Designing spread foundation on inhomogeneous subsoil by various approaches

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In geotechnical practice we can have a situation, when subsoil under spread foundation is inhomogeneous by the way that subsoil is layered. Generally one can differ two cases of inhomogeneous subsoil: a strong layer is overlaying a weak layer and vice versa. For the case when a weak layer is overlying a strong layer, it is a common practice in Poland, that spread foundation is designed to suite a bearing capacity of the weak layer, does not taking account a bearing capacity of the strong layer. For the case when a strong layer is overlaying a weak layer, the Polish Standard [5] (abbreviated as "old PN"), withdrawn from

01.04.2010, prescribes to design the foundation to suite a bearing capacity of the strong layer and to check whether a bearing capacity of the weak layer is sufficient for a substitute foundation.

In the Polish Standard PN-EN 1997-1:2008 (the Polish version of Eurocode 7, Part 1) [6], no design method for spread foundation on inhomogeneous subsoil is specified. The Polish author Puła states this fact in [2] and suggests applying above mentioned method of substitute foundation also in the future (of course, only a principle of the method is applied; verification of limit states, e. g. GEO shall be carried out in accordance with [6]).

Concerning design of spread foundation, the Slovak Technical Standard STN 731001 "Foundation of structures. Subsoil under shallow foundations" [7] (abbreviated as "old STN") had been used until 31.03.2010, when it was replaced by the new Slovak Technical Standard STN 731001 "Geotechnical structures. Foundation" [8] (abbreviated as "new STN"). The new STN respects the design approach number 2 (DA2) of Eurocode 7, Part 1 but modified it for Slovak condition. In the both Standards [7] and [8], no design method for spread foundation on inhomogeneous subsoil is specified. The Standards only state that for inhomogeneous subsoil, an individual approach should be applied.

In Slovakia, in the past and also in the present, the method using shear surface, posted in [4] is often applied when designing spread foundation on inhomogeneous subsoil. By this method, average values of shear strength parameters (angle of internal friction and cohesion) calculated using shear strength parameters of the layers will be applied.

As we can see, Eurocode 7, Part 1 does not specify a design method for spread foundation on inhomogeneous subsoil therefore there are many possibilities to choose from. So a comparison of above mentioned design methods for spread foundation on inhomogeneous subsoil (method of substitute foundation and method using shear surface) can be very helpful.

DETERMINATION OF SHEAR STRENGTH PARAMETERS BY OLD PN AND OLD STN

By the old 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 (Ż) and sand-gravel mix (Po); in the second group there are coarse sand (Pr) and medium sand (Ps) and in the third group there are fine sand (Pd) and silty sand (Pπ). Cohesive soils are divided to 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) and group D (clay, regardless of the geological origin).

By the old PN, the shear strength parameters of soils (internal angle of friction φ_u and cohesion c_u) can be obtained using diagrams in the Standard, based on soil group and relative 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) giving the same soils shear strength parameters (formulas are not introduced in the old PN).

By the old STN, soils are classified to 18 classes (5 classes for gravelly soils, 5 classes for sandy soils and 8 classes for fine-grained soils). For all soils, guiding standardized characteristics, including shear strength parameters (φ_u, c_u, φ_{ef}, c_{ef}) are introduced. By the old STN, similar as by the old PN, the geotechnical parameters of coarse-grained soil are determined based on the soil class and its relative density index I_D and the geotechnical parameters of fine-grained soil are determined based on the soil class and its consistency (consistency index I_C). Even such procedure is not posted in the new STN, it is still widely used in Slovak geotechnical practice.

DESIGNING SPREAD FOUNDATION ON INHOMOGENEOUS SUBSOIL BY OLD PN, OLD STN AND NEW STN

When designing spread foundation, generally, the bearing capacity of foundation soils will predetermine the size of foundation. The size of foundation will be calculated from the condition that bearing capacity of soil is just satisfied (not exceeded) and then the foundation will be checked for the settlement condition [1]. The evaluation of soil bearing capacity is a matter of wide comprehension since it concerns not only the soils but also the actions and the shape of the foundation. The soils can be also inhomogeneous and there is also the water in the foundation soils. The soils bearing capacity can be evaluated also in drained or in undrained condition etc.. More details on various spread foundation design procedures can be found in the specific above mentioned documents [5], [7] and [8]. In the following we will introduce briefly the equations for calculation of designed bearing capacity of the foundation soils by the old PN, the old STN and the new STN.

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

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

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:

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

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

Comparing the old PN, the old STN and new STN 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 formulas. By the old PN, 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 old 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 and the new STN. 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.

The above mentioned equations (1), (2) and (3) are applied for homogeneous subsoil.

Designing spread foundation on inhomogeneous subsoil by the old PN

In case of inhomogeneous subsoil, the old PN does not introduce situation when a weak soil layer is overlying a strong soil layer. It is a common practice, that in such case, a spread foundation is designed using shear strength parameters of weak soil, not taking into account shear strength parameters of a strong soil. In the case, when a weak soil layer is underlying a strong soil layer and surface of weak soil layer is in a depth less than 2*B*, where *B* is foundation width (see Fig. 1), the old PN prescribes to check bearing capacity sufficiency, see Equation (1), for a substitute foundation as it can be seen in Fig. 1 (substitute foundation base is just on the surface of the weak layer).

It is necessary to calculate new parameters (in Fig. 1 marked by apostrophe) such as a vertical load N'_r, eccentricity e'_B, foundation depth $D'_{\min}$. The values *b*, necessary for calculation of substitute foundation width $B' = B + b$ can be obtained using formula:

For cohesive soils:

If $h \le B$ then $b = \dfrac{h}{4}$;   If $h > B$ then $b = \dfrac{h}{3}$.

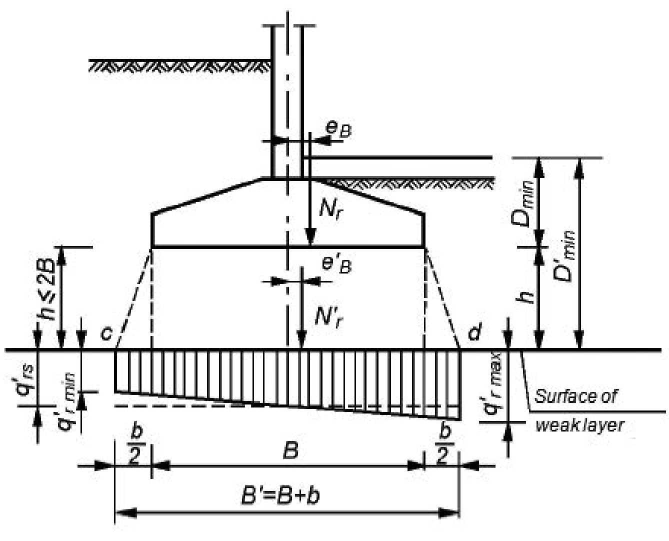

Fig. 1. Definitions of substitute foundation parameters by the old PN [5]

For cohesionless soils:

If $h \le B$ then $b = \dfrac{h}{3}$;   If $h > B$ then $b = \dfrac{2h}{3}$.

where:

h – distance from real foundation base to surface of weak layer [m] (see Fig. 1).

Designing spread foundation on inhomogeneous subsoil by the old and new STN

Both old and new STN state that Equation (2) or (3) is applied only for homogeneous subsoil in a range of shear surface which arises if foundation fails. The depth of shear surface z_s under foundation base and its horizontal dosage l_s from foundation axis (see Fig. 2b) are approximately considered to be:

$z_s = 2B$, $l_s = 6B$ for soil SW, SP and S-F; GW, GP and G-F;

$z_s = B$, $l_s = 2.5B$ for other soil classes.

Subsoil is considered to be homogeneous if difference between minimal and average values should not exceed 4° (for angle of internal friction), 40% of average value (for cohesion) and 5% of average value (for unit weigh). All mentioned conditions should be fulfilled.

For layered subsoil and for other cases when conditions for applying Equation (2) or (3) are not fulfilled, it will be solved individually.

It is common practice in Slovakia, that for layered subsoil, in the beginning, one should construct shear surface base on proposed foundation width B and on an arithmetic mean of angles of internal friction of soils of layers, often using Prandtl´s shear surface, see Fig. 2a). After having the first shear surface, one should calculate average value of angle of internal friction using formula:

$$\varphi = \frac{\varphi_1(l_{1a} + l_{1b}) + \varphi_2(l_{2a} + l_{2b}) + \varphi_3 l_3}{\sum_{i=1}^{3} l_i} \tag{4}$$

where:

φ_1, φ_2, φ_3 – an angle of internal friction of soil of layer No. 1, 2 and 3 [°], see Fig. 2b,

l_{1a}, l_{1b}, l_{2a}, l_{2b}, l_3 – lengths of shear surface crossing layer No. 1, 2 and 3 [m], see Fig. 2b.

The value of average angle of internal friction, calculated by the formula (4) is then compared with the average angle of internal friction, obtained from previous step. If a difference between them is more than 3%, iteration should be applied till condition of maximal 3% difference will be fulfilled [4]. The last average value of angles of internal friction will be applied to calculate bearing capacity of subsoil by Equation (2) or (3).

To calculate bearing capacity of subsoil by Equation (2) or (3), one should calculate also average value of cohesion by the formula:

$$c = \frac{c_1(l_{1a} + l_{1b}) + c_2(l_{2a} + l_{2b}) + c_3 l_3}{\sum_{i=1}^{3} l_i} \tag{5}$$

where:

c_1, c_2, c_3 – cohesions of soil of layer No. 1, 2 and 3 [kPa], see Fig. 2b,

l_{1a}, l_{1b}, l_{2a}, l_{2b}, l_3 – lengths of shear surface crossing layer No. 1, 2 and 3 [m], see Fig. 2b,

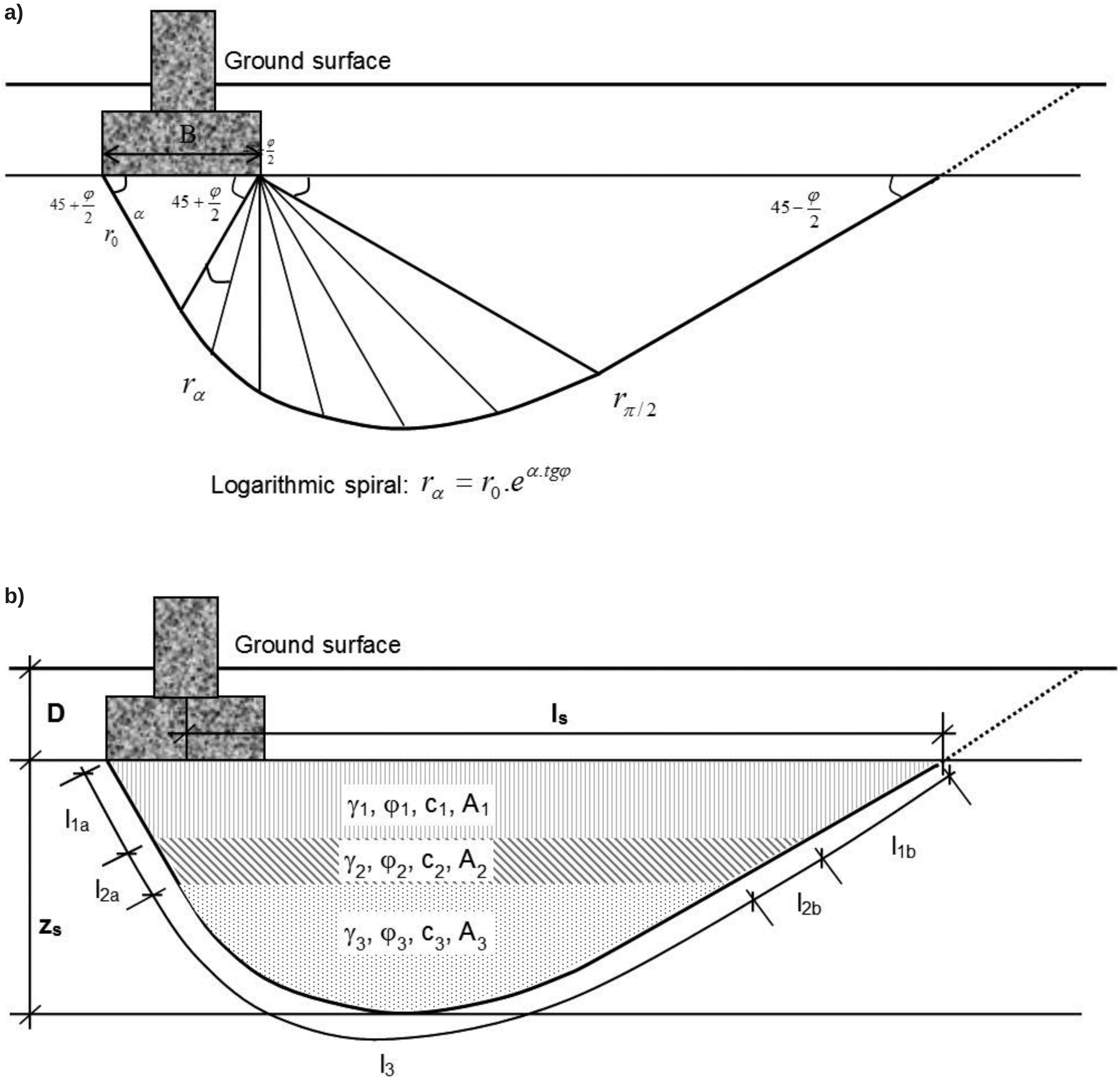

Fig. 2. A construction of shear surface (a) and lengths of shear surface in specific layers and areas (A1, A2 and A3) of soil of specific layers in the shear surface range (b)

and also average value of unit weights by the formula:

$$\gamma = \frac{\gamma_1 A_1 + \gamma_2 A_2 + \gamma_3 A_3}{\sum_{i=1}^{3} A_i} \tag{6}$$

where:

$\gamma_1, \gamma_2, \gamma_3$ – unit weights of soil of layer No. 1, 2 and 3 [kN/m^{-3}], see Fig. 2b,
A_1, A_2, A_3 – areas of soil of layer No. 1, 2 and 3 [m^2], see Fig. 2b.

The values of average cohesion and unit weight obtained from Equation (5) and (6), together with average angle of internal friction obtained from Equation (4) will be applied to calculate bearing capacity of subsoil by Equation (2) or (3) and to design spread foundation (to find e. g. foundation width B_1). Using width B_1, one should repeat all calculation procedures until difference between B_{n+1} and B_n is satisfied.

EXAMPLE

To compare above mentioned methods (method of substitute foundation by old PN and method using shear surface posted in [4]), in the following we will introduce two examples: in the first example, a weak layer is underlying a strong layer and in the second example, a weak layer is overlying a strong layer. The model example is similar to the model introduced by Orr [3].

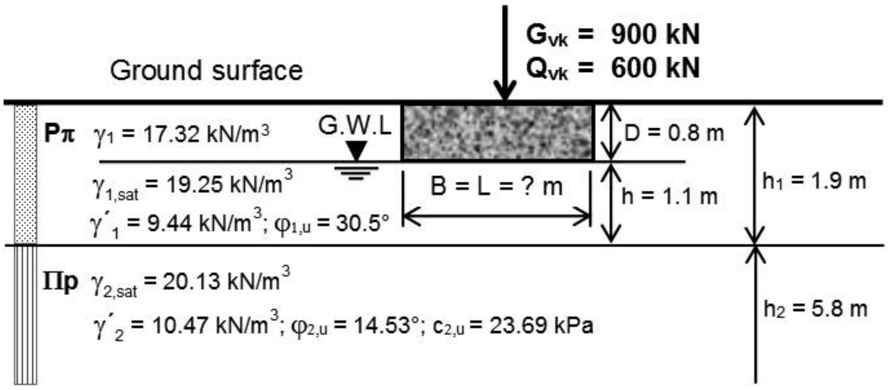

Fig. 3. Model example when a weak layer underlying a strong layer

Designing spread foundation when a weak layer is underlying a strong layer

In Fig. 3 we can see a model example, when a weak layer is underlying a strong layer. Thickness of foundation is 0.8 m, depth of foundation D = 0.8 m. There is a permanent vertical load G_{vk} = 900 kN and a variable vertical load Q_{vk} = 600 kN acting on foundation. The soil of the first layer (strong) is silty sand (in Poland marked as Pπ) with I_D = 0.5, thickness 1.9 m. The soil of the second layer (weak) is sandy silt (in Poland marked as Πp) with I_L = 0.4, thickness 5.8 m. Soils shear strength parameters are obtained in accordance with the old PN, using I_D = 0.5 and I_L = 0.4. Design of foundation was carried out by procedures mentioned in previous chapter. Results are introduced in the Tab. 1, where "SUBSTFOUND" means that foundation was designed using substitute foundation as in the Fig. 1 and "SHEARSURFACE" means that foundation was designed using shear surface as in the Fig. 2.

Tab. 1. The sizes of spread foundation on inhomogeneous subsoil (a strong layer Pπ is overlaying a weak layer Πp) in [m] by various design approaches

Design approach	φ [°]	c [kPa]	γ [kN·m⁻³]	B [m]	z_s [m]	z_s / B [–]	l_s [m]	l_s / B [–]	Diff. in B [m]	Diff. in foundation area [%]
Thickness of a strong layer 1.1 m (bearing capacity of weak layer soil used to 92.8% by the PN)										
Old PN (SUBSTFOUND)	14.53	23.69	10.47	**2.18**	NA	NA	NA	NA	**0.18**	**17.2**
Old PN (SHEARSURFACE)	20.04	16.25	9.91	**2.36**	2.74	1.16	7.20	3.05		
Old STN (SUBSTFOUND)	14.53	23.69	10.47	**3.34**	NA	NA	NA	NA	**-0.11**	**-6.5**
Old STN (SHEARSURFACE)	18.82	18.08	10.03	**3.23**	3.64	1.13	9.41	2.91		
New STN (SUBSTFOUND)	14.53	23.69	10.47	**2.57**	NA	NA	NA	NA	**0.09**	**7.1**
New STN (SHEARSURFACE)	19.54	17.01	9.95	**2.66**	3.05	1.15	7.96	2.99		
Thickness of a strong layer 0.58 m (bearing capacity of weak layer soil used to 100% by the PN)										
Old PN (SUBSTFOUND)	14.53	23.69	10.47	**2.18**	NA	NA	NA	NA	**0.23**	**22.2**
Old PN (SHEARSURFACE)	17.80	19.60	10.14	**2.41**	2.64	1.10	6.75	2.80		
Old STN (SUBSTFOUND)	14.53	23.69	10.47	**3.42**	NA	NA	NA	NA	**-0.06**	**-3.5**
Old STN (SHEARSURFACE)	16.90	20.67	10.22	**3.36**	3.59	**1.06**	9.04	**2.69**		
New STN (SUBSTFOUND)	14.53	23.69	10.47	**2.70**	NA	NA	NA	NA	**0.04**	**3.0**
New STN (SHEARSURFACE)	17.36	20.00	10.17	**2.74**	2.94	1.07	7.44	2.72		

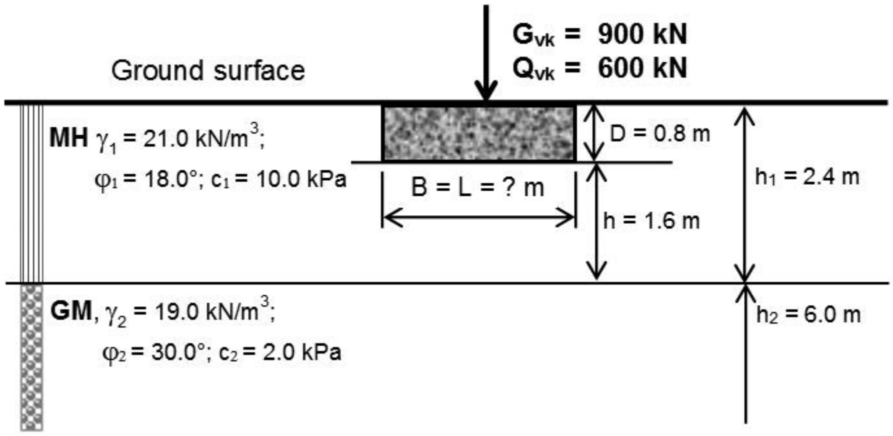

Fig. 4. Model example when a weak layer overlying a strong layer

Designing spread foundation when a weak layer overlying a strong layer

In Fig. 4 we can see a model example, when a weak layer is overlying a strong layer. Thickness of foundation is 0.8 m, depth of foundation D = 0.8 m. There is a permanent vertical load G_{vk} = 900 kN and variable vertical load Q_{vk} = 600 kN acting on foundation. The soil of the first layer (weak) is silt with high plasticity (in Slovakia marked as MH) with I_C = 0.7, thickness 2.4 m. The soil of the second layer (strong) is silty gravel (in Slovakia marked as GM) with I_D = 0.5, thickness 6.0 m. Soils shear strength parameters are obtained in accordance with the old STN, using I_C = 0.7 and I_D = 0.5. Design of foundation was carried out by procedures mentioned in previous chapter. Results are introduced in the Tab. 2, where "IGNORE-GM" means that foundation was designed not taking into account influence of strong layer GM and "SHEARSURFACE" means that foundation was designed using shear surface as in the Fig. 2.

As we can see from the Tab. 1, there are large differences between spread foundations designed by the old PN using substitute foundation and shear surface (0.18 m in foundation width and 17.2% in foundation area) for geological profile posted in Fig. 1, by which the strong layer has thickness 1.1 m and a bearing capacity of underlying weak layer soil used to 92.8% by the old PN. For better analysis, design of foundation is carried out also for thickness of strong layer 0.58 m, when a bearing capacity of underlying weak layer soil used to 100% by the old PN. In this case, above mentioned differences are also very large (0.23 m in foundation width and 22.2% in foundation area). It means that foundation size, designed based on substitute foundation can be insufficient (underestimate). Similar conclusion can be applied for foundation designed by the new STN, even in this case, the differences are not so large (up to 0.09 m and 7.1%).

Designing foundation using substitute foundation seems to be safe in case of the old STN. However, as one can see from the Tab. 1, foundation sizes are too large in comparison with the old PN and new STN. By author´s knowledge, design of spread foundation by the old STN is overestimated in many cases; see high values of foundation sizes in the Tab. 2.

Tab. 2. The sizes of spread foundation on inhomogeneous subsoil (a strong layer GM is underlying a weak layer MH) in [m] by various design approaches

Design approach	φ [°]	*c* [kPa]	γ [kN·m^{-3}]	*B* [m]	z_s [m]	z_s/B [–]	l_s [m]	l_s/B [–]	Diff. in *B* [m]	Diff. in foundation area [%]
Old PN (IGNORE-GM)	18.00	10.00	21.00	**2.71**	NA	NA	NA	NA	**-0.51**	**-34.1**
Old PN (SHEARSURFACE)	25.10	5.38	20.38	**2.20**	2.95	1.34	8.28	3.76		
Old STN (IGNORE-GM)	18.00	10.00	21.00	**3.64**	NA	NA	NA	NA	**-1.06**	**-49.8**
Old STN (SHEARSURFACE)	25.86	4.82	20.20	**2.58**	3.54	**1.37**	10.01	**3.88**		
New STN (IGNORE-GM)	18.00	10.00	21.00	**3.16**	NA	NA	NA	NA	**-0.76**	**-42.3**
New STN (SHEARSURFACE)	25.53	5.06	20.28	**2.40**	3.26	1.36	9.20	3.83		

Concerning the case when a weak layer is overlaying a strong layer (see Tab. 2), neglecting the strong layer leads to very uneconomical design. Taking into account influence of strong layer by the design approach using shear surface can reduce foundation size up to 1.06 m (and foundation area up to 49.8%) as in the case of the old STN. By the old PN, there are 0.51 m and 34.1%.

Concerning the depth of shear surface z_s under foundation base and its horizontal dosage l_s from foundation axis, values of z_s/B varies from 1.06 to 1.37 and values of l_s/B varies from 2.69 to 3.88 (see bold underline numbers in the Tab. 1 and Tab. 2). Generally, mentioned ratios are larger for the case when a weak layer is overlaying the strong layer.

CONCLUSIONS

When designing spread foundation on inhomogeneous subsoil with a weak layer overlying a strong layer, neglecting the strong layer leads to uneconomical design. We would like to recommend in such case to design foundation with average shear strength parameters, obtained e. g. from proposed shear surface. In the case when a weak layer is underlying a strong layer, we would like to recommend designing foundation using both substitute foundation and shear surface to ensure that the design is safe and economical.

From introduced analyses, foundation sizes designed by the old PN are the smallest and by the old STN are the largest. However, it is necessary to carry out more analyses to draw general conclusion.

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