and q_{dyn} of the DPH test. The data set was classified respectively according to the relative density of the gravels.

3.1 Well-graded gravel (G1/GW)

For well-graded gravels, the data set analyzed consisted of 16 results (N_{10}, q_{dyn}, φ_{ef}) which were categorized into two classes of relative density, i.e., medium dense and dense (Tab. 3). According to the correlation in STN 72 1032, the angle of shear strength of G1 is in a range of 25° – 40.8° (medium dense to

Tab. 3 *Statistics of data for G1/GW*

Variable	Relative Density	N	Mean	Standard Deviation	Min.	Median	Max.
N_{10} [-]	Medium Dense	10	8.72	4.78	2.00	9.86	15.24
	Dense	6	20.81	4.40	16.50	19.22	28.17
q_{dyn} [MPa]	Medium Dense	10	9.46	3.58	3.05	9.27	14.11
	Dense	6	22.25	5.84	15.61	21.75	29.37
φ_{ef}[°] (STN 72 1032)	Medium Dense	10	31.15	3.47	25.00	32.43	35.12
	Dense	6	37.77	1.95	35.75	37.11	40.79
φ_{ef}[°] (Švasta)	Medium Dense	10	34.01	2.45	28.69	34.22	36.66
	Dense	6	39.27	1.68	37.25	39.27	41.22

dense). Using Švasta's correlations, the φ_{ef} of well-graded gravels has higher values, i.e., 28.7° - 41.2° (medium dense to dense).

The distribution of the results of the angle of shear strength for well-graded gravel derived by both correlations (Švasta, STN 72 1032) is graphically shown in Fig. 5.

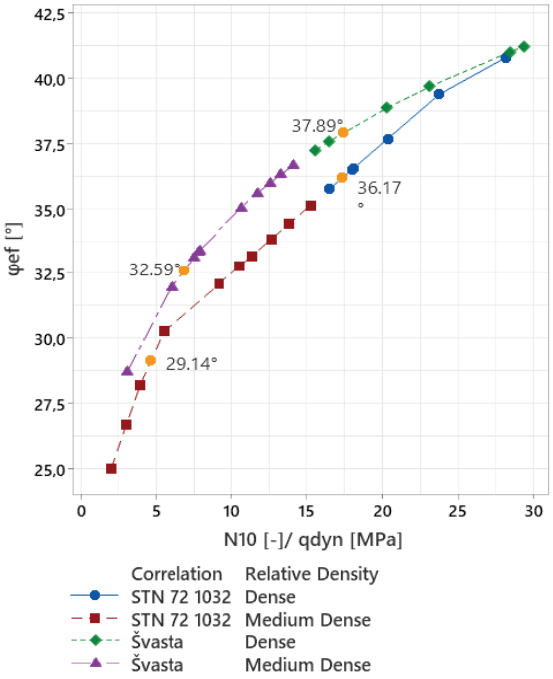


Fig. 5 *Angle of shear strength of G1/GW derived by Švasta and STN 72 1032*

In the same figure the representative value of φ_{ef}, which was evaluated separately according to each correlation and relative density respectively (marked with orange dot and number), is also denoted. From a comparison of the respective values (Tab. 3 and Fig. 5), the difference between the mean and characteristic values of φ_{ef} varies from 1.4° to 2°.

3.2 Poor-graded gravel (G2/GP)

The data set for poor-graded gravel contain 39 results of N_{10} and q_{dyn}, from which the φ_{ef} was derived. The results were categorized according to relative density to N_{10}, q_{dyn}, and the φ_{ef} of loose, medium dense, and dense gravels G2 (Tab. 4).

Using the correlation in STN 72 1032, the angle of shear strength of the loose G2 is determined to be in the range of 20° – 32.1°.

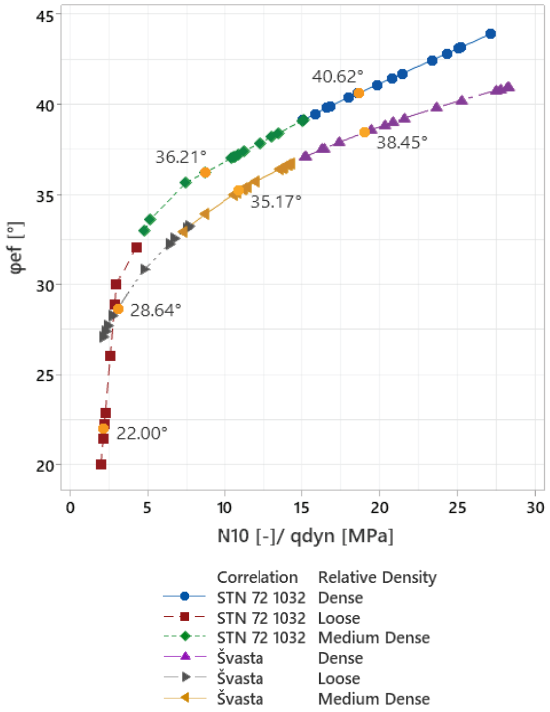


Fig. 6 *Angle of shear strength of G2/GP derived by Švasta and S TN 72 1032*

Tab. 4 *Statistics of data for G2/GP*

Variable	Relative Density	N	Mean	Standard Deviation	Min.	Median	Max.
N_{10} [-]	Loose	9	2.60	0.72	2.00	2.29	4.27
	Medium Dense	15	10.81	3.16	4.82	10.92	15.09
	Dense	15	20.42	3.82	15.06	19.79	27.08
q_{dyn} [MPa]	Loose	9	4.74	2.38	2.12	4.78	7.69
	Medium Dense	15	12.09	2.17	7.29	12.01	14.32
	Dense	15	21.59	4.93	15.22	20.87	28.30
φ_{ef} [°] (STN 72 1032)	Loose	9	24.83	4.56	20.00	22.86	32.11
	Medium Dense	15	37.02	1.78	33.03	37.24	39.13
	Dense	15	41.29	1.49	39.12	41.08	43.88
φ_{ef} [°] (Švasta)	Loose	9	30.27	2.66	27.07	30.83	33.27
	Medium Dense	15	35.68	1.12	32.98	35.72	36.74
	Dense	15	39.11	1.45	37.10	39.02	40.97

For medium to dense gravels, the φ_{ef} is in a range of 33° - 43.9°. Using Švasta's correlations, the φ_{ef} of loose, poor-graded gravel is higher, i.e., from 27.1° to 33.3°. The values of φ_{ef} for a medium dense to dense state are – 32.9° - 40.9° (Tab. 4).

A graphic representation of the φ_{ef} derived from both correlations *(Švasta, STN 72 1032)* is shown in Fig. 6. The corresponding representative value of the angle of shear strength is marked with an orange dot and number. The comparison of the results (Tab. 4 and Fig. 6) shows that the difference between the mean and the characteristic value of φ_{ef} for loose gravels G2 is 2.8°. For medium and dense gravels, the difference between the values varies from 0.6° to 0.8°.

3.3 Gravel with fine grained soil (G3/G-F)

The data set analyzed for gravels with fine-grained particles contains 51 results of N_{10}, q_{dyn}, and φ_{ef}, which were organized according to their relative density into the results of the medium dense and dense gravels G3 (Tab. 5). According to the correlation in STN 72 1032, the angle of shear strength for G3 is evaluated to be from 30.6° – 44.8° *(medium dense to dense)*.

According to Švasta´s correlation, the φ_{ef} of G3 gravels is from 32.6° to 42.4° (medium dense to dense) and indicates lower values of φ_{ef} than the correlation in STN 72 1032 (Tab. 5, Fig. 7).

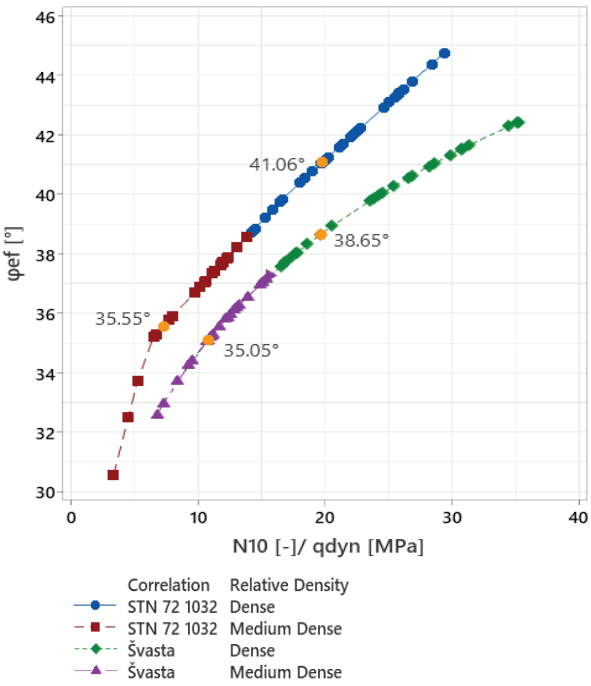


Fig. 7 *Angle of shear strength of G3/G-F derived by Švasta and STN 72 1032*

Tab. 5 *Statistics of data for G3/G-F*

Variable	Relative Density	N	Mean	Standard deviation	Min.	Median	Max.
N_{10} [-]	Medium Dense	20	9.62	3.04	3.33	10.53	13.83
	Dense	31	21.18	4.31	13.84	21.42	29.35
q_{dyn} [MPa]	Medium Dense	20	11.91	2.61	6.75	12.24	16.71
	Dense	31	22.86	7.26	8.35	23.85	35.27
φ_{ef} [°] (STN 72 1032)	Medium Dense	20	36.35	2.05	30.56	37.06	38.56
	Dense	31	41.56	1.70	38.56	41.70	44.75
φ_{ef} [°] (Švasta)	Medium Dense	20	35.56	1.31	32.57	35.83	37.66
	Dense	31	39.31	2.17	33.71	39.87	42.44

Tab. 6 *Comparison of φ_{ef} values determined by the laboratory, field tests, and table values*

Soil	Relative density	φ_{ef} [°]						
		Lab. Tests	Field tests					Table values (STN 73 1001)
			Švasta	STN 72 1032	BS 8002	EC7/ DIN	Bolton/ Robertson	
G1/GW	Medium dense	-	32.59	29.14	34	36	-	38.5
	Dense	40.9/42.8	37.89	36.17	38	40	55/35	41.5
G2/GP	Loose	-	28.64	22.00	30	30	-	-
	Medium dense	-	35.17	36.21	32.5	34	-	35.5
	Dense	41 – 48.5	38.45	40.62	35	38	-	38.5
G3/G-F	Medium dense	-	35.05	35.55	34	36	-	32.5
	Dense	44 – 51.9	38.65	41.06	55/35	38	40	35.5

A graphic representation of the φ_{ef} results derived by both correlations *(Švasta, STN 72 1032) and* their representative values are shown in Fig. 7. From a comparison of the results (Tab. 5 and Fig. 7), the difference between the mean and characteristic values of φ_{ef} varies from 0.5° to 0.8°, which is not significant.

Tab. 6 summarizes the representative (characteristic) values of the analytical determination of φ_{ef} from the results of the N_{10} and the q_{dyn} of the heavy dynamic penetration test. These results are compared with the laboratory results, other correlations, and the table (nominal) values, which were published in the canceled Slovak standard STN 73 1001. Despite the fact that the Slovak standard has been canceled, these table (nominal) values are still used for purposes of comparison.

It can be seen from the comparison in Tab. 6 that for the ***loose gravels,*** there is no recommendation of φ_{ef} in STN 73 1001:1987. However, according to the analytical evaluation using correlations by Švasta, STN 72 1032, and BS 8002:1994, the angle of shear strength of G2 gravels reaches a minimal value of 25° to 30°. The correlation in Eurocode 7 and the German standard (EN 1997-2:2008, DIN 4094-3:2002) also specifies 30° for the angle of shear strength of loose gravel.

For ***medium dense and dense gravels*** of the class G1, the angle of the shear strength derived by Švasta and STN 72 1032 is lower than the φ_{ef} determined by other correlations and the table (nominal) values. The laboratory test indicates higher values as well. The angle of shear strength of medium dense and dense gravels G3 is greater than the φ_{ef} of G1 gravels.

Based on the analysis and a comparison of the results with the non-Slovak correlations, we recommend the correlation according to Švasta for the evaluation of the angle of the shear strength of the Danube gravels. It is also appropriate for the medium dense and dense Danube G1, G2, and G3 gravels when reevaluating the table (nominal) values of φ_{ef}. For loose gravels, we recommend using 30° for the angle of shear strength; it represents a conservative estimation.

4 CONCLUSION

In the article, we analyzed the angle of the shear strength of Danube gravels derived from the results measured of a dynamic penetration test. The correlations that were used for the analytical derivation of the angle of shear strength have regional (Slovak) applicability (Matys et al, 1990). These correlations, unlike the correlations in standards (STN EN 1997-2:2008, DIN 4094-3:2002, EN ISO 22476-2, PN-B-04552:2002, STN 72 1032: 1997; BC 8002:1994), express a direct relation between the results of the dynamic penetration and the required soil property. Furthermore, the results of the dynamic penetration resistance consider physical aspects, such as the influence of the groundwater level, friction on the rod, and the increasing weight of the probe with depth, and are therefore more accurate (Matys et al, 1990).

For the design of geotechnical structures, it is necessary to know the representative value of the geotechnical parameters. In the second generation of Eurocode 7 (EN 1997-1:2024), the representative value could be either a nominal or characteristic value. For the determination of the characteristic value, the new Eurocode 7 gives a recommended procedure that works with the basic statistical characteristics. This method is clearly described and easy to follow for the average user.

In following the above, we determined the characteristic value of the Danube gravels from the data set of the derived angles of shear strength. The results and characteristic value of the angle of shear strength were sorted according to the relative density of the gravel. Total of three classes of gravels (G1/GW, G2/GP, and G3/G-F) were analyzed. The characteristic value was determined for each class and stage of the relative density of the soil. The characteristic values of the angle of shear strength were compared with the table (nominal) values from the canceled Slovak standard STN 73 1001:1987, which are still used for purposes of comparison. It must be said that the table values and most of the available correlations between the DP results and gravel properties are generalized and do not consider the genesis of the soil (roundness, shape, size, roughness of the grain surface).

Therefore, in order to observe the effect of the genesis on the appropriateness of the correlations used, the table values, and the parameters evaluated, we compared the results of the characteristic values of the angle of shear strength obtained with the laboratory results and other correlations. Based on the analysis of the loose gravels, we recommend values that are conservatively selected, as STN 73 1001:1987 does not list any values of the angle of the shear strength for loose coarse-grained soil.

For the medium dense and dense gravels, the most significant difference between the characteristic values of the angle of shear strength and the recommended values in STN 73 1001:1987 is shown for the G1 and G3 gravels. The values of the angle of shear strength of G1 gravels derived from DP using the Slovak correlations are lower than the values determined by other correlations (BS 8002:1994; EN 1997-2:2008; DIN 4094-3:2002; Bolton, 1979, Robertson and Hughes; 1986) and the table values. The angle of the shear strength of the G3 gravels derived from DP using Slovak and foreign correlations is greater than the angle of shear strength of the G1 gravels. This is also confirmed by the results of the laboratory tests. Therefore, it would be appropriate to reevaluate the table values for all the gravel classes analyzed.

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