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ANALYSIS OF CHANGES IN OVERCONSOLIDATION RATIO IN SELECTED PROFILES OF NON-LITHIFIED DEPOSITS

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Abstract
The changes in overconsolidation ratio OCR under different geological conditions are analyzed in the paper. The application of modern subsoil testing methods, dilatometer tests (DMT) and cone penetration test (CPTU), made possible almost continuous observation of changes in overconsolidation ratio with depth. This fact allowed observing regularities and irregularities in stress history of investigated deposits. Some of these changes in stress were interpreted as consecutive stages of sedimentation and erosion, which made possible to find different stages of sedimentation and stratigraphic gaps along tested profiles. The paper points out the potential application of DMT and CPTU tests in geological analyses, particularly those connected with the analysis of stratigraphy of Cainozoic sediments.

Streszczenie
W artykule przedstawiono analizę zmian wartości wskaźnika prekonsolidacji (OCR) gruntu, w zależności od geologicznych warunków występowania. Zastosowanie w badaniach nowoczesnych technik in-situ, sondowania statycznego CPTU i badania dylatometrem płaskim (DMT), umożliwiło niemal ciągłą identyfikację wartości OCR wzdłuż analizowanych profili. Możliwość ta pozwoliła na obserwację pewnych nieregularności w przebiegu historii obciążenia podłoża. Niektóre z tych nieregularności zostały zinterpretowane jako przejaw następujących po sobie procesów sedymentacji i erozji. Takie spostrzeżenie pozwoliło na bardziej pełne odtworzenie stratygrafii badanych osadów. W pracy podkreślono możliwości jakie daje zastosowanie nowoczesnych badań in-situ (CPTU i DMT) w analizie historii geologicznej podłoża zbudowanego z kenozoicznych gruntów nieskalistych.

Keywords: **OCR (overconsolidation ratio); In situ test; Stress history.**

1. INTRODUCTION

The overconsolidation ratio (OCR) is a geotechnical parameter, related to historical changes in the state of stress in the subsoil. The concept of overconsolidation ratio was proposed by Cassagrande [3]. The idea of recording the overconsolidation ratio resulted from the observation of changes in strength parameters of non-lithified deposits, depending on the state of stress found in the subsoil. An example illustrating this dependence is an increase in shear strength of a deposit homogenous in terms of its physico-chemical properties with an increase in depth. Under such conditions determined strength parameters of a given deposit, higher than expected, were thus considered to be connected with a different state of stress in the subsoil than that generated as a result of normal consolidation of the deposit. It needs to be emphasized that consolidation is considered to be normal if it results from a successively increasing load, affecting the deposited sediment at a specific depth. A good example illustrating the process of normal consolidation is free sedimentation of glacilacustrine deposits, not undergoing erosion processes. The overconsolidation ratio OCR was defined by Casagrande as a ratio of maximum effective value of the vertical component of geostatic stress, found at any time in a given subsoil point, to the present effective value of the vertical component of geostatic stress.

However, the OCR index does not always unambiguously reflect changes in strength parameters, generated as a consequence of the overconsolidation process. This results from the effect of several postsedimentation geological processes on the behavior of the subsoil [5]. In relation to these processes we should rather talk about the effect of overconsolidation, which is a wider concept and refers to all postsedimentation transformations in the deposit [23].

The paper presents several examples of interpretation for results of geotechnical analyses, facilitating the assessment of the overconsolidation ratio. The selected deposits include both those which may definitely be considered normally consolidated in the strict sense of the term and those which may have been subjected to historical overload, i.e. should show distinct symptoms of overconsolidation. A combination of results of geotechnical analyses with available geological knowledge in certain cases made it possible to find traces of past geological processes and to attempt and recreate their consequences.

2. METHODOLOGY OF THE ANALYSIS

The application of information related to the overconsolidation ratio is closely connected with the methodology of its determination. An extensive review of research methods facilitating the assessment of OCR was presented in his studies by Wierzbicki [23]. Generally the overconsolidation ratio may be determined by means of both laboratory and in situ methods. The application of laboratory methods requires the recreation of the state of stress found in nature, but it also makes it possible to simulate such conditions which historically could have affected the analyzed deposit [9]. In turn, in situ methods facilitate the determination of strength and deformation parameters in the state of stress found in situ. The main problem connected with laboratory testing is the fact that it is difficult to collect a sample with an undisturbed structure. Collecting a high quality sample, especially at lower depths, is hardly feasible [6]. In certain deposits even samples of high quality lose the properties they had in the subsoil [8]. In recent years numerous in situ testing methods have been developed, facilitating e.g. the assessment of OCR, among which special interpretation potential is ascribed to cone penetration test [10] and dilatometer [11] [17]. The primary advantage of these tests is the analysis of deposits found in the natural state. In case of non-cohesive deposits, in which collecting a sample with a satisfactory quality is practically impossible, OCR assessment until recently was preformed only by analogy with the neighboring cohesive deposits. The development of the dilatometer test in the 1980's for the first time in history made it possible to assess OCR of such deposits [11]. In turn, the application of a more universal cone penetration test to assess the overconsolidation ratio was made possible by interpretation proposals given by Mayne and Kulhawy [14] and Mayne [13], supplemented by Wierzbicki [23].

For a correct interpretation of CPTU and DMT testing results it is also required to take into consideration basic grain size parameters and the state of the analyzed deposit [23] [24]. Thus, for each testing site supplementary analyses of grain size composition were performed and parameters describing the state of soil found in the subsoil were determined. Due to the point wise character of laboratory measurements, not corresponding to the frequency of measurements taken during DMT and CPTU testing, the value of overconsolidation ratio was given only for the depths from which samples were collected or for the entire profile, assuming results of laboratory analyses as representative for individual layers.

In the assessment of OCR on the basis of DMT the methodology proposed by Marchetti [11], and Schmertmann [19] [20] was applied. In case of both cohesive and non-cohesive deposits these methods are based on index KD established on the basis of DMT results. When investigating non-cohesive deposits also effective internal friction angle of soil is used to assess OCR.

In turn, methods developed by Sully et al. [21], Mayne [12] as well as Powell et al. [18], including also remarks by Szymański et al. [22], were used for the determination of OCR in cohesive soils on the basis of CPTU tests.

The method developed by Sully et al. [21] requires the performance of cone tests with possibility to measure "double" pore pressure (CPTUU). Tests of this type were performed only in one of the analyzed testing sites. As it was shown by Wierzbicki and Wołyński [26] and Wierzbicki [23], precise assessment of the overconsolidation ratio in non-cohesive deposits requires, among other things, also the application of a special conical sleeve part unique for CPT, i.e. a dilatocone (DCPT) (equation 1). Since this device is not currently available, some analyses were also conducted on the basis of a formula, using the measurement of normalized cone resistance – Q_t – as well as parameters of state and grain size characteristics of the analyzed soil (equation 2).

$$OCR = \left(\frac{2,75 + 2,65 I_D - 0,08\varphi' - 0,35(f_{Pr}/f_s) - 0,003Q_t + 3,34 f_s + 0,09Q_d}{0,428} \right)^{2,415} \quad (1)$$

$$OCR = \left(\frac{3,45 + 1,486 I_D - 0,088\varphi' - 0,342(f_{Pr}/f_s) - 0,002Q_t + 3,18 f_s}{0,428} \right)^{2,415} \quad (2)$$

where: I_D – relative density in decimal; ϕ' – drained friction angle; f_{Pr} - percentage content of coarse sand grains; f_{Ps} – percentage content of medium sand grains; Q_t – normalized cone resistance; Q_d – normalized dilato resistance; f_s – sleeve friction resistance [MPa].

At one of the testing sites in which undisturbed samples were collected using the MOSTAP sampler, oedometer tests were also performed using the CRS method, defining OCR on their basis. Interpretation procedures for compressibility curves proposed by Becker et al. [2] were used for this purpose.

3. TESTING SITES

The study presents results of tests performed in three sites characterized by different geological structure. Sands deposited at the mouth of the Drammen River in Norway, in literature sources referred to as the Holmen sands (from the name of the island which is formed of them) were selected as an example of deposits considered to be normally consolidated. Based on archive tests and available literature [4] [7], the geological profile may be presented (Fig. 1). The deposits between 22 and 28 meters are composed primarily of silty sands and fine and medium-grained sands. It is assumed that these deposits represent the first stage of fluvial sediment deposition of the Drammen River. The highest part of the profile of natural deposits, between 2 and 22 m below ground level, is formed from medium- and coarse-grained sands. It is thought that this part of the deposits constitute the second series of the alluvial cone, corresponding to the later stage of their formation.

The profile, at which both normally consolidated and overconsolidated sediments were expected, may be deposits in Toporów in the Lubuskie province, Poland. The testing site was located within so-called Pliszka outwash plain. The area of the Pliszka outwash plain was described in detail by Żynda [27]. Outwash deposits are composed primarily of sands and gravels, occasionally of loams. These deposits lay on top of older overconsolidated sands, the so-called inter-moraine sands. However, studies conducted by Wierzbicki [22] showed that, in accordance with the obtained profile to the depth of 20 m (Fig. 1), between upper and lower sandy deposits the series of varied clays has been deposited.

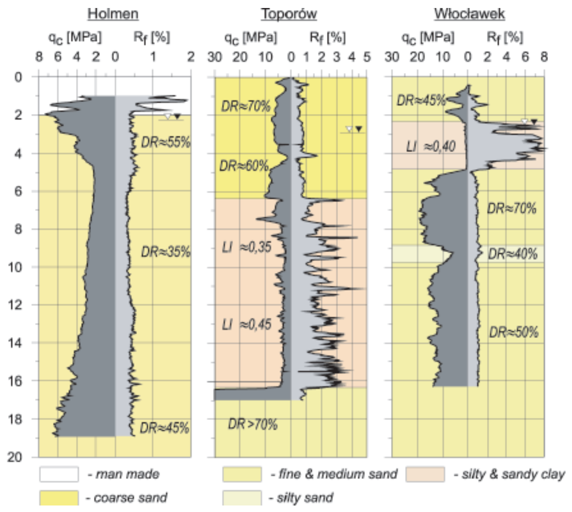

Figure 1.
Subsoil profile of the test sites, along with basic static penetration characteristics (DR – relative density, LI – liquidity index, q_c – cone resistance, R_f – friction ratio)

The third testing site selected for analysis was the area around the town of Włocławek. According to archival data [1], the analyzed area is found within the outcrop of fluvioglacial sands of the Pomeranian phase of the Vistulian (Würm, Wisły) glaciation. These deposits, of several meters in thickness, fill depressions eroded in older glacial or fluvioglacial sediments, genetically connected with Riss (Saale, Odry/Warty) glaciations. Younger fluvioglacial deposits may occur both on moraine deposits and directly on older, overconsolidated fluvioglacial deposits. Numerous, presently fixed dunes are found on the surface of the ground in the vicinity of the testing site. Results of performed preliminary testing [15] showed that sands stratified with fine-grained with admixtures of clayey sands at the testing site from the surface medium-grained sands are found, (Fig. 1). These deposits lay on a layer of compact silty clay, with numerous silty laminae, which may be considered glacilacustrine deposits. In turn, cohesive deposits lie on a series of interbedding medium- and fine-grained sands. Following the adopted geological model, the lower series of non-cohesive deposits may be considered deposits overconsolidated by the continental ice-sheet.

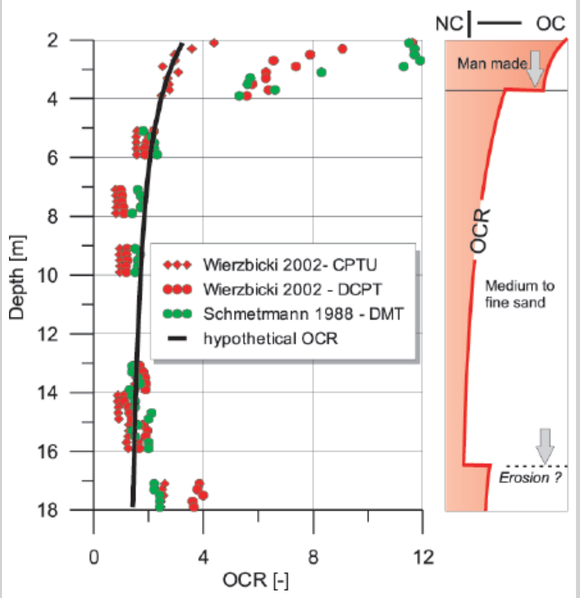

Figure 2.
Changes in overconsolidation ratio (OCR) along the Holmen sands profile (NC – normally consolidated, OC – overconsolidated)

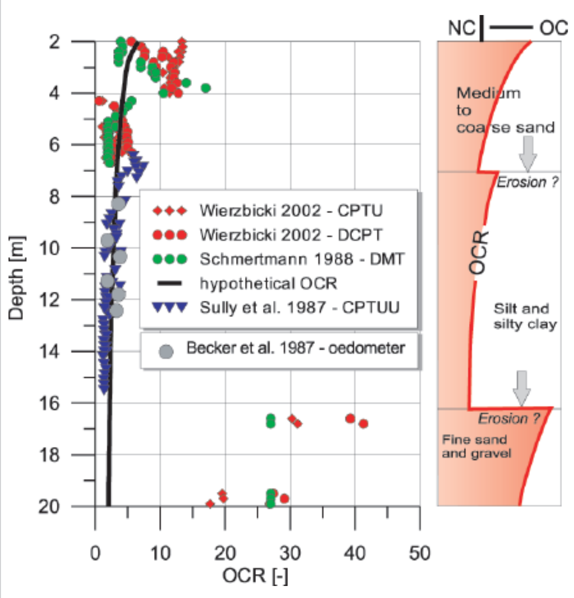

Figure 3.
Changes in overconsolidation ratio OCR recorded in Toporow (NC – normally consolidated, OC – overconsolidated)

4. RESULTS AND DISCUSSION

The determined overconsolidation ratio for the Holmen deposits is presented in Fig. 2. Apart from the OCR value, defined following the adopted methodology, a graph was also presented showing changes with depth in the value of the hypothetical overconsolidation ratio. Hypothetical values were established with the assumption that the effect of overconsolidation was caused by geostatic load, acting in such a way that at the depth of 2 m the overconsolidation ratio was approx. 3. Such an OCR value was assumed as rational, ascribed by researchers to the Holmen sands [25]. For this reason the plot of hypothetical OCR values may serve as a reference point during the analysis.

When observing data presented in Fig. 2, we need to stress a similar trend of OCR changes with depth, observed irrespective of the adopted research method. A decrease in the overconsolidation ratio was comparable with the hypothetical plot to the depth of approx. 16 m. A slightly more rapid drop in values measured in the upper and lower part of the profile may be explained by the imperfect character of the adopted geostatic model of load and the only partially known effect of the decay of the vertical component of stress on the present value of the horizontal component of stress. High OCR values found on the basis of DMT and DCPT results between 2 and 4 m of the profile are markedly different from those determined on the basis of measured Q_t (CPTU) and from the course of the hypothetical curve. The observed difference may be affected by the effects of earth work performed during the redevelopment of the island surface or changes in deposit structure, which to a different degree affects results obtained by means of individual methods [16]. This zone constitutes at the same time the zone of ground water table, subjected to natural changes, related to fluctuations in the sea level. Thus it seems likely that high OCR values in this part of the profile are the results of changes in ground water level and related changes in run-off pressure. These changes may lead to generation of the effect of quasi-overconsolidation and increase in the value of vertical component of geostatic stress [16]. In relation to the discussed part of the profile deposits lying at a depth below 16 m are markedly different. In this part of the profile an increase is observed in the overconsolidation ratio, whose value exceeds 2. Although the quantitative change is not considerable and still it is difficult to classify these deposits as definitely overconsolidated, results of analyses indicate unambiguously a change in subsoil geotechnical parameters in this zone. Based on the conducted investigations a hypothesis

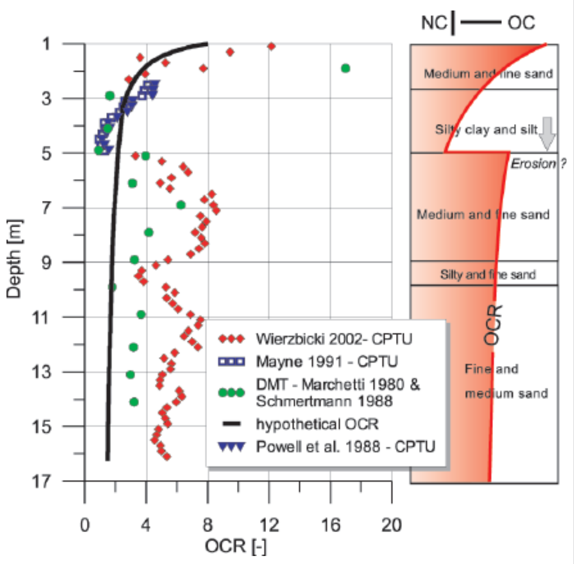

Figure 4.
Changes in overconsolidation ratio OCR recorded in the testing site in the Włocławek site profile (NC – normally consolidated, OC – overconsolidated)

may be proposed that deposits found in the analyzed profile represent two stages of deposition, i.e. the older, whose deposits are consolidated to a higher degree and the younger, exhibiting in the surface zone definite symptoms of overconsolidation. The observed effect of overconsolidation in younger deposits might be caused primarily by the erosion of a layer of sediments of several meters in thickness, resulting from the isostatic relative seal level fall. In turn, a local increase in OCR recorded in the zone adjacent to the ground water table results most probably only from the contemporary fluctuations in the sea level.

Analysis of testing results in Toporów requires a joint presentation of values of the overconsolidation ratio determined in cohesive and non-cohesive deposits (Fig. 3). When analyzing OCR changes in the profile, its distinct division into two parts is clearly seen: the upper part to the bottom of cohesive deposits found at the depth of approx. 15 m and the lower one, including non-cohesive deposits found below this depth. In the upper part a characteristic drop is observed in OCR values with depth. For comparison calculated values were presented in Fig. 3 together with hypothetical values calculated on a similar basis as in case of the Holmen sands. In view of the hypothetical values it may be observed that to a certain degree mean OCR values, calculated by means of different methods, reflect the expected trend for changes in the overconsolidation ratio. Such a finding suggests a thesis on uniform mechanical overload, as a cause for the effect of overconsolidation in this part of the profile. Rather rapid increments in OCR, observed in the roof parts of the series of deposits – both cohesive and non-cohesive, may be in turn explained by the effect of drying out in the surface parts of these deposits. In case of the non-cohesive series it is connected with contemporary changes in the level of ground waters. In turn, in case of the cohesive series it may be assumed that the observed effect results from the stratigraphic discontinuity and changes in environmental conditions between the deposition of the cohesive series and the beginning of the accumulation of non-cohesive deposits. The lower part, composed solely of non-cohesive deposits, differs markedly from the upper part of the profile, discussed above. Values of the overconsolidation ratio determined in this part of the subsoil are very high and show unambiguously that deposits found there are strongly overconsolidated. This conclusion is confirmed by all three applied testing methods. A characteristic decrease in OCR value with depth is also observed in this case, which confirms the assumption on the mechanical overconsolidation of the deposit. Determined values of the overconsolidation ratio, on average approx. 30, may not be explained by changes in the ground water level, drying out or ageing of the deposit [5]. The only two processes, which may lead to such a marked overconsolidation effect, are overload and cementation. When analyzing the undisturbed sample collected from that depth no effect of cementation was found, which would considerably increase the cohesion and internal friction angle of the analyzed sediment material [23]. Thus mechanical overload – found on a large scale – remains an option in this respect.

Results obtained in the area of Włocławek exhibited a certain similarity to the profile in Toporów. At that testing site subsoil may also be divided into two parts (Fig. 4). In the upper part of the profile, composed both of non-cohesive and cohesive deposits, a marked overconsolidation effect is observed with its course homogenous for both types of deposits. Also in this case the distribution of calculated hypothetical values of OCR suggests the adoption of the effect of mechanical overload of the ground surface as the source of overconsolidation of the profile. The lower part of the profile differs markedly from its upper part. Deposits lying below the bottom of cohesive soils exhibit a higher degree of overconsolidation, which undergoes only slight changes with depth. In this respect these deposits do not behave as typical mechanically strongly overconsolidated deposits, or at least not those whose overconsolidation results solely from a change in load. Such an almost homogenous OCR distribution is characteristic for lower part of subsoil, being mechanically overconsolidated, or for deposits subjected to the action of run-off pressure with a similar gradient along the profile or cemented deposits. Unfortunately, the scope of the conducted laboratory analyses did not make it possible to find a possible effect of cementation. However, indirectly the values of the degree of consolidation, characterizing the analyzed deposit, do not prove its cementation. Sands with a high degree of consolidation and at the same time cemented should exhibit much bigger cone resistance values during cone penetration test than those recorded here. In turn, the assumption of consolidation by overload of the ground surface requires the adoption of a thesis that deposits presently located at the depth of approx. 6 m were in the past covered by deposits not only several times thicker, but also strongly overconsolidated.

5. CONCLUDING REMARKS

Conducted analyses facilitated an assessment of changes in overconsolidation ratio OCR under different geological conditions. The application of modern subsoil testing methods, dilatometer tests and cone penetration test, made possible an almost continuous observation of changes in overconsolidation ratio with depth.

Results obtained by means of different methods in all the three testing sites discussed in the study were similar. A characteristic element of this assessment is the fact that in spite of certain differences in absolute values of the overconsolidation ratio, obtained using different methods, the recorded course of OCR changes along the profile was very similar in all cases. This shows that if OCR values themselves may differ from the unknown actual values of the overconsolidation ratio, in the course of the investigations characteristics of changes in the degree of deposit overconsolidation are observed to be clearly consistent.

When interpreting the testing results it may be useful to apply the graph of hypothetical overconsolidation ratio, which indicates the distribution of OCR values with the assumption of influence of only mechanical overload of subsoil on the effect of overconsolidation. A comparison of calculated values with hypothetical values showed that only in some cases determined overconsolidation ratio may be treated as consistent with that resulting from subsoil overload. Processes affecting deposit overconsolidation may overlap, enhance recorded effect, especially in surface parts of subsoil. These processes may include changes in ground water level and run-off pressure they caused, cementation or reconstruction of structure as a result of deposit creep.

An especially valuable piece of information is possibility to identify and indicate in subsoil successive phases of deposit accumulation, separated by stratigraphic gaps. This possibility results from the fact that deposit subjected to the action of different geological processes records environmental changes, which is manifested by changes in specific geotechnical parameters. However, such an interpretation of the OCR profile requires considerations on possibility of individual processes affecting the deposited sediment in the past.

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