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Overconsolidation Ratio Determination of Cohesive Soil

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Abstract. In order to evaluate overconsolidation ratio (OCR) of soil, the necessity to restore them as much as possible to in situ conditions appears, because sometimes when it is not taken into account, mistakes could be made while interpreting mechanical – strength properties of the soil.
According to the work purpose, overconsolidation ratio of the investigated soil was set by performing odometer test and the obtained values were compared with the OCR calculated from cone and seismic penetration data.
When the tests were performed and data analysed, it was found that OCR values depends on soil occurance depth, strength characteristics and stress conditions. The OCR values decreases with the declination of the depth. As many authors noted in the literature – the upper part of the soil is consolidated abnormally, thereby we can see that in our work. When results are evaluate, we can conclude that all of the analysed soils was overconsolidation. That was demonstrated by calculations according static penetration, oedometer test and seismic waves results. OCR values differences between the laboratory and field tests can show low quality of soil sampling, also due to correlations which was applied.

Keywords: Consolidation, overconsolidation ratio (OCR), oedometer test (OED), cone penetration test (CPT), overconsolidate soil, overconsolidation pressure, glacial clay, Lithuania.

Conference topic: Soil and rock investigation.

Introduction

Overconsolidation ratio (OCR) is one of the key criteria conditioning soil behaviour and characteristics from the geotechnical perspective. This coefficient defines formation of soils and is described as the ratio of previous maximal preconsolidation pressure *(σ'_p)* and current effective geostatic stress *(σ'_{vo})* (Szymanski *et al.* 2006). Stresses and strains in soil depend on previous stresses and their interaction. Those previous stresses in soil, conditioning preconsolidation degree, are generally expressed with overconsolidation ratio (Józsa 2013). Overconsolidation ratio and preconsolidation pressure are considered as the main characteristics of clayey soils, essential in geotechnical design to indicate soil stains under constructions. The definition of overconsolidation ratio itself was suggested by Cassagrande (1936). OCR and preconsolidation pressure values influence such characteristics of soil as strength, strain and compressibility. OCR is most often established from a compression curve as a result of laboratory oedometer tests of incremental loading of a sample of undisturbed soil sample. Other possibilities to establish OCR include field methods with derived relations among field methods and OCR parameter established in the laboratory. Based on the current stress magnitude and stress history, overconsolidation ratio OCR soils are divided into nonconsolidated (OCR < 1.0), normally consolidated (1.0–1.5), overconsolidated (1.5–10.0) and higly overconsolidated (OCR > 10.0).

The aim of the present paper is to establish overconsolidation ratio using the results of oedometer tests and compare such values with OCR calculated using the results from tests of seismic cone penetration. Also, to compare additionally derived OCR values with those of overconsolidation ratio resulting from the undrained shear strength (*Cu*).

The studies involved analysis of till sandy silt clay of the Nemunas suite, from western Samogitian Plain, Pagėgiai District, Strepeikų Village (Fig. 1).

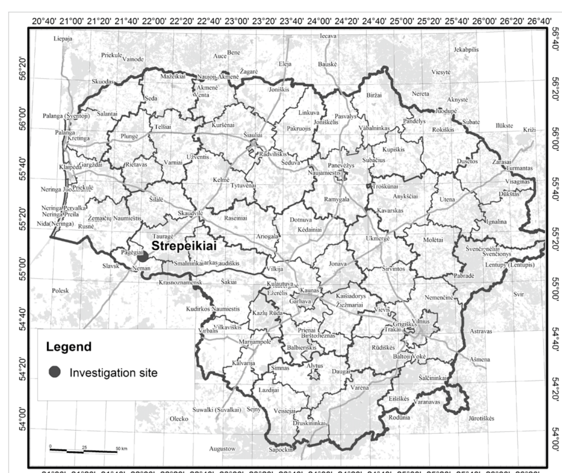

Fig. 1. Investigation site

In the world, there exist a number of theoretic and empiric correlations to establish OCR (Mayne 1991). However, it is essential to try the theory in practice for each soil type under geological conditions of the studied place (Szymanski 2000). In Lithuania, overconsolidation ratio for till soils has been scarcely studied among scientists; it is usually confined with the opinion that due to the size of glacier the majority of soils prevailing in our territory are overconsolidated or higly overconsolidated. This hypothesis is partially confirmed by tests of private companies using cone penetration test and calculating OCR values during such tests, involving correlations established worldwide.

Methodology

The studies included field and laboratory works. In field, soil was examined using cone penetration test (CPT) and additionally there was established the crosscurrent speed *Vs*. Samples of undisturbed soil required for laboratory tests were taken by means of core-percussion method.

In the laboratory, overconsolidation ratio was established from the results the oedometer test with incremental loading. The steps of sample loading included: an initial load – 25 kPa, further, loads were doubled till 1.6 MPa. Afterwards, unloading was performed removing 0.8; 0.4 and 0.3 MPa. During the second loading, loads were in succession increased as following – 0.1; 0.2; 0.4 and 0.8 MPa (Head 1994). The data of the compressor test are given in the compression curve (Fig. 2), showing dependence of the void ratio on stress.

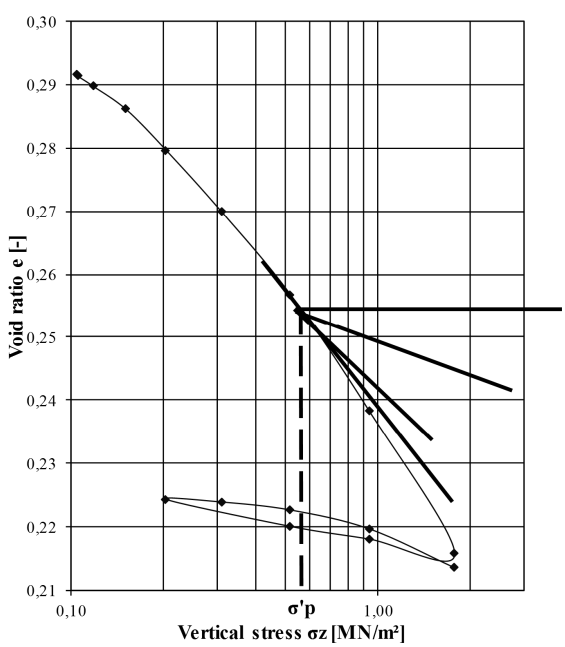

Fig. 2. Compression curve

The point in the compression curve, established using the Cassagrande graphic method show that stress which soil is beaten with and starts plastically deforming and indicate preconsolidation pressure ($\sigma'p$) (Habtegiorghis 2012). Normally, overconsolidation degree is called overconsolidation ratio (OCR):

$$OCR = \frac{\sigma'_p}{\sigma'_{vo}}, \qquad (1)$$

where $\sigma'vo$ – vertical effective stress, and $\sigma'p$ preconsolidation pressure, established from porosity ratio *e* derived from oedometer test and semi logarithmic diagram of $\log\sigma'vo$ ratio (Fig. 2).

Additionally, undrained shear strength (Cu) was established in the laboratory. This soil index was established performing unconfined compression tests. The deformation curve shows that soil deformation is plastic, thus, in the case when soil decay is not obvious, it is accepted that soil strength is at 15% of relative deformation (Fig. 3). According to the Eq. (2), we can calculate the undrained shear strength:

$$C_u = \frac{q_u}{2}. \qquad (2)$$

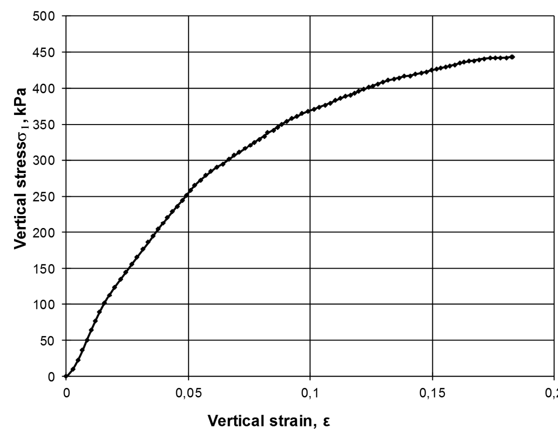

Fig. 3. Typical unconfined compression test

Skempton offered the equation to evaluate the undrained shear strength in normally consolidated soils, using plasticity index (I_p) (Skempton 1954, 1957):

$$\frac{c_u}{\sigma'_{vo}} = 0.11 + 0.37 I_P. \qquad (3)$$

For overconsolidated soils, the Eq. (4) is applied that based on empyric basis, employing additional theoretic solutions based on critical mechanical conditions of soils, found to calculate OCR (Ladd *et al.* 1977; Muir Wood 1990):

$$\frac{c_u / \sigma'_{vo}}{\left(c_u / \sigma'_{vo} \right)_{nc}} = \left(OCR \right)^{\wedge}, \qquad (4)$$

where $\wedge$ – empyric exponent, which varies from 0.85 to 0.75 and depends on OCR value. Using the Eqs (2) and (3) and slightly correcting them, we have the relation that can be used to calculate overconsolidation ratio OCR:

$$OCR = \left[\frac{c_u / \sigma'_{vo}}{0.11 + 0.0037 \left(I_P \right)} \right]^{1.25}. \qquad (5)$$

In field, soil were studied using cone penetration – one of the best and most efficient tests for soil examination ***in-situ***, with no distruction on their natural environment. During cone penetration test (CPT) cone tip resistance (q_c) and friction ratio (*fs*) were measured. Overconsolidation ratio (OCR) was calculated according to the equation suggested by Mayne and Kemper (1988). When making this equation, the authors performed 102 laboratory tests and had the correlation coefficient – 0.91.

$$OCR = k \cdot \left(\frac{q_c - \sigma_{vo}}{\sigma'_{vo}} \right)^{11}, \quad (6)$$

where k – coefficient. The interval of this coefficient is the range of 0.2–0.5, and the average value k = 0.3 (Kulhawy, Mayne 1990).

In the equation No 6, the average value of the coefficient k suggested by the authors in the initial calculations is 0.33. It should be noted that the value of the coefficient k has not been studied yet in Lithuania.

Natural state soils have also been studied with a seismic standby instrument for cone penetration test that enables measuring seismic wave velocity. The seismic cone is pressed into soil and stopped at each 0.5 m to perform seismic measurements. The wave soured is activated in each interval to excite seismic waves. All the results are registered in the oscilloscope – signal form observation and measurement device. The overconsolidation ratio is calculated according to the aforementioned Eq. (1). Here, we can find the preconsolidation pressure using these dependences (Eqs 7–9). The first Eq. (7) was applied to clayey coils (Mayne *et al.* 1998):

$$\sigma'_p = 0.107 \cdot V_S^{1,47}. \quad (7)$$

Afterwards, one of the authors (Mayne 2007) improved the equation introducing the impact of shear modulus and effective stress on the preconsolidation pressure:

$$\sigma'_P = 0.101 \left(\sigma'_{atm}\right)^{0.102} \left(G_O\right)^{0.478} \left(\sigma'_{vo}\right)^{0.420}, \quad (8)$$

where: σ_v – vertical (geostatic) stress; G_o – shear modulus, established using test of shear waves *Vs* (m/s); σ'_{atm} – atmospheric pressure that equals 101.3 (kPa).

Introducing the value of atmospheric pressure as a constant, Eq. (8) can be written as simplified:

$$\sigma'_P = 0.161 \cdot \left(G_O\right)^{0.478} \left(\sigma'_{vo}\right)^{0.420}. \quad (9)$$

Discussion

According to the bore drawing the studied glacial (till) sandy silt clays occur in the depth from 0.3 m to 27.0 m. These are till soils of the upper suite of the Nemunas rich with watery sand lenses and microlenses and gravel admixtures up to 3–5%. Water in the explored territory is found in the depth of around ~0.3–1.0 m, and knowing that in the upper part, in the bore location, there occur the same till soils, so in different seasons, due to melting snow and after long-term rains, ground water level can be very close to the ground surface. Therefore, in calculations of the effective stress, water level is accepted as 0.3 m.

Following the Attenberg limits, the studied soil is very stiff (*Ic* > 1.0), plasticity index (I_p) ranges from 0,090 to 0,130 (average – 0,109). The void ratio (*e*) changes from 0.30 to 0.35. The particle density (ρ_s) is 2.72 Mg/m^3. Natural density (ρ) changes from 2.26 to 2.30 Mg/m^3, natural moisture (*w*) – from 0.103 to 0.125. After grain size distribution by hydrometer and according to Standard LST EN ISO 14688-2 the studied soil is defined as sandy silt clay with rare gravel admixture. The grain size distribution of soil is diverse; clay fraction changes from 8.3 to 18.0%, silt fraction changes from 34.9 to 42.1%, sand fraction – from 37.0 to 48.6% and gravel – from 2.6 to 4.3%. According onconfined compression test results calculated average undrained shear strength – 220 kPa.

Having performed the laboratory, incremental loading soil oedometer tests compression curves were formed (Fig. 2) and used to calculate values of preconsolidation pressure, and according to the depth, soil strength and compression curve shape they changed from 350 to 550 kN/m^2. Having calculated the preconsolidation pressure and evaluating the effective stress (σ'_{vo}), the overconsolidation ratio was established. OCR values were established from soil samples taken in the depth from 3.5 to 20.0 m. Attempts to take representative samples from deeper layers that demonstrated significantly bigger strength based on the results of cone penetration test were not successful. OCR values established in the laboratory change from 1.4 to 8.8.

Based on strength characteristics of the studied till clay and the data of cone penetration test in the depth range ~ 2.0–3.9 m from the ground surface, increase of the is observed (Fig. 4), This shows that soil of very high strength occurs here. In this depth range, namely, OCR values calculated using the results of field methods CPT and SCPT are extremely high > 10 (15.6–20.0 – highly overconsolidated). This upper area distinguishes, and other authors (Wierzbicki 2009) also relate this to processes going on and finished in the upper part of ground thickening, with changes of ground water mode, which influences conditions of stress; also, it relates to likely soil carbonization.

Upon a greater depth, clay strength based on the results of cone tip resistance remains similar, and OCR values decrease <10 (9.9–1.8 – overconsolidated) but increase in the areas where soil strength increases. One more increase of OCR values is observed in the depth from ~ 20.6 m, when values of cone tip resistance q_c increase to >4 MPa, and the calculated OCR is 12 to 20 (Fig. 5). According to grain size distribution, grain size of soil in this depth changes slightly, and in the soil, there appear more gravel fraction and clay volume decreases. Moreover, in this depth range, soil compression is lower; void ratio decreases from 0.35 to 0.30.

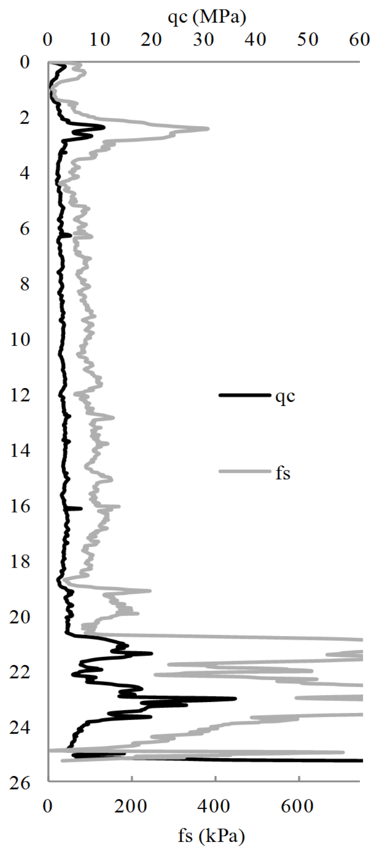

Fig. 4. Results of cone penetration test (CPT)

According to the results of seismic cone penetration test (SCPT), the studied soil is also overconsolidated (Fig. 5); however, values resulting from this method are mildly lower (Table 1) to compare with OCR value recalculated based on the results of cone penetration test. When estimating overconsolidation ratio using the method of crosscurrent, the upper part and the depth range 2.0–3.3 m also distinguish, where increased values of cone tip resistance are observed, and OCR values reach 5.0 to 7.0. When going deeper, OCR value within the total study depth (25 m) is 2–4 on average (Fig. 5). Employing this method in preconsolidate pressure (σ'_p) calculations from *Vs* waves and shear modulus *(Go)* and having calculated OCR, the studied soil is overconsolidated in all cases.

The highest OCR values are derived recalculating them from undrained shear strength using the Eq. (5). This mainly depends on the numeric value of the used exponent; when decreasing it, OCR values would be significatly lowered and closer to the values derived using other methods.

The OCR value differences in the methods employed (Table 1) are partially influenced by the fact that both cone penetration test, drilling and seismic test were performed in a close distance to one another every 2–4 m, and natural errors are possible when comparing them according to a respective depth, as soil occurrence and their characteristics may change in the depth both horizontally and vertically, especially in till soils. However, when the depth decreases, the change of results increases.

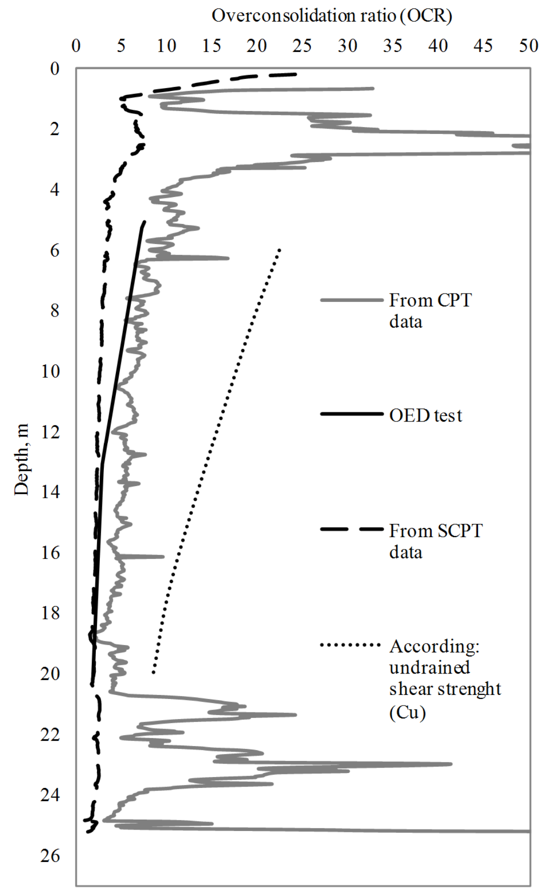

Fig. 5. OCR values according to the depth based on the data from CPT, OED and SCPT tests

Table 1. OCR comparison among different methods

Depth, m	5.0–12.0 m	12.0–20.0 m	5.0–12.0 m	12.0–20.0 m
OCR values from OED	5.0–7.3	1.7–2.7	5.0–7.3	1.7–2.7
OCR values from Cu	16.5–22.4	8.5–15.8	5.2–7.5	2.6–5.0
OCR values from CPT	5.0–12.0	2.5–6.5	2.5–9.0	1.2–4.5
OCR values from SCPT	2.3–3.6	1.6–2.3	2.3–3.6	1.6–2.3
Difference %				
	Real data		After correction	
OED/CPT	23	50	6,5	22
OED/SCPT	45	5	45	5
OED/Cu	68	80	3	35
CPT/SCPT	60	55	45	30
CPT/Cu	55	35	10	25
SCPT/Cu	83	82	50	48

Moreover, this result discrepancy when evaluating OCR values of laboratory results and CPT may be related to the selected value of coefficient *k*. Since it is not established for Lithuanian soils, for this paper the average values selected is 0.33. With a lower value of coefficient k 0.20, OCR, calculated from the results of cone penetration test, nears to the laboratory results and practically coincide. Thus, in calculations of till soil, it is reasonable to use lower values of coefficient k than this average one suggested by the authors (Kulhawy, Mayne 1990). The largest discrepancies appear between OCR established in the laboratory and the one calculated according to the undrained shear strength. The most coinciding OCR values are the ones derived from the laboratory tests and results of seismic probing.

After adjustments of OCR calculations according to the undrained shear strength and selection of the exponent 0.7 in the Equation (5), the evaluated OCR practically coincides with the OCR values established in the laboratory. Additionally, for comparison there has been introduced OCR value distribution derived from CPT results when coefficient *k* is 0.20 (Fig. 6).

With some corrections, the results become much closer when calculating using different methods (Table 1).

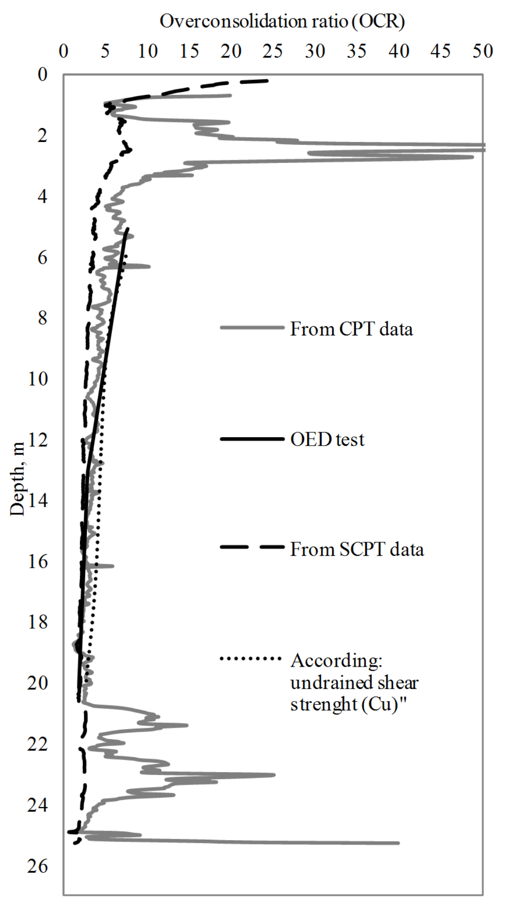

Fig. 6. Modified OCR values according to the depth from based on the data from CPT, OED and SCPT tests

To sum up, it could be stated that the studied glacial (till) sandy silt clay is overconsolidated. This is evidenced with calculations according to the results of cone penetration test and seismic waves, confirmed with laboratory oedometer tests. As many authors in difference resources claim, the upper soil thickening is anomalously overconsolidated with increased values. This area also distinguishes in the studies site. This can be related to processes effecting the surface soil, such as underground water changes, impact of effective stress, etc.

Conclusions

Summarizing OCR values derived from both field and laboratory estimation methods, it was established that the studied soil is overconsolidated in all cases.

Overconsolidation ratio (OCR) was established employing four different methods: field test – cone penetration and seismic tests (CPT, SCPT) and laboratory tests – soil consolidation test (OED) results and derivative calculation according to undrained shear strength.

Discovering of preconsolidation pressure is significantly dependant on taking a composition sample with a proper soil extractor, its preservation, transportation, storage and placing into test rings. The mentioned factors mostly influence successful and effective laboratory evaluation of OCR.

When evaluating the received results, it could be stated that with larger depth OCR values decrease. This shows that previous increased stress has a greater influence in the upper part of thickening. The results distinguish the upper studied area where high OCR values were indicated. In this area, there observed ground water mode changes influencing the state of stresses.

Having used the methods to calculate OCR from CPT, it is suggested to use a lower coefficient *k* value than the average one, taking ~0.20–0.25. For more detailed coefficient *k* exclusion additional tests from different sites is required. According to the undrained shear strength and selection of the exponent 0.7 in the Eq. (5), the evaluated OCR practically coincides with the OCR values established in the laboratory.

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