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# INFLUENCE OF SOIL PARAMETERS CHANGES ON THE BEARING CAPACITY OF SOIL

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## 1. Introduction

The bearing capacity of foundations depends on the mechanical properties of the soil (density, shearing strength and deformation characteristics), on the characteristics of the foundation (size, depth, shape), and on the original stresses and the water conditions in the ground. The strength of soil is a key parameter in designing foundations and other earth structures.

In simplification, shear stress $\tau$ is an effect of frictional mechanism and cohesive resistance between the interface of mutually moving soil elements (Fig. 1), so soil strength may be attributed to two distinctly different mechanisms of material. They are the frictional and cohesive resistance along the shearing zone. Frictional resistance $\tau_f$ follows Coulomb's friction law ( $\tau_f = \sigma \tan \varphi$ ) where $\sigma$ is the normal stress, and $\varphi$ is the angle of internal friction of soil [1, 2].

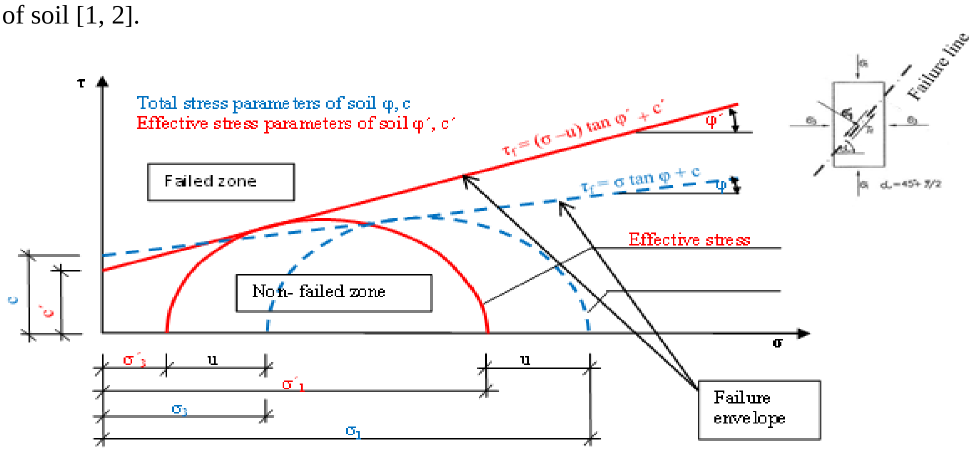


Fig. 1. Total and effective parameters of shear stress.

The angle $\varphi$ can be interpreted as the friction angle between facing soil elements along the shear surface. Cohesion resistance $c$ is the cohesion of soil. In soils, normal stress independent cohesion is a material property of fine particles (cohesive soils). The total shear stress at failure $\tau_f$ (Fig. 1) is expressed according to the well-known formula

$$\tau_f = \sigma \tan \varphi + c \,. \tag{1}$$

Equation (1) is called the Mohr-Coulomb failure criteria. It is a linear relationship between $\sigma$ and $\tau_f$. Terzaghi (1925) modified the Mohr-Coulomb equation in order to include his effective stress concept as:

$$\tau_f = \sigma' \tan \varphi' + c' = (\sigma - u) \tan \varphi' + c' \tag{2}$$

The strength parameters $c'$ and $\varphi'$ are expressed in terms of the effective normal stress ( $\sigma' = \sigma - u$ ). The basic concept is that soil strength is controlled by the effective stress (stresses in the soil's skeleton) rather than the total stress. In Fig. 1, the total and effective stress is graphically interpreted. There are many laboratory devices as well as in situ shear devices to determine soil's strength parameters which enable determination of total or effective strength parameters of soil.

The example of individual authors' studies in this thematic scope is shown in the further part of this work where some results of calculations for the bearing capacity of soil under a square foundation footing with the unitary dimensions are presented in the case of a specific range of variability of properties for clay of low plasticity.

## 2. The bearing capacity of soil

Bearing capacity is a key parameter for foundation design. This is the maximum stress that the soil can support at foundation level without failure. Terzaghi (1943) developed the bearing capacity solution for a continuous shallow foundation with a footing width $B$ and an depth of footing $D$ under the level of ground. He adopted the punching shear theory for metals of Prandtl (1920) to soils, including soil's gravitational force. He assumed that: a) soil shear strength is given by equation (1), b) footing depth $D$ is replaced by a surcharge load ($q = \gamma D$), and c) the footing base has a rough surface. To extend the applicability of Terzaghi equation to more general situations, the modifications of determining the bearing capacity were proposed by several researchers (De Beer (1970), Hansen (1970), Vesic (1973), Hanna and Meyerhof (1981) and others) [1]. The following equation (3) to determine the general bearing capacity $R_d$ is according to Eurocode 7 (Design Approach 2) [3] and STN 73 1001 [4] where the design bearing capacity of the soil $R_d$ for drained conditions is determined in kPa

$$R_d = (c_d' N_c s_c d_c i_c j_c + q' N_q s_q d_q i_q j_q + 0.5\, \gamma' B N_\gamma s_\gamma d_\gamma i_\gamma j_\gamma) / \gamma_R \,. \tag{3}$$

The symbols used in the equation above are explained in the section "Denotation of symbols" put at the end of work. The bearing capacity factors $N_c$, $N_q$ and $N_\gamma$ are functions of the effective angle of internal friction $\varphi'$ of the subsoil as it is shown in Fig. 2. The term $q' N_q$ is a contribution from the surcharge load $q' = \gamma_1 D$ at the footing base level. Symbol $\gamma_1$ is the unit weight of soil above the base of footing level, and $\gamma'$ is the unit weight of soil below the base level. On the other hand, the $c_d' N_c$ term is a contribution to the bearing capacity from the cohesion resistance along the failure surface, and the $0.5\, \gamma' B N_\gamma$ term is coming from the frictional resistance along the failure surface.

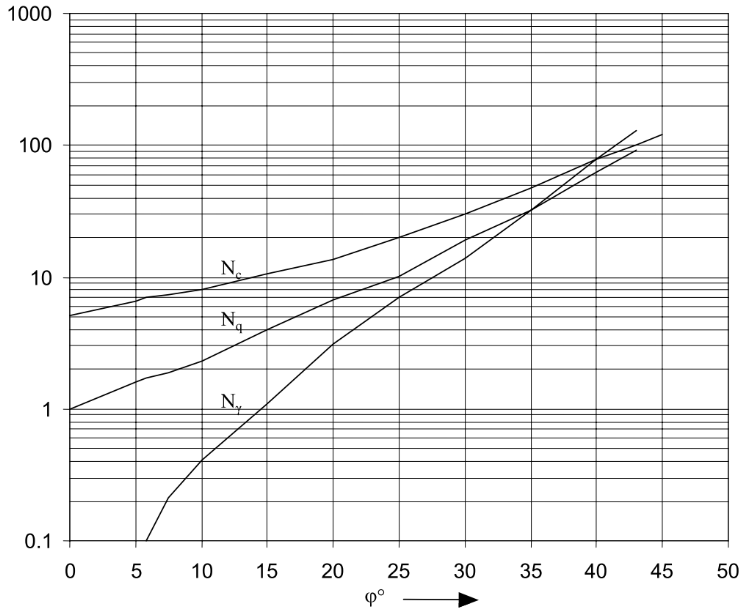


Fig. 2. Graph to determine the bearing capacity factors [4].

The shape of foundation factors ($s_c$, $s_q$, $s_\gamma$), the depth factors for deeper shallow foundations ($d_c$, $d_q$, $d_\gamma$), the inclination factors of the load (of the vertical load) ($i_c$, $i_q$, $i_\gamma$), and the inclination factors of the terrain surface ($j_c$, $j_q$, $j_\gamma$) can be determined from the following relations respectively:

$$s_c = 1 + 0.2\frac{B}{L} \qquad s_q = 1 + \frac{B}{L}\sin\varphi_d \qquad s_\gamma = 1 - 0.3\frac{B}{L}, \tag{4}$$

$$d_c = 1 + 0.1\sqrt{\frac{D}{B}} \qquad d_q = 1 + 0.1\sqrt{\frac{D}{B}\sin 2\varphi_d} \qquad d_\gamma = 1, \tag{5}$$

$$i_c = i_q = i_\gamma = (1 - \tan\theta)^2, \tag{6}$$

$$j_q = j_\gamma = (1 - \tan\beta)^2 \qquad j_c = j_q - \frac{1 - j_q}{N_c \tan\varphi_d} \tag{7}$$

where: $\beta$ is the inclination angle of the terrain from the horizontal [°], and $\theta$ is the angle of deflection of the resultant force from the vertical one [°]. For $\theta > 30°$, it is progressing individually.

The bearing capacity $R_d$ is the ultimate gross bearing capacity which is the ultimate stress value that the soil can carry at the base of the footing level. The soil is assumed to fail along the potential failure surface. Obviously, the bearing capacity must be calculated based on correct shear parameters of soil since there may be a failure.

## 3. The bearing capacity of soil from experimental results

The bearing capacity was calculated for a square foundation footing ($B$ x $L$ = 1 m x 1m) which was based on the cohesive soil (CL) on the depth $D$ = 1.6 m. The values of the geotechnical characteristics for clay of low plasticity (CL), denoted as group F6, are given in Table 1.

Table 1. The geotechnical parameters of investigated soil.

| **Properties** | **Group F6 – CL (low plastic clay)** |
|---|---|
| Poisson's ratio $\upsilon$ [-] | 0.40 |
| Unit weight $\gamma$ [kNm$^{-3}$] | 21.0 |
| Total stress parameters – cohesion $c$ [kPa] | 50 |
| Total stress parameters – angle of friction $\varphi$ [°] | 0 |
| Effective stress parameters – cohesion $c'$ [kPa] | 8 - 16 |
| Effective stress parameters – angle of friction $\varphi'$ [°] | 17 - 21 |

The bearing capacity of a foundation is a function of the shear strength of the soil. In the calculations, different values of cohesion $c_k'$ = 8÷16 kPa and of frictional angle $\varphi_k'$ = 17÷21° were used as coming from Table 2 for the considered clay.

The design bearing capacity of the clay of low plasticity for drained conditions was determined according to equations 3-7. The impact of shear strength parameters on the bearing capacity for drained soil is illustrated in Fig. 3.

Table 2. The bearing capacity of the cohesive soil (CL) for drained conditions.

| **The parameters of shear strength** | **The bearing capacity of the soil for drained conditions depending on the change in parameters of shear strength** | | | | |
|---|---|---|---|---|---|
| | $\varphi_k'$ = 17° | $\varphi_k'$ = 18° | $\varphi_k'$ = 19° | $\varphi_k'$ = 20° | $\varphi_k'$ = 21° |
| $c_k'$ = 16 kPa | 353.29 | 386.60 | 423.68 | 465.01 | 511.16 |
| $c_k'$ = 15 kPa | 341.22 | 373.67 | 409.81 | 450.12 | 495.15 |
| $c_k'$ = 14 kPa | 329.14 | 360.74 | 395.95 | 435.23 | 479.14 |
| $c_k'$ = 13 kPa | 317.07 | 347.81 | 382.08 | 420.34 | 463.13 |
| $c_k'$ = 12 kPa | 305.00 | 334.80 | 368.21 | 405.45 | 447.12 |
| $c_k'$ = 11 kPa | 292.93 | 321.95 | 354.34 | 390.56 | 431.11 |
| $c_k'$ = 10 kPa | 280.85 | 309.02 | 340.47 | 375.67 | 415.10 |
| $c_k'$ = 9 kPa | 268.78 | 296.08 | 326.61 | 360.77 | 399.08 |
| $c_k'$ = 8 kPa | 256.71 | 283.15 | 312.74 | 345.88 | 383.07 |

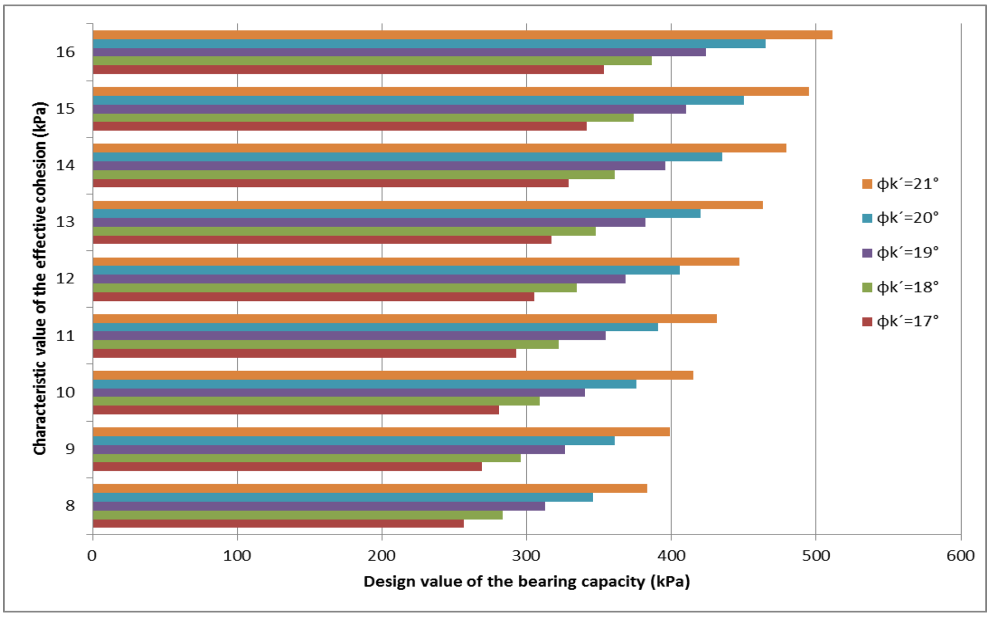


Fig. 3. Influence of shear strength parameters on the bearing capacity of soil.

## 4. Conclusion

Designing of foundations must satisfy generally two main requirements: complete failure of the foundation must be avoided with an adequate margin of safety, and the total settlements of the foundation must be kept within limits that can be tolerated by the construction. This article concerns only the analysis of the ultimate bearing capacity for specific subsoil from the clay of low plasticity.

The specific range of the geotechnical properties for the clay presented in the work results in significant changes of the bearing capacity of subsoil under the square foundation footing. The analysis indicates that, in general, the influence of the shear strength parameters of subsoil on the bearing capacity is very important, especially, when changing the angle of internal friction. Using incorrect shear parameters of soil may obviously lead in practice to local shear failure. The calculation of bearing capacity of subsoil for the specific soil parameters (for analyzed in the work low plastic clay under foundation footing of unitary area) shows exemplary that the reliability of the input data is the basic prerequisite for the optimal design of foundation without failure.

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## Denotations of symbols

$c_d'$ – design value of the effective cohesion, $c_d' = c_k' \gamma_c$, [kPa];
$c_k'$ – characteristic value of the effective cohesion, [kPa];

$d_c$, $d_q$, $d_\gamma$ – depth factors for deeper shallow foundations;
$i_c$, $i_q$, $i_\gamma$ – inclination factors of the load;
$j_c$, $j_q$, $j_\gamma$ – inclination factors of the terrain surface;
$q'$ – design effective overburden pressure at the level of the foundation base, $q' = \gamma_1 D$, [kN/m$^2$];
$s_c$, $s_q$, $s_\gamma$ – shape of foundation factors;
$B$ – foundation width, [m];
$D$ – embedment depth, [m];
$L$ – foundation length, [m];
$N_c$, $N_q$, $N_\gamma$ – bearing capacity factors (dependent on the design value of effective angle $\varphi_d$); the graph enabling determination of the bearing capacity factors according to [4] is shown in Fig. 2;
$\gamma_1$ – effective unit weight of soil above the base of footing level, [kN/m$^3$];
$\gamma_c$ – partial factor for the effective cohesion, for Design Approach 2 $\gamma_c = 1.0$;
$\gamma_R$ – partial factor for a resistance, for Design Approach 2 $\gamma_R = 1.4$;
$\gamma_\varphi$ – partial factor for the effective angle, for Design Approach 2 $\gamma_\varphi = 1.0$;
$\gamma'$ – design effective weight density of the soil below the foundation level, [kN/m$^3$];
$\varphi_d$ – design value of the effective angle, $\varphi_d = \varphi_k' \gamma_\varphi$, [°];
$\varphi_k'$ – characteristic value of the effective angle, [°].

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**Summary**

The strength of soil is a key parameter in designing foundations and other earth structures. In shallow foundation design, the capacity of the foundation to support footing load is dependent on the soil's bearing capacity which is a function of its strength parameters. According to [4], bearing capacity is the maximum pressure that the soil can support at foundation level without failure. Proper interpretation of specific shear strength parameters of clay and the application of this case to bearing capacity problems was presented and reviewed in this paper. The influence of the shear strength parameters of subsoil on its bearing capacity are very important, especially, when changing the angle of internal friction. The results of calculations for low plastic clay subsoil, shown in the work, illustrate exemplary how a level of its bearing capacity can be determined with significant errors when using incorrect shear parameters of soil.