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OEDOMETRIC TESTS OF COHESIVE SOILS – TESTING METHODS AND THEIR RESULTS

Robert RADASZEWSKI [a], Katarzyna STEFANIAK [b]

[a] Dr.; Institute of Geology, Adam Mickiewicz University, Maków Polnych 16, 61-606 Poznań, Poland
E-mail address: *micho@amu.edu.pl*

[b] Dr.; Institute of Construction and Geoengineering, Poznań University of Life Sciences, Piątkowska 94, 60-649 Poznań, Poland
E-mail address: *kst@up.poznan.pl*

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Abstract

The paper presents results of analyses of compressibility for four cohesive soils from the Wielkopolska region, Poland, differing in terms of their lithogenesis and geotechnical parameters. Laboratory tests were conducted using a conventional IL oedometer and a CRS oedometer. Analyses focused on characteristics of oedometric constrained modulus during primary consolidation [M_0] within the range of loads of 0-200 kPa. Presented results, which should to be treated as those of pilot studies, indicate that a significant role in the characterization of soils compressibility is played by the adopted laboratory testing scheme. No potential correlation was found for [M_0] values from IL and CRS tests. Thus in the opinion of the authors extensive discussion is required concerning optimization of selection of testing methods for soil compressibility, because the situation when an arbitrary selection of a research method may affect the result of an experiment, is unacceptable. This is particularly crucial here, as parameters of soil compressibility are significant for the design process of building structures. At the same time it was stressed in this paper that irrespective of the applied research method, results of [M_0] are inconsistent both with the results of in-situ tests (CPTU) and standard values contained in the PN-81/B-03020 standard [10], according to which until recently the so-called B (correlation) method has been commonly used and which continues to be applied occasionally.

Streszczenie

W artykule przedstawiono wyniki analiz ściśliwości czterech zróżnicowanych litogenetycznie i geotechnicznie gruntów spoistych z obszaru Wielkopolski uzyskane z badań laboratoryjnych w klasycznym edometrze IL oraz w edometrze CRS. Skupiono się na charakterystyce edometrycznych modułów ściśliwości pierwotnej [M_0], w zakresie obciążeń 0-200 kPa. Prezentowane rezultaty, które należy traktować jako efekt pilotażowych badań wskazują, że istotne znaczenie przy charakteryzowaniu ściśliwości gruntów ma przyjmowany schemat ich badań w laboratorium. Nie stwierdzono przy tym możliwości korelacji wartości [M_0] z badań IL i CRS. Tym samym konieczna jest zdaniem autorów dyskusja na temat optymalizacji wyboru metodyki badań ściśliwości gruntów, ponieważ niedopuszczalna wydaje się sytuacja, w której swobodny dobór metody badawczej wpływa na wynik badania. Szczególnie, że parametry ściśliwości gruntów, mają niebagatelne znaczenie w procesie projektowania obiektów budowlanych. Podkreślono jednocześnie, że niezależnie od zastosowanej metody badań, wyniki [M_0] odbiegają zarówno od oznaczeń in-situ (CPTU), jak również od wartości normowych zawartych w normie PN-81/B-03020 [10], która jeszcze do niedawna była powszechnie (a czasami w dalszym ciągu jest nadal), stosowana do wyznaczania parametrów gruntowych tzw. metodą „B" (korelacyjną).

Keywords: **CRS and IL tests; Oedometer test; Oedometric constrained modulus [M_0].**

1. INTRODUCTION

Defining parametric characteristics of soil compressibility is a key task for engineering geologists and geotechnicians when determining suitability of subsoil for foundations of building structures. This process is based on e.g. such parameters as the oedometric constrained modulus during primary consolidation [M_0] and constrained modulus during secondary compression [M], constrained modulus [a_v] and coefficient of consolidation [cv] [1], [4], [18]. Among other things these parameters are used in design calculations to determine and monitor the volume of subsoil settlement under the load of a building structure. Safety of building structures depends on the accuracy of the established values for the above-mentioned parameters. Parameters of compressibility may be determined using several methods, which may be generally divided into 2 groups: in-situ and laboratory tests. The former are performed maintaining the spatial state of strains and stress in the soil, while the latter typically require adequate soil samples (undisturbed soil samples), which are tested while maintaining the uniaxial state of strain at the spatial state of stress. In both cases the specific character of the tests differs, thus their final results are frequently divergent. It still remains an open and crucial question which of them should be considered as more reliable. However, this paper does not present a definite answer to this problem, but rather focuses mainly on studies involving laboratory tests. Among them we may distinguish two basic research schemes, i.e. conventional tests of soil compressibility, applying gradual (step-wise) loading of soils and tests based on a continuous increase in loading. In the latter case 2 testing variants may be adopted: the constant rate of strain (CRS) method [16] or the constant rate of loading (CRL) method [1], [8], [14]. This paper presents results concerning the constrained modulus during primary consolidation [M_0] in cohesive soils differing in their lithogenesis and geotechnical parameters, found in the city of Poznań and its environs, and recorded in convention-

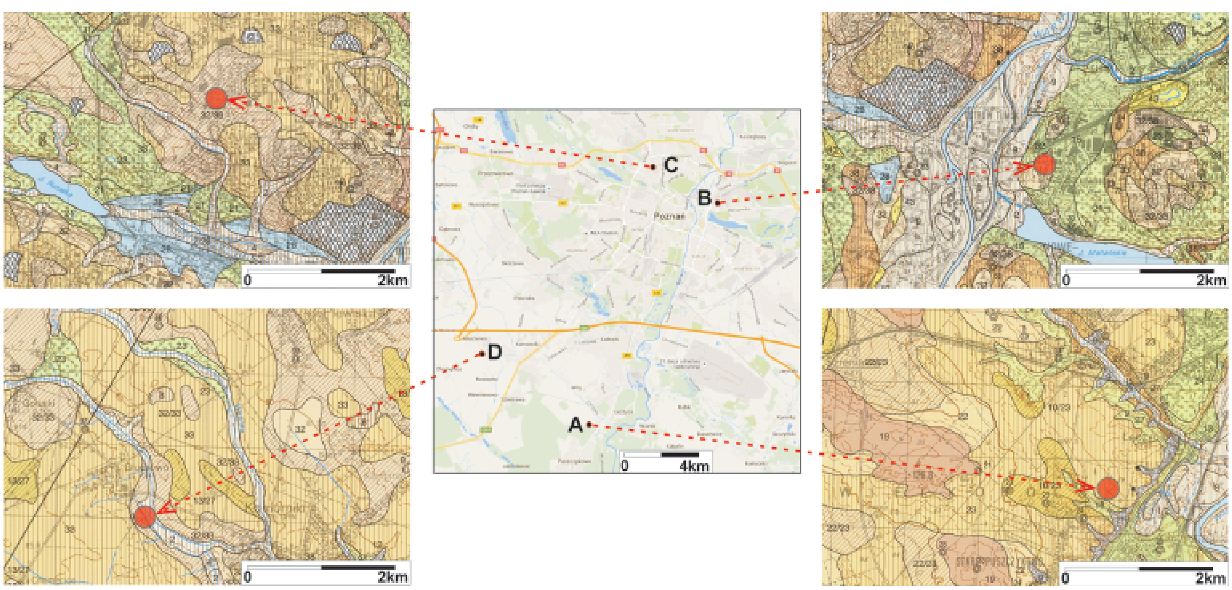

Figure 1.
Location of sampling sites for soil samples collected for laboratory analyses, viewed in the Large-scale Geological Map of Poland, sheets: Poznań [471] [3] and Mosina [507] [2]
Legend:
A) glacial till of the Leszno stage of the Vistulian glaciation (lithologically, according to [10], [11] – sandy clays of genetic group B (denoted on SMGP [507] as no. 23)
B) glacial tills of the Warta glaciation (Riss glaciation) (no. 38 on SMGP [3], genetic group A according to [10]), underlying clays of the Leszno stage of the Vistulian glaciation (no. 33)
C) Pleistocene sandy silts belonging to compartment no. 33 on SMGP sheet [3]), i.e. glacial tills of the Leszno stage of the Vistulian glaciation; according to [10] genetic group B
D) Holocene silts being a part of compartment no. 2 on SMGP [3], i.e. sandy warps of valley bottoms (genetic group C according to [10])
Legend to the numbers of the other compartments of SMGP seen in the figure – consistent with the legend to sheet: [507] (fragment A of the figure) and [471] (fragments: B, C, D of the figure)

al oedometric tests (IL) and using the CRS method. The paper presents a comparison of collected results obtained by the authors of this paper and those published by *Skrzypczyński* [15], considering the various lithogenesis and stratigraphy of tested soils, as well as the type of tested soil samples and ranges of applied loads. At the same time several potential causes for the variation in values of [M_0] provided by both methods are suggested. In relation to selected soils the results of laboratory compressibility tests were compared with those of in-situ tests.

2. CHARACTERISTICS OF TESTED SOILS

The study concerns selected soils of the Poznań Lake District, which is a western part of the Wielkopolska Lake District [6]. Locations of sampling sites are given in Fig. 1. According to the assumed approach, soils selected for analyses represented a potentially broad spectrum of cohesive soils. They differ in terms of their lithology, genesis, stratigraphy, as well as geotechnical parameters. Their only common characteristics is their classification as mineral cohesive soils (*plastic* according to the PN-EN ISO 14688 standard [9]). Depending on the situation and technical feasibility, undisturbed samples (in Polish: NNS) and samples with natural moisture content (in Polish: NW) and natural grain size distribution (in Polish: NU) were collected for laboratory analyses. NNS samples were collected from outcrops using PCV pipe rings, while the other samples were collected from the drill core from mechanical drillings with a Ø100 mm soil auger.

The following soils were collected from locations marked in Fig. 1:

A) sandy clay of the Leszno stage of the Vistulian glaciation, from a trial pit at Gołębia Street in Puszczykowo, from a depth of approx. 2 m (10 NNS samples),

B) clay of the Vistulian glaciation, from a drilling at Małachowskiego Street in Poznań, from a depth of 6 m (10 NW/NU samples),

C) sandy silt from the Leszno stage of the Vistulian glaciation, from an outcrop at Piątkowska Street in Poznań, from a depth of 6 m (14 NNS samples),

D) Holocene silt from an outcrop in Głuchowo (ok. 10 km SW from Poznań), from a depth of approx. 2 m (14 NNS samples).

A total of 38 NNS samples and 10 NU samples of soils with a relatively broad spectrum of cohesiveness (clay fraction content 9%-20%) and contents of the sandy fraction (26%-64%) and the silty fraction (16%-65%) – see Fig. 2, at variation of their liquidity index IL ranging from 0.2 (soils from areas C and D) through 0.45 (soil from area A) to 0.55 (soil from area B) were collected. Plasticity of soils from area B in relation to natural plasticity was modified at the stage of preparation of the restructured samples. The natural liquidity index of these soils was 0.18.

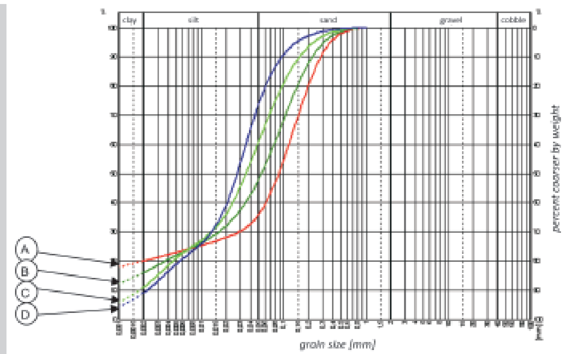

Figure 2.
Averaged accumulation curves for grain size distribution of analyzed soils (*denotations of curves correspond to denotations of study areas*)

Analyzed soils were subjected to different postdeposition processes, which finally modified their properties. Soils from area B were preconsolidated under the influence of ice-sheet overload during the Vistulian glaciation. Soils from area C constitute the bottom section of glacial tills of the Leszno stage and underwent preconsolidation caused by their overburden. Soils from area D underwent quasi-preconsolidation processes, e.g. cementation, which caused the effect of preconsolidation. Soils from area A are considered to be normally consolidated soils.

The presented selection of soils facilitated a comparison of oedometric constrained modulus during primary consolidation from both testing methods, i.e. IL and CRS, in soils with diverse geological history, different grain size distributions and varied plasticity, as well as when related to the type of tested samples (NNS/NU). Moreover, the adopted testing procedures facilitated these comparisons in relation to various ranges of stresses. The preliminary stage of presented analyses and the fact that some of them were conducted as part of other research projects and only partial data are used in this paper, do not permit the authors to draw final conclusions. For this reason further studies are being conducted, covering a markedly greater number of soil samples. The methods adopted in these investigations are closely related to the above-mentioned problems.

3. METHODS

The constrained modulus during primary consolidation in the analyzed soils was determined applying a standard uniaxial compression test with limited lateral expansion. Two types of oedometers were used: a conventional IL (incremental loading) oedometer with a step-wise loading increment, and a CRS (constant rate of strain) oedometer, facilitating continuous loading of soil samples at a constant rate [7], [14], amounting to 0.01 mm/min.

Soils from areas A, C and D were cut to oedometric rings of 20 mm in height and diameters of 65 mm (IL oedometer) and 67 mm or 50 mm (CRS oedometer) from NNS samples. Soils from area B were placed in rings of identical dimensions as restructured samples, whose bulk density was consistent with the value reported in literature [18], applicable to the moisture content of prepared samples.

Tests using the IL oedometer were performed following [12]. The testing procedure consisted in a gradual increase in loading from 12.5 to 200 kPa (in the cycle of 12.5, 25, 50, 100 and 200 kPa), each time increasing the load following a stabilization of sample strain, i.e. when two successive readings of sample height taken at a 24 h interval, were identical. Oedometric constrained modulus during primary consolidation was determined from equation 1.

$$M_0 = \frac{\Delta\sigma}{\varepsilon} \tag{1}$$

where:

$\Delta\sigma$ – the range of stress causing deformations

ε – vertical strain of sample ($\Delta h/h$)

h – initial height of soil sample in oedometer

Δh – the difference in sample height during test (caused by an increase in strains $\Delta\sigma$)

Tests conducted at a constant rate of strain were performed in a computer-controlled CRS oedometer by Geonor (Norway), equipped with a converter, ensuring a programmable testing procedure and continuous electronic recording of testing parameters. All samples were subjected to variable loading, so that

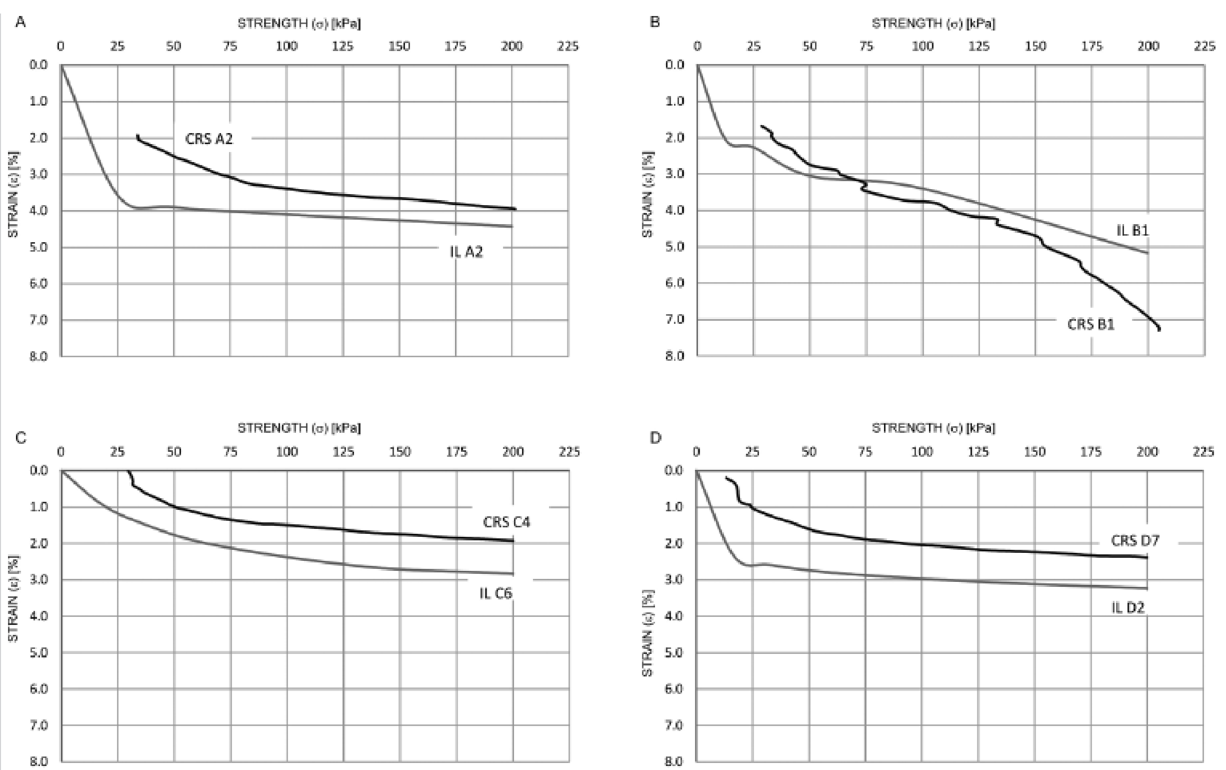

Figure 3.
Curves of soil compressibility from oedometric IL and CRS tests for samples from analyzed study areas (*denotations of soil samples in parts: A-D of the figure correspond to the denotations of areas adopted in Fig. 1*)

the gradient of relative sample strain remained constant during the test. The testing procedure was different for soils from areas A and B and from areas C and D. In the former case samples were loaded at 200 kPa for 48 h, while in the latter case it was 1200 kPa for 16 h. In order to compare the behavior of tested soils over such a range of loads, in the latter case data from the range of 0 to 200 kPa were used. Differences in the method of CRS tests result from the fact that these tests were partly focused on the research problem presented in this paper (soils from areas A and B), and in part (soils from areas C and D) they include results of studies conducted in the course of other research projects (e.g. [17]).

4. RESULTS

Testing results are presented based on example results of specific soil samples from each area, which following analyses of the entire range of data were considered to be reliable and representative. Figure 3 shows curves of compressibility obtained from both testing methods (IL and CRS).

Maximum values of strains [ε] for IL tests range from 3% to 5% depending on soil type and they are greatest in restructured samples of clays from area B. In CRS tests values of maximum strains range from approx. 2% to 7% and they are also greatest for samples from area B. Such a picture correlates well with the liquidity index of analyzed soils. With an increase in their plasticity, irrespective of the adopted testing method, total strains also increase. The course and position of curves of compressibility for soils from IL and CRS tests are generally repeatable in relation to samples from areas A, C and D. For them the differences in the results of both methods are particularly evident in the initial stage of loading, in which in IL tests samples undergo markedly greater deformations. After the value of approx. 25 kPa (total strength [σ]) is exceeded, the course of IL and CRS curves is practically parallel, while maintaining regularity of greater total strains in soils analyzed using the conventional IL method. An opposite picture was observed for curves of compressibility of soils from area B. Here greater strains were observed for samples tested using the CRS method. However, in this case the divergence in the course of curves of compressibility between both methods for the range up to approx. 150 kPa (total strength [σ]) is relatively slight. Only at loads of approx. 200 kPa (total strength [σ]) the deviation of the curves from CRS is markedly greater than that of the curve from IL. The recorded high values of strain in tested loams from area B (markedly greater than in soils from the other areas), recorded irrespective of the applied testing method, probably result from their high liquidity index, while additionally it may also be caused by the fact that they were the only analyzed soil samples tested as restructured samples. Model samples were identical for both testing methods (soil for the rings was collected from the same batch of material), thus due to the greater strains of samples recorded each time in the CRS oedometer it may be assumed that this device is more sensitive to their quality. This may also be explained by the temporal increase in load for the maintenance of a constant gradient of strains in the CRS oedometer, which have a more effective impact on the strongly plasticized samples of tested soils ($I_L = 0.55$) than the static load in IL oedometers. Based on the presented curves of compressibility values of oedometric constrained modulus during primary consolidation [M_0] were also calculated, as presented in Fig. 4.

Values of [M_0] for soils from all the analyzed areas for both applied testing methods fall within the range of extreme values from several to approx. 30 MPa. They specifically show variation between soils from individual study areas as well as within the same soil depending on the adopted testing method, taking into consideration the ranges of stresses assumed for calculations.

For comparison the presented results of [M_0] from the conducted laboratory analyses for soils from areas C and D were referred to values of constrained modulus recorded in the CPTU static probe test and calculated using the commonly applied formula by Mayne [13]. In sandy silts from area C this value, for stresses of 100 kPa, is over two-fold greater (22.9 MPa) than the analogous values from IL and CRS tests. In turn, in silts from area D, in CPTU (for a stress of 50 kPa) values of the constrained modulus were approx. 4 times greater (12 MPa). This clearly shows a lack of compatibility in the results of both methods, at least in relation to the formula proposed by Mayne, applied in the CPTU calculations. The situation is comparable in relation to the standard values of oedometric constrained modulus according to [10]. It needs to be observed here that results from IL tests are closer to the standard values. While making no attempt at evaluating reliability of results for all the above mentioned methods, the further part of the paper focuses solely on a comparison of the laboratory testing results for both applied methods.

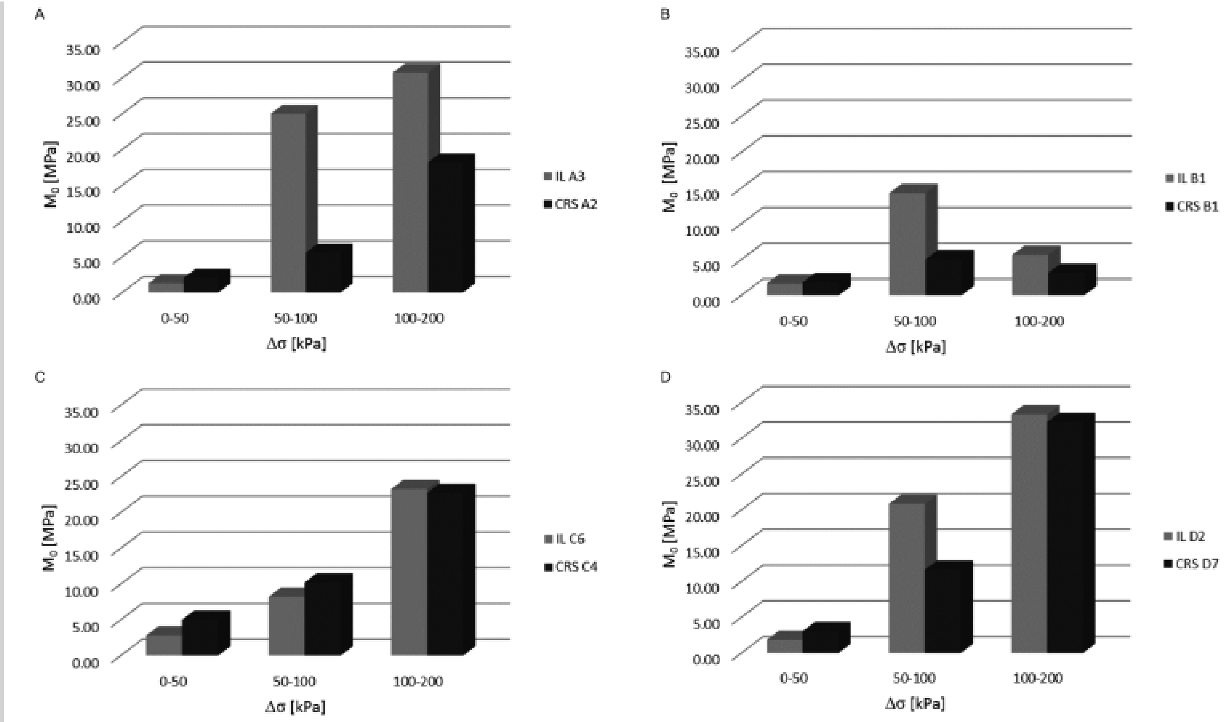

Figure 4.
A comparison of values of oedometric constrained modulus [M_0] from IL and CRS tests

The most consistent results from IL and CRS tests, irrespective of the adopted ranges of stresses, were obtained for NNS samples of overconsolidations sandy silts from area C. It was assumed that the most probable cause for such a compatibility of results may be related to the stabilized structure of tested soils, resulting from the effect of preconsolidation at loads greater than those applied in the performed oedometric tests. Thus the varied rate of applied loads in both types of oedometers had no decisive effect on the final strain of samples and the markedly shorter time of loading in the CRS oedometer was sufficient to provide their stabilization (analogously as in the IL tests). In contrast to the above-mentioned sandy silts, no compatibility of values of modulus from CRS and IL tests was obtained in glacial tills of the Warta glaciation from area B. Although genetically they are also preconsolidated soils, their structure was relatively thoroughly overconsolidated when model samples were being prepared. In conclusion it needs to be assumed, similarly to the generally accepted opinion (e.g. [5]), that the type and quality of samples play a decisive role in oedometric tests. This may also be confirmed by the relatively low, even for the strongly plasticized clays, values of [M_0] (maximum up to approx. 12 MPa), recorded irrespective of the adopted testing method, which are at least 2-fold lower than those assumed in literature sources [10], [18].

In plastic sandy clays of the Leszno stage of the Würm glaciation, i.e. normally consolidated soils, significant discrepancies were observed in [M_0] values obtained using both methods. Modulus from IL tests are markedly higher for the range of total stress of 50-100 kPa and 100-200 kPa. Comparable values are only found for the range of total stress of 0-50 kPa, in which in IL tests almost 90% absolute strains (see Fig. 3) were obtained, providing complete stabilization of height in samples within 32 days. In the assumed research scheme for CRS tests the value of stress of 50 kPa was obtained already 30 min from the onset of analysis. Thus it may be assumed that at that moment the sample did not undergo complete consolidation and for this reason in the successive ranges of stress it will undergo further strain, resulting in a reduction of values of constrained modulus. At the same time it needs to be mentioned here that a long period of sample height stabilization in IL tests causes changes in properties of tested soil, e.g. in the range of its moisture content. In the case of the described sandy clays this moisture content in the IL test decreased within 1 month of testing by approx. 1/4 value, while in the CRS test this value obviously did not change within the period of 30 min.

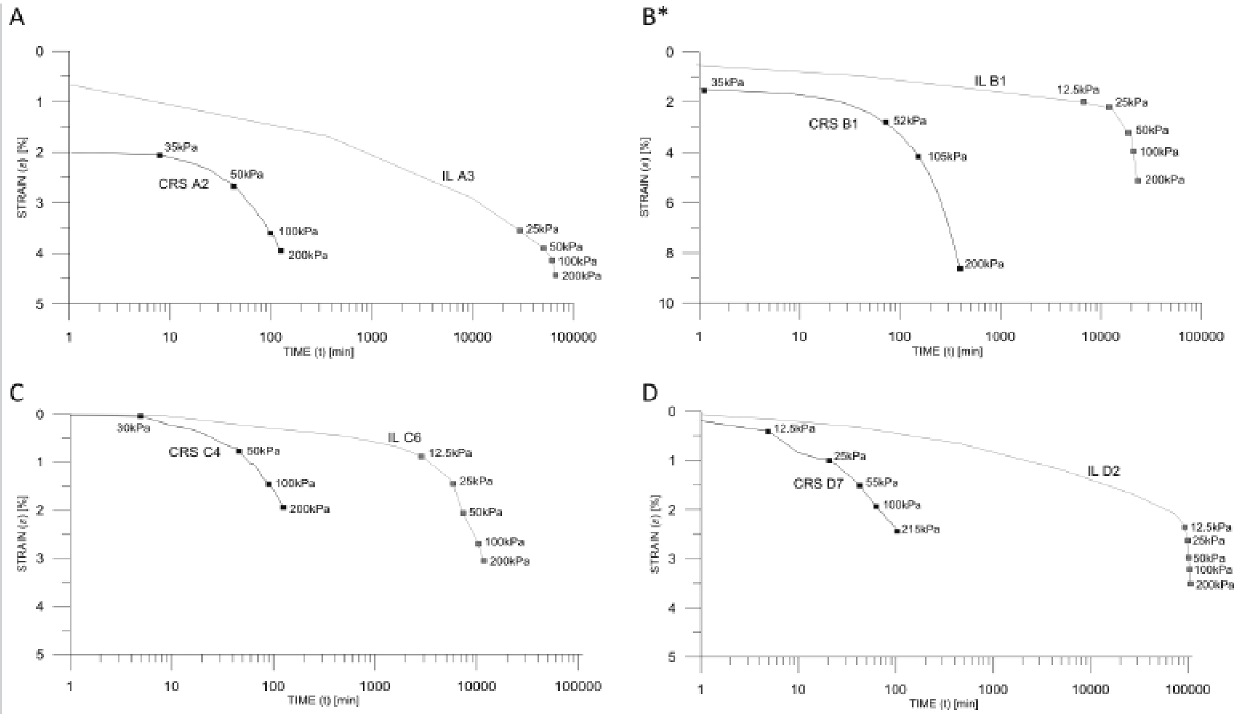

Figure 5.
The course of soil sample settlement in time, taking into consideration changes in their loading ***(points denote moments of strain stabilization at successive loading values) A – sandy loams from Puszczykowo; B – clays from Poznań; C – sandy silts from Poznań; D – silts from Głuchowo***
**** Remark: the scale of the Y axis increased two-fold in relation to the other graphs in this figure***

Values of constrained modulus in Holocene silts from area D are consistent in the case of CRS and IL tests within the range of stresses of 0-50 kPa and 100-200 kPa. In turn, they differ 2-fold within the range of stress of 50-100 kPa. Based on the data collected to date it is not possible to clarify the cause for such differences. They may have been caused by local strengthening of soil structure, connected with carbonate cementation observed in the tested silts, which is anisotropic in character.

Figure 5 presents a compilation of results of conducted compressibility tests, illustrating the course of sample settlement in time, taking into consideration loads applied on them at that time. Differences in loading values for both types of oedometers, occasionally evident in the graphs, are caused by the manner of data recording and electronic generalization of data in the CRS test. It was attempted in this study to ensure they were possibly close to the values of loads applied in standard IL tests.

5. CONCLUDING REMARKS

Presented results were obtained in preliminary tests, which will be continued, thus the presented concluding remarks needs to be considered preliminary. At the present stage of work the conducted analysis of compressibility for 4 soils from the Wielkopolska region, differing in terms of their lithogenesis and geotechnical parameters, was based on oedometric constrained modulus during primary consolidation, recorded in oedometric IL and CRS tests. In the case of soils from 3 areas (A, B and D) this study showed a lack of compatibility in the results provided by both methods. Only in preconsolidated sandy silts from Poznań, tested as NNS samples, values of [M_0] are relatively consistent. No correlations were observed also between the results of [M_0] obtained from both methods. On the one hand, this may have been influenced by the frequently overlapping various factors determining potential strains in soils. Among them we need to mention first of all lithogenesis of the tested soils, their geotechnical properties, as well as the type and quality of tested samples. However, we may not exclude a possibility that such a dependence simply does not exist. Obtained results of $[M_0]$ are inconsistent both in the case of in-situ testing and the values assumed in standards. Both adopted testing techniques have some indisputable advantages. For example, within a relatively short CRS tests the sample retains its natural properties, whereas the markedly longer IL tests facilitate complete control of strain stabilization in the sample. However, despite the indicated technical and methodological advantages of both tests from the point of view of a designer, at the discrepancy of results between both tests stated in this study, an alternative possibility of their application seems to be dubious. Thus we face a problem, which values are reliable, leading to the dilemma which values should be used to calculate subsoil settlement under a building structure?

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