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The Laboratory Study of Shear Strength of the Overconsolidated and Quasi - Overconsolidated Fine - Grained Soil

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Abstract. The paper presents results of laboratory shear strength test conducted on fine-grained soil samples with different grain size distribution and with different geological age and stress history. The Triaxial Isotopic Consolidation Undrained Tests (TXCIU) were performed under different consolidation stress in normal and overconsolidadion stress state on the samples with natural structure. Soil samples were selected from soil series of different age and geological origins: overconsolidated *sensu stricto* Miopliocene silty clay (siCl) and quasi overconsolidated Pleistocene clayey silt (clSi). Paper pointed out that overconsolidated sensu stricto and quasi overconsolidated fine-grained soil in same stress and environmental condition could show almost similar behaviour, and in other condition could behave significantly different. The correct evaluation of geotechnical parameters, the possibility of predicting their time-correct ability is only possible with appropriately recognized geological past and past processes that accompanied the soil formation.

1. Introduction

Shear strength is usually described and interpreted using the Mohr - Coulomb equation [1]:

$$\tau = \sigma_v' \tan\varphi' + c' \quad (1)$$

where: c' - effective cohesion and φ'- effective friction angle.

The values of parameters φ' and c' defined through tests and using the formula (1) will depend on, among other things, which strength is being adopted: peak value, residual or critical state value. The strength according to the Critical States theory is described by the Critical State Line (*CSL*) [2] with the equation:

$$q = M p' \quad (2)$$

drawn in the stress space q - p' (figure 1) where $q = (\sigma'_1 - \sigma'_3)$ and $p' = 1/3\ (\sigma'_1 + 2\ \sigma'_3)$ (σ'_1 is axial effective stress and σ'_3 is radial effective stress) or more commonly in the space of normalized stress with yield stress σ'_y in space : $q/\sigma'_y - p'/\sigma'_y$ [3-5]. This way of presenting results is more convenient as it does not require the use of Mohr's circles and the *CSL* line is obtained from points representing the critical state of failure.

According to theoretical assumptions [2] for normal stress $\sigma'_n = 0$, shear stress is $\tau = 0$ in the case of soil without structural bonds for which effective cohesion is c '= 0 [2]. In soils that have such bonds (cohesion, c ' > 0), the peak value of strength will be greater than the value of critical stress state – the stress paths will break above the *CSL* line and below the yield envelope (figure 1). At high normal stresses exceeding the strength of interstitial bonds the paths of peak stress will reach the critical state line, not exceeding it [4]. The limit of the stress state is the effective stress, which represents in some way the strength of the inter-granular bonds. This stress is considered to be the main parameter of the state within the Critical States Theory, and is called the yield stress σ'_y and identified with pre-consolidation stress σ'_p [3, 6].

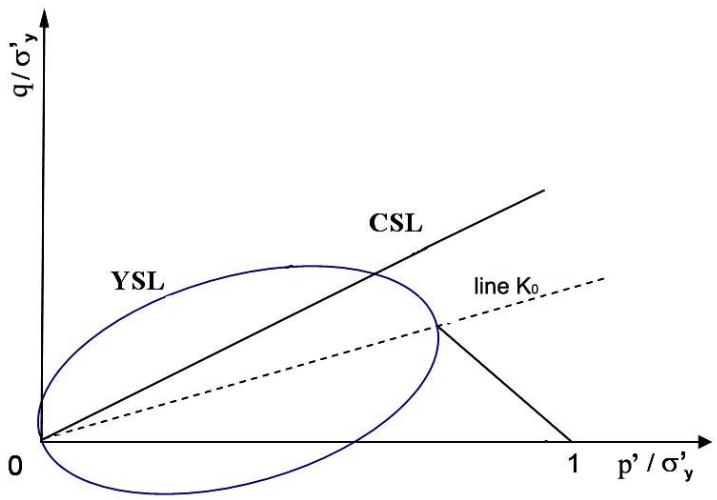

Figure 1. The Yield Stress Limit concept of the (*YSL* yield stress envelope, *CSL* critical state line, σ'_y - yield stress, q/σ'_y and p'/σ'_y normalized stress)

The most convenient of classification of soil due to the stress state in situ is the division into normally consolidated (*NC*) and overconsolidated (*OC*) soil. *NC* soil are those whose virgin effective vertical stress in situ σ'_{v0} corresponds in terms of value to effective yield stress σ'_y determined from the laboratory or in situ geotechnical tests [1,3,6]. This means that when soil is overloaded the strength of inter-granular bonds will be exceeded and the stress path will be on the wet side of the critical state, and the peak strength will coincide with the critical state line *CSL* but will not exceed it.
Overconsolidated soils *OC* are such that are in the state of effective vertical stress in situ σ'_{v0} lower than effective vertical yield stress σ'_y. When applying load to the soil their stress level is initially within the overconsolidation range. With increased load, the interstitial bonds are not broken, as the bond strength can withstand higher loads than only those of the overlapping upper layers in situ. The completed shear stress path will initially be on the dry side of the critical state, and the shear strength peak will be above the *CSL* line. In order for the peak strength to overlap with the *CSL* line, it will be necessary to load the soil above the yield stress σ'_y - achieving the envelope of yielding (Figure 1).
The measure of overconsolidation is the value of *YSR* yield stress ratio, defined as [3,6]:

$$YSR = \sigma'_y / \sigma'_{vo} \tag{3}$$

where: σ'_y - effective vertical yield stress, σ'_{vo} - effective vertical stress in situ,

Soil for which *YSR* given by equation (3) is *YSR* > 1 will be considered as a overconsolidated *OC* and soil for which *YSR* = 1 we consider to be in the state of normal consolidation *NC*.

In a special case when on the basis of recognition of the origin of the soil and its geological past and history we are able to show that the effective yielding stress σ'_y determined in the geotechnical tests corresponds to the value of effective vertical overburden consolidation stress (in Terzghagi's sense (see [1]) preconsolidation stress σ'_p ($\sigma'_p = \sigma'_y$) we consider this soil as overconsolidated *sensu stricto.* In such soils the degree of yield stress *YSR* = *OCR*. We can describe the *OCR* overconsolidation ratio (see [1]) as:

$$OCR = \sigma'_p / \sigma'_{vo} \tag{4}$$

where: σ'_p - effective vertical overburden consolidation stress at which the soil consolidated, σ'_{vo} - effective vertical stress *in situ.*

Quasi overconsolidated soil is such soil in which we can observe the effect of overconsolidation [7,8]. This means that the yield stress shown in the tests σ'_y is greater than the original effective vertical stress in situ $\sigma'_y > \sigma'_{vo}$ (*YSR* > 1) and at the same time higher than the consolidation stress σ'_p □$\sigma'_y > \sigma'_p$) that can be reproduced based on the geological history and geomorphological tests [3,6]. The apparent overconsolidation may be the result of geological and mechanical processes that have reinforced the structure by, for example, cementing the skeleton and secondary compression, etc. [3,6,8]. In *quasi* overconsolidated soil the inter-granular bonds are able to withstand higher stresses than would result from only the consolidation (mechanical consolidation) of the material.

The paper presents the results of the shear strength tests performed on a triaxial compression apparatus for soils from the south-western part of Poland (Wrocław region). The research was carried out on soil samples occurring *in situ* in the overconsolidated state OC. Two types of soil of known geological history have been selected. Overconsolidated soils *sensu stricto* - Miopliocene silty clay, overconsolidated by mechanical loading by the Pleistocene glacier [9-11], and *quasi* overconsolidated soil - Pleistocene clayey Silt, unconsolidated, formed in the form of aeolian deposits formed on the front of the youngest glacier [12].

2. Material and methods

2.1. Material
Two types of soil from the south of Wroclaw were chosen for the study. The intact soil samples were cut from the slopes in the form of blocks, preserving their natural structure and natural water contents. After being transported to the laboratory, the samples were manually cut into specimens 76 mm high and 38 mm diameter. Table 1 presents the basic geotechnical parameters that characterize the soil selected for research: *YSR* value, consistency, ρ - volumetric density, w – natural water contents, e - porosity index and percentage content of soil fractions: *Sa* – sand, *Si* – silt and *Cl* – clay fraction.

Soil sample (A) - overconsolidated soil *sensu stricto*. Soil with a known history of load - Miopliocene silty Clay (*siCl*), in a stiff consistency, in saturated state, Sr = 0.97, a part of the Poznan Clay formation [8,11]. The typical Poznan Clays are usually in stiff consistency and highly expansive (swelling clay) [13]. The examined sample was taken from mo silty layer and the swelling pressure was lower than 20 kPa. The soil was overloaded by Pleistocene glacier. It is assumed that it consolidated under the continental glacier in Pleistocene [8, 10].The test sample was taken at the depth of 9 m below terrain level. The yield pressure determined by the oedometric tests σ'_y = 940 kPa [8,11], and the estimated *YSR* = 6.5 [8,11]. On the basis of geological history [11] it was assumed that *YSR=OCR*.

Table 1. General geotechnical parameters of tested soils.

Sample	YSR[a] [-]	Consistency	ρ [g/cm^2]	w [%]	e [-]	Fraction cl [%]	si[%]	sa[%]
SiCl (A)	6.5	stiff	1.9	25.4	0.70	39.3	59.5	1.2
clSi (B)	4.9	stiff	1.71	9.3	0.71	12.0	49.0	39.0

[a] from oedometric test.

Soil sample (B) *quasi* overconsolidated soil sample. Soil with a known history of overburden load, not loaded i geological past Pleistocene clayey Silt (clSi) in a stiff consistency, and in unsaturated state with a degree of saturation Sr = 0.34. The soil formed as a sediment deposit at the front of the youngest glaciation. The deposit resembles a loess-like cover [12]. The sample was extracted at a depth of 3m below terrain level. Laboratory tests have shown that the stress σ'_y is much higher than effective vertical stress in situ σ'_{vo} and is σ'_y = 250 kPa, and determined is *YSR* = 4.9. The maximum calculated effective consolidation overburden stress was estimated at σ'_p = 59 kPa. It is much smaller than the yield stress measured in the oedometric study σ'_y = 250 kPa. The observed effect of overconsolidation is the result of inter-granular bonds created at the stage of geological processes. The tests show that this effect disappears when the sample is saturated with water [14].

2.2. Method

As a preliminary study, soil microstructure studies in a Scanning Electron Microscope (SEM) were conducted to compare soil samples.

Shear strength tests were carried out for both soils using a triaxial compression apparatus *TXCIU* (triaxial isotropic compression, undrained shearing). The tests were conducted with isotropic consolidation and under undrained conditions during shearing with pore water pressure control [15]. The research was conducted on samples with natural intact soil structure and natural water content. Specimens were cut manually in the laboratory to 38 mm in diameter and 76 mm in height. After consolidation and in same cases initially saturated the samples were sheared, the shear rate was 0.045 mm / min.

The tests for both samples were performed after saturation with water (the moisture content was $Sr > 0.95$) and at natural humidity under conditions in which they work in situ without pre-treatment of pores with water. For sample (A), which occurs in situ in a saturated state only one study series was performed. In the case of a sample (B) occurring in situ in a non-saturated state, where he observed effect of overconsolidation disappears under compression conditions at full saturation of the pores with water, two series of tests were performed. The results are shown in graphs of stress paths in the q - p' [2,15]. Using the Mohr-Coulomb Criterion and abasing on the Critical States Theory the soil strength parameters for the overconsolidation stress state were determined: friction angle ϕ' and cohesion c' from equation (1) and state parameter M from equation (2). The behaviour of the soil in the overconsolidation stress range and normal consolidation after exceeding the value of yield stress σ'_y was discussed.

3. Results and discussions

The results of the *SEM* scanning microscope are shown in figure 2. Tests have shown that in Sample A - Miopliocene silty Clay (siCl) - a locally turbulent natural microstructure [16], and mineral deposits with numerous smectite minerals, and less present kaolin were found. In the case of sample B, the fragment of microstructure is shown in figure 3 - clayey Silt (clSi) revealed a disordered skeletal microstructure with high porosity [16]. The minerals found in the sample included mainly quartz and individual feldspars. Between the quartz grains, clay minerals were found, forming inter-granular bridges bonding the soil grains (quartz grains). It can be assumed, therefore, that the bridges are responsible for the overconsolidation effect, strengthening the bond between the grains. This would explain the disappearance of the overconsolidation effect by saturating the soil pores with water, due to the reduction of clay bond strength in the presence of water.

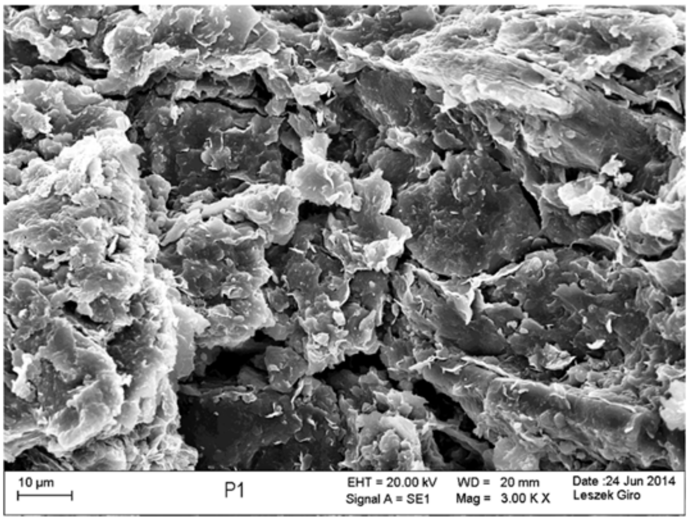

Figure 2. Microstructure of soil A (siCl) with SEM - overconsolidated clay *sensu stricto.*

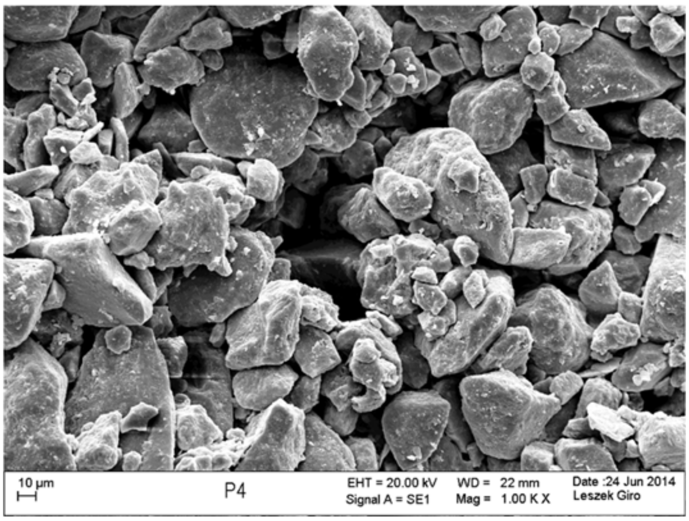

Figure 3. Microstructure of soil B (clSi) with SEM – *quasi* overconsolidated silt.

The results of the tests performed on the triaxial compression apparatus *TXCIU* are shown in Figures 4 - 6 and Table 2.

In the A tests set, the overconsolidated *sensu stricto* soil sample, the tests were performed at natural water contents and in saturated state. The degree of saturation of the specimen before the test was $Sr = 0.97$. The 9 specimens were cut off from the sample, then were axially sheared after consolidation of soil at isotropic pressures σ_3 of: 80, 100, 200, 300, 400, 600, 800, 1000 and 1200 kPa. Selected test results are shown in Figure 4. The resulting stress paths are shown in Figure 5 in the space of the effective stresses q - p'.

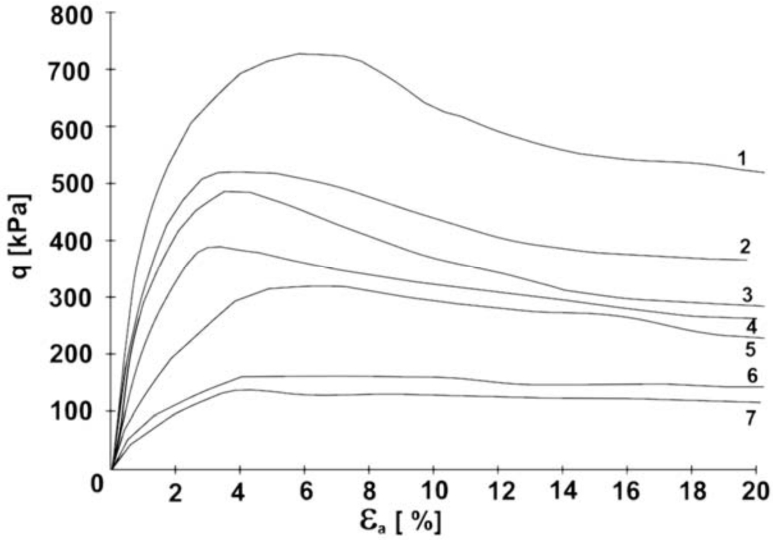

Figure 4. Undrained triaxial test on sample A
(Confining stress: 1-1200kPa, 2-800kPa, 3-600kPa, 4-400kPa, 5-300kPa, 6-100kPa, 7-80kPa).

The study allowed to designate the *CSL* line and the *M* value from the equation (2), which for the examined soil was $M = 0.95$. Using Mohr Coulomb Criterion, the equation (1) was used to determine shear strength parameters: effective internal friction angle φ' = 36° and effective cohesion $c' = 60$ kPa, Table 2. The parameters in equation (1) were determined within the overconsolidation stress range, in the range of 80÷ 200 kPa, for which the cohesion of soil was the highest. It was noted that with the increase in soil stress above the yield stress σ'_y the value of cohesion c' determined from (1) decreases.

Table 2. TXCIU test results.

Sample	σ'₃ [kPa]	q_{peak} [kPa]	M [-]	φ' [deg] (50 ÷200 kPa)	c' [kPa] (50 ÷200 kPa)
A - siCl S_r=0,97	80	120	0.95	36	60
	100	160			
	200	230			
	400	390			
	600	490			
	800	510			
	1200	728			
B - clSi S_r=0.34	50	125	0.61	28	50 [a]
	80	127			
	100	108			
	200	136			
	400	241			
B - clSi S_r<0.95; 1>	50	80	0.61	41	0.0
	80	75			
	100	70			
	200	105			
	400	185			
	600	204			
	800	238			
	1200	362			

[a] suction has not been taken into account.

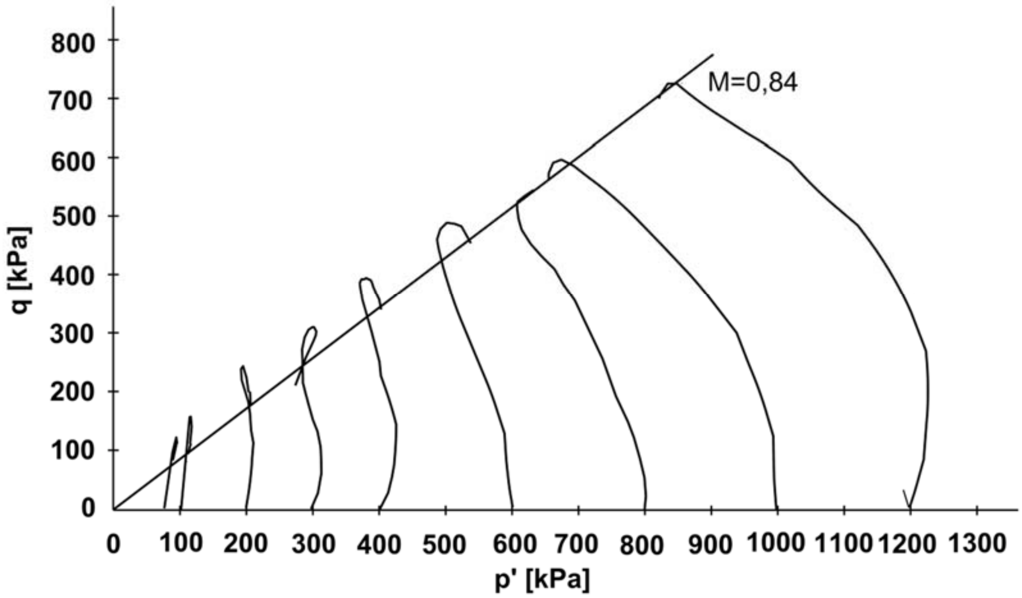

Figure 5. Undrained triaxial test on sample A.

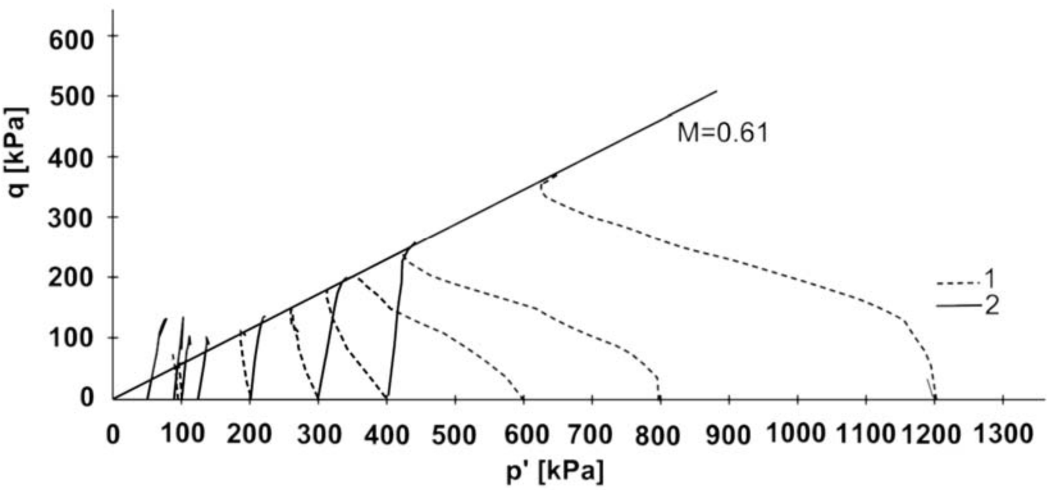

Figure 6. Undrained triaxial test on sample B
(solid line - unsaturated soil state, dashed line - saturated soil state).

Figure 5 clearly shows that the peaks in the overconsolidation state are above the *CSL* limit line. When stress exceeds the yield stress the strength peaks overlap with the *CSL* line, and the influence of cohesion *c'* is of lesser importance. As shown in Figure 5, with the increase of stress the structural bonds resulting from cohesion *c'* are destroyed and, after reaching normal *NC* consolidation, shear strength is determined mainly by soil compaction, caused by friction between the grains of the soil skeleton.

In the case of soil sample B – *quasi* overconsolidated clayey Silt, the tests were performed in two series. The first series of tests was carried out with pre-saturation of the soil sample, *Sr* <0.95,1>. The ample was not saturated in the second series because the effect of overconsolidation disappears as a result of the saturation of the sample. In total 15 specimens were cut from sample B, which were then axially sheared after pre-saturation and without water pre-saturation, and after consolidation of soil at chamber pressures σ_3 equal to: 50, 80, 100, 150, 200, 300, 400, 600, 800, 1000 and 200 kPa. The results are shown in the form of stress paths in Figure 6. Dashed line shows the saturated stress path and solid line shows not saturated stress path. The selected parameter values obtained from the tests are presented in Table 2. It was noted that the tested soil when sheared after water saturation practically did not exhibit the characteristics of overconsolidation, and generally no clearly visible peak strength value was observed and visible slip surface on tested specimen [17]. A slight effect of overconsolidation can be observed for some of the shear stress path at $\sigma_3 < 100$ kPa. Above this value, the strength peaks do not exceed the *CSL* line. The stress paths for unsaturated soil are different at natural water contents. The observed effect of overconsolidation is clearly visible - peak strength values exceed the *CSL* line, as shown in Figure 6. The effect of overconsolidation disappears, however, after the value of the yield stress is exceeded σ'_y. It has been observed that for soil B the values of the parameters determined from equation (1) are different. With loads smaller than σ'_y, and with the effect of *OC* overconsolidation, soil B is characterized by high cohesion c' = 50kPa, which disappears after the transition to the state of normal consolidation *NC*, where $c' = 0$ (the transition is obtained by exceeding the stress σ'_y, or by saturating the sample with water irrespective of the given stress). The parameter of equation (2) M remains the same for both cases at $M = 0.61$.

4. Conclusions

The shear strength of fine-grained overconsolidated soil is related to the mechanism of overconsolidation. As far as normal consolidation is concerned, *NC* soils exhibit similar behaviour. During shearing in the *OC* in overconsolidation stress range, however, soil *sensu stricto* overconsolidated and *quasi* overconsolidated demonstrate different behaviour. The observed effect of overconsolidation is related to the presence of inter-granular bonds, whose character determines shear strength of fine-grained soils. In the case of overconsolidated soil *sensu stricto* the strength parameters are easier to predict. Strength is the result of soil compacting, and peak stress values are always above the *CSL* line. In the case of *quasi* overconsolidated soil, shear strength in the range of *OC* state is much more variable. It may vary locally and depends on soil working conditions. In the analysed samples (silty soil), the saturation of ground water can significantly reduce its shear strength.

Therefore, in order to assess the strength of the overconsolidated soil, it is necessary to determine natural level of the overconsolidation and the process, which led to the observed effect, in addition to the determination of strength parameters.

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