Sensitivity of spread foundation size on values of shear strength parameters of gravelly and sandy soils

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Before implementation of Eurocode 7, part No. 1 [12] (EC7-1) and part No. 2 [13] (EC7-2), Polish Standard PN-81/B-03020 [15] (in the following abbreviated as the PN) was applied in designing shallow foundation in Poland. After 31.03.2010 the full implementation of the EC7-1 and EC7-2 and withdrawal of conflicting national Standards should be made, so at the present time, the PN is withdrawn (without replacement by the new specific standard on designing shallow foundation) and EC7-1 and EC7-2 are implemented in Poland.

In Slovakia, before implementing EC7-1 and EC7-2, the old Slovak Technical Standard STN 73 1001:1987 [16] (in the following abbreviated as the old STN) was applied in designing shallow foundation. The old STN was replaced by the new specific standard on designing shallow foundation STN 73 1001:2010 [17] (in the following abbreviated as the new STN) on 01.04.2010. So at the present time, the new STN is applied and coexists with implemented EC7-1 and EC7-2.

In [12], three Design Approaches (DA) are outlined (DA1 with 2 combinations C1 and C2; DA2 and DA3). They differ in the way they distribute partial factors between actions, the effects of actions, material properties and resistances. In the Annex D, a sample analytical method for bearing resistance calculation is posted.

Topic on comparison of spread foundation designed by various approaches, including DAs in EC7-1 is very large, see e.g. [6, 8, 9, 10, 11]. The newest information on the EC7 can be found in [1, 3].

The key issue in designing geotechnical structures is precise determination of geotechnical parameters. The article 2.4.5.1 of EC7-1 states that the selection of characteristic values for geotechnical parameters shall be based on derived values resulting from laboratory and field tests, complemented by well-established experience and the characteristic values of a geotechnical parameter shall be selected as a cautious estimate of the value affecting the occurrence of the limit state.

When determining geotechnical parameters, comparable local experience is very important. In Poland as so as in Slovakia, geotechnical parameters can be determined based on comparable local experience, on local correlations (e. g. geotechnical parameters values posted in the PN and old STN) for the structures of the Geotechnical Category 1 (GC1). From a reason that in many cases there is no time for carrying out laboratory and in-situ tests and also for low finance (by [2], cost of geotechnical investigation in Poland is about 0.1% of investment), so values of geotechnical parameters posted in withdrawn standards (the PN and old STN) are applied also for the structures of the GC2. Of course, it is not recommended and the tests should be carried out.

We would like to note, that e. g. neither direct shear tests do not provide reliable values of shear strength parameters. There are many factors influencing results of direct shear test so values of shear strength parameters obtained from direct shear tests, carried out by various standards are different [5].

By Godlewski [2], values of density index I_D of river sand under bridge abutment, obtained from various in-situ tests (DP, CPT, SPT), using various correlations by various authors are different. Dispersion of results is large and in an extreme cases reaches 3.5 times. "Cautious estimate" as mentioned in EC7-1 means in this case taking into account influence of uniformity coefficient $C_u < 3$ (typical for alluvial soil), giving value of I_D smaller on 0.2 in comparison with the case when influence of uniformity coefficient $C_u < 3$ is not taken into account.

By Lechowicz [4], building structures of GC2 and GC3 are more than 50% of building structures in Poland. Then we can propose that building structures of GC1 are more than 40%. Therefore dealing with geotechnical parameters posted in withdrawn standards is still useful.

Concerning sensitivity of spread foundation size on values of shear strength parameters, the author has analysed it for all types of soils according to classification system applied in Slovakia (24 types of soil with particles smaller than 63 mm), using design approaches by the old STN, by the new STN and by the EC7-1. Since soil classification system applied in Slovakia is not the same as in Poland (e. g. by the old STN and also by the new STN, there are 5 types of gravelly soil GW, GP, G-F, GM and GC); determination of shear strength parameters of gravelly soils posted in the old STN is also not the same as by the PN, results are not comparable. By [6], small difference in angle of internal friction (4°) of soil GW causes difference in foundation size up to 37.0% and small difference in angle of internal friction (2.5°) and cohesion (4 kPa) of soil GM causes difference in foundation size up to 27.0%.

This paper aims to introduce the procedure of determination of shear strength parameters of gravelly and sandy soils posted in the PN and to show sensibility of spread foundation size on their values. To illustrate sensitivity, spread foundation design by various design procedures such as by the PN, by the old STN, by the new STN and by the EC7-1 will be applied.

DETERMINATION OF SHEAR STRENGTH PARAMETERS OF GRAVELLY AND SANDY SOIL BY THE PN

By the PN, soils are divided to two kinds: cohesionless and cohesive. There are 6 classes of cohesionless soils, divided to 3 groups (in the first group there are gravel and sand-gravel mix, in the following marked as Ż and Po – see also Tab. 1; in the second group there are coarse sand and medium sand, in the following marked as Pr and Ps – see also Tab. 2 and in the third group there are fine sand and silty sand, in the following marked as Pd and Pπ - see also Tab. 3). Cohesive soils are divided into four groups: group A (moraine consolidated cohesive soils); group B (other consolidated cohesive soils or moraine unconsolidated cohesive soils); group C (other unconsolidated cohesive soils); group D (clay, regardless of the geological origin).

By the PN, the shear strength parameters of soils (internal friction and cohesion) can be obtained using diagrams in the Standard, based on soil group and density index I_D (cohesionless soil) or liquidity index I_L (cohesive soils). Instead of using the diagrams, one can use also formulas (as a function of I_D and I_L), posted in [7], giving the same soils shear strength parameters as diagrams. In the Tab. 1, Tab. 2 and Tab. 3 we can see values of shear strength parameters of gravelly and sandy soil, calculated using designed values of I_D. We would like to note that values of internal friction angles posted in Tab. 1, Tab. 2 and Tab. 3 are characteristic and total (by the PN), characteristic and effective (by other Standards) and partial factors were used to obtain their designed values in accordance with specific Standard.

To examine sensitivity of spread foundation size on gravelly and sandy soils shear strength parameters; various values of I_D (0.35; 0.65; 0.85; and 1.0) are used and obtained corresponding values of shear strength parameters are applied to design spread foundation by various design procedures. The values of I_D 0.35, 0.65, 0.85 and 1.0 are limit values for various soil density intervals [14].

DESIGNING SPREAD FOUNDATION BY VARIOUS DESIGN PROCEDURES

The evaluation of soil bearing capacity is a matter of wide comprehension since it concerns not only the soils but also the actions, foundation depth, foundation width, foundation shape etc. Subsoil can be also inhomogeneous and there can be also water in subsoil. The soils bearing capacity can be evaluated also in drained or in undrained condition. More details on various spread foundation design procedures can be found in the above mentioned specific documents [12, 15, 16 and 17]. In the following we will introduce briefly the equations for calculation of designed subsoil bearing capacity by the PN, the old STN, the new STN and EC7-1.

By the PN, the designed bearing capacity of the foundation soils can be calculated by the formula:

$$Q_{fNB} = \overline{B}\,\overline{L}\left[\left(1+0.3\frac{\overline{B}}{\overline{L}}\right)N_c c_u^{(r)} i_c + \left(1+1.5\frac{\overline{B}}{\overline{L}}\right)N_D \rho_D^{(r)} g D_{\min} i_D + \right.$$
$$\left. + \left(1-0.25\frac{\overline{B}}{\overline{L}}\right)N_B \rho_B^{(r)} g \overline{B}\, i_B\right] \quad (1)$$

By the old STN, the designed bearing capacity of the foundation soils can be calculated by the formula:

$$R_d = c_d N_c s_c d_c i_c + \gamma_1 d N_d s_d d_d i_d + \gamma_2 \frac{b_{ef}}{2} N_b s_b d_b i_b \quad (2)$$

By the new STN, the designed bearing capacity of the foundation soils for the drained condition can be calculated by the formula:

$$R_d = \left(c'_d N_c s_c d_c i_c j_c + q' N_q s_q d_q i_q j_q + \gamma' \frac{B}{2} N_\gamma s_\gamma d_\gamma i_\gamma j_\gamma \right) / \gamma_{R,V} \quad (3)$$

By the EC7-1, the designed bearing capacity of the foundation soils for the drained condition can be calculated by the formula:

$$R_{d;d} / A' = (c' N_c b_c s_c i_c + q' N_q b_q s_q i_q + 0.5 \gamma' B' N_\gamma b_\gamma s_\gamma i_\gamma) \quad (4)$$

The meanings of symbols in equations (1), (2), (3) and (4), including meanings of dimensionless factors are well-known to geotechnical community.

Comparing the PN, the old STN, the new STN and the EC7-1 we can conclude, that there are many differences between them. Formally, equations for the calculation of bearing capacity are similar but the number of parameters in the equations is not equal and equations parameters are calculated not by the same formula. By the PN, the old STN and the new STN there are no factors for the inclination of the foundation base (they are by the EC7-1 only, specified by the symbols b_c, b_q, b_γ). By contrast, by the PN and by the EC7-1, there are no factors for foundation depth (specified by the symbols d_c, d_d, d_b in the old STN and d_c, d_q, d_γ in the new STN) and no factors for the terrain inclination (specified by the symbols j_c, j_q, j_γ in the new STN). Furthermore, by the PN, designed values of the soils strength parameters are obtained from their characteristic values using different partial factors as they are by the old STN, the new STN and EC7-1. The differences are also in the factors for load inclination etc. Partial factors on actions or effects of actions for permanent and variable actions are also different. From mentioned reasons, the dimensions of the spread foundations designed by the PN, the old STN, the new STN and by the EC7-1 will be different. It will be shown in the example in the following chapter.

EXAMPLE

To illustrate sensibility of spread foundation size on shear strength parameters of gravelly and sandy soils; various values of shear strength parameters, obtained from various values of I_D, will be used to design square spread footing foundation (see Tab. 1, Tab. 2 and Tab. 3).

The design of spread footing foundation is carried out by design procedures mentioned in [12] (DA1-C1; DA1-C2; DA2 and DA3), by the old STN [16], by the new STN [17] and by the PN [15]. The model example for comparison of spread footing foundation designed by various design procedures is similar to the model introduced by Orr [9]; see Fig. 1. The sizes of foundations designed by various design procedures are introduced in the Tab. 1, Tab. 2 and Tab. 3.

For better analysis of sensibility of spread footing foundation size on shear strength parameters, maximal and minimal differences in area of spread foundation designed by the PN are shown in the Tab. 4 (“area” tells us more than “size”). Maximal and minimal differences in area of spread footing foundation designed by all above mentioned procedures are shown in the Tab. 5.

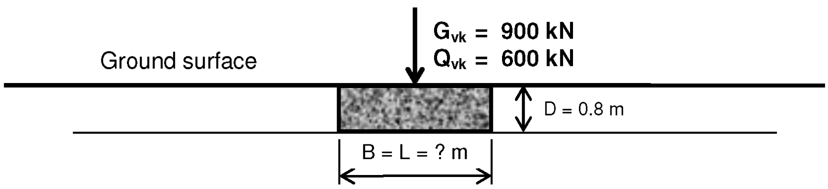

Fig. 1. Model example for comparison of spread foundation designed by various design procedures [9]

Tab. 1. The sizes of spread foundation on gravel (Ż) and sand-gravel mix (Po) in (m) by various design procedures

Gravel (Ż) and sand-gravel mix (Po) – (symbol in Polish) and their shear strength parameters for various values of I_D		*DA1 (C1)*	*DA1 (C2)*	*DA2*	*DA3*	*Old STN*	*New STN*	*PN*
I_D = 0.35 (φ = 37.4°, c = 0 kPa) (1)		1.25	1.64	1.46	1.83	1.56	1.46	1.47
I_D = 0.65 (φ = 39.6°, c = 0 kPa) (2)		1.06	1.42	1.23	1.58	1.32	1.23	1.27
I_D = 0.85 (φ = 41.1°, c = 0 kPa) (3)		0.94	1.28	1.09	1.43	1.18	1.09	1.15
I_D = 1.0 (φ = 42.3°, c = 0 kPa) (4)		0.86	1.19	1.00	1.32	1.08	0.99	1.07
Differ. in foundation size: (1) – (2)	[m]	0.19	0.22	0.23	0.25	0.24	0.23	0.20
Differ. in foundation area: (1) – (2)	[%]	***39.1***	***33.4***	***40.9***	***34.2***	***39.7***	<u>***40.9***</u>	<u>***33.9***</u>
Differ. in foundation size: (2) – (3)	[m]	0.12	0.14	0.14	0.15	0.14	0.14	0.12
Differ. in foundation area: (2) – (3)	[%]	***27.2***	***23.1***	***27.3***	***22.1***	***25.1***	***27.3***	***21.9***
Differ. in foundation size: (3) – (4)	[m]	0.08	0.09	0.09	0.11	0.10	0.10	0.08
Differ. in foundation area: (3) – (4)	[%]	***19.5***	***15.7***	***18.8***	***17.4***	***19.4***	***21.2***	<u>***15.5***</u>

Tab. 2. The sizes of spread foundation on coarse sand (Pr) and medium sand (Ps) in (m) by various design procedures

Coarse sand (Pr) and medium sand (Ps) – (symbol in Polish) and their shear strength parameters for various values of I_D		*DA1 (C1)*	*DA1 (C2)*	*DA2*	*DA3*	*Old STN*	*New STN*	*PN*
I_D = 0.35 (φ = 32.0°, *c* = 0 kPa) (1)		1.80	2.25	2.10	2.51	2.22	2.13	1.98
I_D = 0.65 (φ = 34.0°, *c* = 0 kPa) (2)		1.57	2.00	1.83	2.22	1.90	1.85	1.76
I_D = 0.85 (φ = 35.3°, *c* = 0 kPa) (3)		1.42	1.83	1.66	2.04	1.76	1.67	1.63
I_D = 1.0 (φ = 36.3°, *c* = 0 kPa) (4)		1.33	1.73	1.55	1.92	1.65	1.55	1.53
Differ. in foundation size: (1) – (2)	[m]	0.23	0.25	0.27	0.29	0.32	0.28	0.22
Differ. in foundation area: (1) – (2)	[%]	***31.5***	***26.6***	***31.7***	***27.8***	<u>***36.5***</u>	***32.6***	<u>***26.6***</u>
Differ. in foundation size: (2) – (3)	[m]	0.15	0.17	0.17	0.18	0.14	0.18	0.13
Differ. in foundation area: (2) – (3)	[%]	***22.2***	***19.4***	***21.5***	***18.4***	***16.5***	***22.7***	***16.6***
Differ. in foundation size: (3) – (4)	[m]	0.09	0.10	0.11	0.12	0.11	0.12	0.10
Differ. in foundation area: (3) – (4)	[%]	***13.9***	<u>***11.9***</u>	***14.7***	***12.9***	***13.8***	***16.1***	<u>***13.5***</u>

Tab. 3. The sizes of spread foundation on fine sand (Pd) and silty sand (Pπ) in (m) by various design procedures

*Fine sand (*Pd*) and silty sand (Pπ) – (symbol in Polish) and their shear strength parameters for various values of I_D*		*DA1 (C1)*	*DA1 (C2)*	*DA2*	*DA3*	*Old STN*	*New STN*	*PN*
I_D = 0.35 (φ = 29.8°, *c* = 0 kPa) (1)		2.12	2.60	2.48	2.91	2.63	2.52	2.29
I_D = 0.65 (φ = 31.3°, *c* = 0 kPa) (2)		1.90	2.36	2.22	2.64	2.35	2.25	2.08
I_D = 0.85 (φ = 32.3°, *c* = 0 kPa) (3)		1.76	2.21	2.06	2.46	2.18	2.08	1.95
I_D = 1.0 (φ = 33.0°, *c* = 0 kPa) (4)		1.67	2.10	1.94	2.35	2.06	1.97	1.86
Differ. in foundation size: (1) – (2)	[m]	0.22	0.24	0.26	0.27	0.28	0.27	0.21
Differ. in foundation area: (1) – (2)	[%]	***24.5***	***21.4***	***24.8***	***21.5***	***25.3***	<u>***25.4***</u>	<u>***21.2***</u>
Differ. in foundation size: (2) – (3)	[m]	0.14	0.15	0.16	0.18	0.17	0.17	0.13
Differ. in foundation area: (2) – (3)	[%]	***16.5***	***14.0***	***16.1***	***15.2***	***16.2***	***17.0***	***13.8***
Differ. in foundation size: (3) – (4)	[m]	0.09	0.11	0.12	0.11	0.12	0.11	0.09
Differ. in foundation area: (3) – (4)	[%]	***11.1***	***10.8***	***12.8***	<u>***9.6***</u>	***11.9***	***11.5***	<u>***9.9***</u>

Tab. 4. The maximal and minimal differences in area of spread foundation designed by the PN

Soils	*Gravel (Ż) and sand-gravel mix (Po)*	*Coarse sand (Pr) and medium sand (Ps)*	*Fine sand (Pd) and silty sand (Pπ)*
Maximal differences [%]	<u>**33.9**</u>	<u>**26.6**</u>	<u>**21.2**</u>
Between I_D	0.65 and 0.35	0.65 and 0.35	0.65 and 0.35
Difference in φ [°]	2.2	2.0	1.5
Minimal differences [%]	<u>**15.5**</u>	<u>**13.5**</u>	<u>**9.9**</u>
Between I_D	1.00 and 0.85	1.00 and 0.85	1.00 and 0.85
Difference in φ [°]	1.2	1.0	0.7

Tab. 5. The maximal and minimal differences in area of spread foundation designed by all design procedures

Soils	*Gravel (Ż) and sand-gravel mix (Po)*	*Coarse sand (Pr) and medium sand (Ps)*	*Fine sand (Pd) and silty sand (Pπ)*
Maximal differences [%]	<u>**40.9**</u>	<u>**36.5**</u>	<u>**25.4**</u>
Between I_D	0.65 and 0.35	0.65 and 0.35	0.65 and 0.35
Difference in φ [°]	2.2	2.0	1.5
By design procedure	New STN	Old STN	New STN
Minimal differences [%]	<u>**15.5**</u>	<u>**11.9**</u>	<u>**9.6**</u>
Between I_D	1.00 and 0.85	1.00 and 0.85	1.00 and 0.85
Difference in φ [°]	1.2	1.0	0.7
By design procedure	PN	DA1-C2	DA3

As we can see from the Tab. 4 and 5, spread footing foundation area is very sensitive on the values of angle of internal friction. Not large difference in angle of internal friction of gravel (Ż) and sand-gravel mix (Po) 2.2° causes difference in foundation area up to 33.9% (by the PN) and 40.9% (by the new STN), see also bold, underline numbers in Tab. 1 and Tab. 4, Tab. 5.

High sensitivity can be seen also in case of coarse sand (Pr) and medium sand (Ps) as so as fine sand (Pd) and silty sand (Pπ), see other underline numbers in Tab. 2, Tab. 3 and Tab. 4, Tab. 5. So e.g. smaller difference in angle of internal friction of fine sand (Pd) and silty sand (Pπ) 1.5° causes difference in foundation area up to 21.2% (by the PN) and 25.4% (by the new STN).

Of course, there is also question of measurement uncertainty, which depends on human factors, tests conditions, tests methods, precision of equipment, soil inhomogeneity, specimen quality etc. We can propose that uncertainty in values of I_D can be larger than 0.1 and uncertainty of internal friction angle is often more than 1° so values of minimal differences in foundation area in the Tab. 4 and Tab. 5 are for illustrated purpose only. On the other hand, we can state that irrespective of design approach, difference in value of internal friction angle about 1° makes difference in foundation area more than 10%.

We can also see that for all cases; the size of foundation is the biggest when designed by the DA3 and the smallest when designed by the DA1-C1. Concerning the old and new STN, for all cases, the size of foundation designed by the new STN is smaller as by the old STN. By the author´s knowledge, such rules are not applied for cohesive soils, when there is also influence of cohesion. The size of foundation designed by the PN is close to this one, designed by DA2.

CONCLUSIONS

The size of spread foundation is very sensitive on the values of shear strength parameters of gravelly and sandy soils. Even small difference in the values of angle of internal friction causes big difference in the spread foundation size. So the precise determination of angle of internal friction is very important and has big impact on economy of the design.

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