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Consolidation parameters of Neogene green clays from Bełchatów – a study on CL test interpretation

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The article presents the results of consolidation tests of Neogene green clays from the geological profile of the Bełchatów lignite mine (Central Poland). Reliable characteristics of the consolidation parameters are essential for forecasting settlements and for assessment of their insulation features. The reliability criteria of the test results for consolidation at a constant rate of loading are analysed. Quasi-stabilization of the c_v value in the stress function σ_v may be used as a simple and effective criterion. Criteria based on comparisons with the theoretical course of the process indicate the key role of the steady phase of the test. In the analysed clays, a high consistence of the course of their consolidation with a theoretical solution in the steady phase was obtained. Corrections based on Wissa and Janbu suggestions or the reinterpretation of c_v using theoretical rules introduced to CL tests are necessary, especially for the non-steady phase.

Key words: consolidation CL tests, coefficient of consolidation c_v, pore water pressure parameter C_{CL}, Neogene green clays, Bełchatów lignite mine, Central Poland

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INTRODUCTION

Advanced researches of soil consolidation are increasingly used both for assessment of settlements conditions for buildings and embankments and for determination of permeability of low-permeable soils. However, in classic interpretations of these researches, a high variability of results has been observed. To improve the correctness of parameter specification, it is necessary to compare the consistence of experimental data with consolidation theory solutions.

Consolidation theory was proposed by Terzaghi for constant loading (IL test). In the recent years, though, tests under continuous loading (CL tests) have been increasingly common. Interpretation of such tests required adaptation of Terzaghi's solutions to a different type of loading.

Analysis of the theoretical model of consolidation process with continuous loading enabled presentation of theoretical relations which can be compared with experimental data. While presenting these relations, it is necessary and very useful to apply the following parameters of CL test:

– pore water pressure u_b measured at the impervious base of a consolidometer, kPa

– pore water pressure parameter $C_{CL} = u_b / \sigma_v$

– specific consolidation time $t_{(T=1)} = H^2/c_v$, s

– relative time of consolidation T_{CL}, [–] defined as $T_{CL} = t_{CL} / t_{(T=1)} = t_{CL} c_v / H_2$,

where:

σ_v – total vertical stress, kPa

t_{CL} – time from the start of the CL test, s

c_v – coefficient of consolidation at the moment t_{CL} calculated using different formulas (Wissa et al., 1971; Janbu et al., 1981; Dobak , 1999), m^2/s

H – length of drainage way consistent with the present height of the sample, m.

All these parameters are determined in randomly selected stress ranges and illustrate changes of consolidation conditions occurring during the entire CL test.

In the consolidation test, with increasing the load, an initial non-steady phase occurs. The values of the coefficient c_v, calculated in this phase, are significantly too high and unreliable. Later in the test the steady phase begins. In practice, this is usually a quasi-steady phase where only some of its features are met.

There are four criteria for determining the steady phase and the correctness of specification of the consolidation coefficient:

- stabilization of pore pressure
- values of the consolidation coefficient at the diagram c_v–σ_v are quasi-linear and asymptotically go to the σ_v axis
- relative time of consolidation has a value of $T_{CL} > 2$,

- consistence of the experimental course with the theoretical pattern of C_{CL}–T_{CL}.

This article analyses the above-mentioned criteria with respect to the test results on consolidation of Neogene green clays overburdening the Bełchatów lignite deposit (Central Poland).

These clays are extremely widely spread in the Neogene deposits of Central Poland. However, in the deep Kleszczów tectonic graben these clays have a specific facial seating. The examined clays were taken from the depth of 90–110 m from two different places marked as I and II. Their basic characteristics are presented in Table 1.

The tests were conducted in consolidometers adapted both for a low (LS) and high (HS) consolidation stress σ_v. Loading of soil samples in the LS tests was made using elements of a triaxial apparatus system, and in HS tests an MTS press was used. In LS tests, variable rates of loading were obtained, and they were situated in the range from 0 to 20 kPa/min, while in the MTS press three values of a constant rate of loading were applied: 25, 40, 50 kPa/min. Therefore, these tests can be classified to the CRL type.

DISTRIBUTION OF PORE WATER PRESSURE DURING CL TEST

Figure 1 presents the results of theoretical calculations of pore water pressure distribution for continuous loading (CL) tests. Changes of the pore water pressure values are influenced by the

Table 1. **Basic physical properties of soil**

Parameter		Symbol	Unit	Localization of samples in Bełchatów open pit	
				I	II
Density of solid particles		ρ_s	Mg/m³	2.67–2.74	2.80–2.82
Bulk density of soil		ρ	Mg/m³	1.99–2.21	1.84–1.93
Density of dry soil		ρ_d	Mg/m³	1.68–1.90	1.41–1.47
Natural moisture content		w_n	[%]	13.8–21.0	28.9–35.0
Plastic limit		w_p	[%]	17.7–20.1	36.4–38.0
Liquid limit * Casagrande apparatus ** ELE penetrometer		w_L	[%]	*49.8–60.9 **52.0	*106.6–110.6 **105.4
Liquidity index		I_L	[–]	(–0.03)÷(–0.09)	(–0.07)÷(–0.09)
Plasticity index		I_p	[%]	30.7–40.8	70.2–72.6
Porosity		n	[–]	0.30–0.39	0.48–0.50
Void ratio		e	[–]	0.42–0.51	0.92–1.00
Grain-size fraction	Sand fraction	f_p	[%]	38–51	0
	Silt fraction	f_π	[%]	3–11	7–10
	Clay fraction	f_i	[%]	44–52	90–93

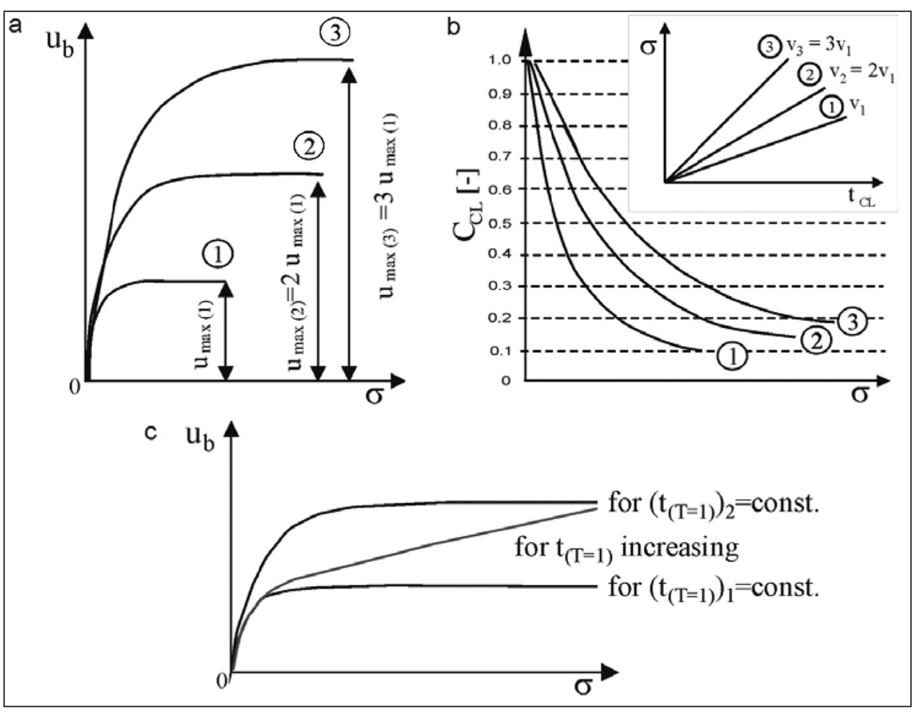


Fig 1. Theoretical rules of pore water pressure distribution during CL tests (after Dobak, 1999)

loading velocity Δσ / Δt, permeability and consolidation properties of the soil expressed by means of the specific consolidation time $t_{(T=1)}$.

Figure 1 (a and b) presents the results of theoretical calculations of the pore water pressure distribution with $t_{(T=1)}$ = *constans* and the constant loading velocity. For each case, (1), (2), (3), a different constant loading velocity was applied, and the value of the stabilized pore pressure was proportional to the applied soil loading velocity.

Then (Fig. 1c) we analysed the distribution of pore pressure under a constant loading velocity $\Delta\sigma / \Delta t$ and different consolidation features expressed by two values $(t_{(T=1)})_2 = 2\,(t_{(T=1)})_1$. In such conditions, the values of theoretical pore water pressure stabilization $(u_b)_{stab}$ are proportional, too. In the situation when a possible increase of the specific consolidation time in the course of the tests is taken into account, the pore pressure will never be constant, but slightly increasing.

The relations obtained during model calculations are confirmed by the experimental data. In the tests, no stabilization of pore pressure was obtained (Fig. 2a), although it was theoretically expected. This is caused not only by changes of the loading values (Fig. 2b), but first of all by an increase of the specific consolidation time $t_{(T=1)}$ during the tests (Fig. 2c).

It happens because the value of the consolidation coefficient c_v decreases faster than the drainage way H. An increase of the pore pressure during the tests indicates that seepage and consolidation conditions deteriorate while the stress σ_v and the pore pressure u_b increase.

CHANGES OF THE COEFFICIENT C_V DURING CONSOLIDATION TESTS

The second analysed criterion was changes of c_v values in the stress function. These c_v values are very high and unrealistic at the beginning, and later in the tests the c_v course is quasi-linear, going asymptotically to the σ_v axis.

Such character of variability is consistent with consolidation theory. However, the problem is to specify the point where we can assume that c_v values are correct. With a smooth, continuous course of the diagram we can assume a convergence with the linear approximation c_v at an advanced stage of the test. It is also important to assess the reasons for the high, unreliable c_v values at the beginning of the test. It is caused both by the c_v calculation formula (Fig. 5) and by the initially low values of pore pressure.

During the tests, several types of pore pressure distribution were observed, which were more or less different from the theoretical model and were demonstrated by experimental models: QT, PT, NZ[a] and NZ[b] and CR (Dobak, 1999; Kowalczyk, 2005).

In many cases, the maximum CCL value is lower than the theoretically assumed value 1 and occurs not at the beginning of the test, but somewhat later. This means that when the soil is loaded, the mobilization of pore pressure is gradual but not immediate. The time needed to reach $C_{CL\,\max}$ was named by Kowalczyk (2005) as the response time. A reliable interpretation is possible after C_{CL} reaches the maximum and later decreases. Hence the proper consolidation phase is obtained. Points cor-

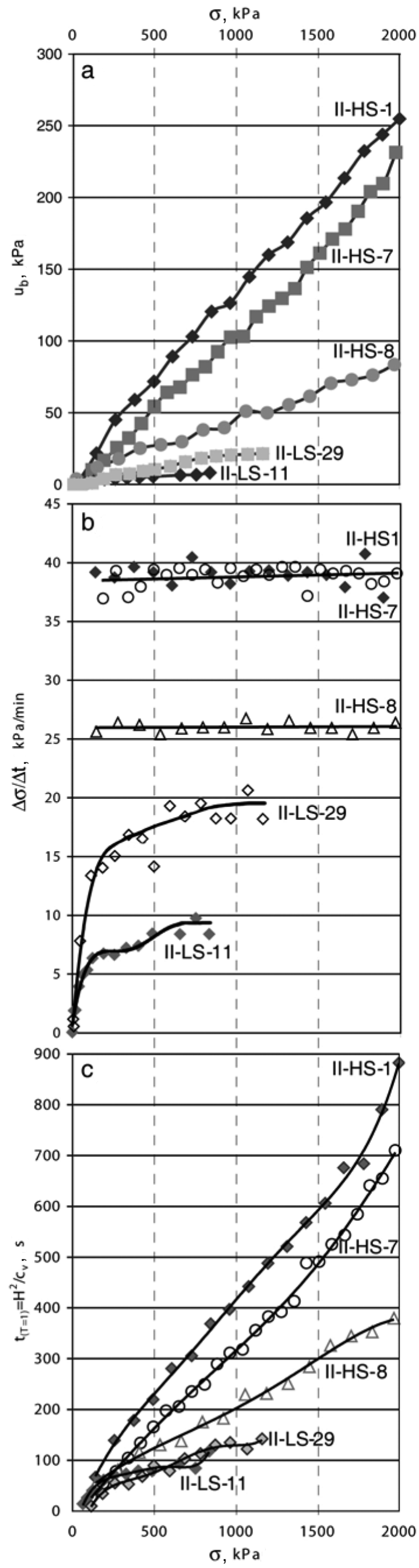


Fig. 2a. Increase of pore water pressure in Neogene green clays during CL tests

Fig. 2b. Rate of loading during CL tests

Fig. 2c. Changes of consolidation properties expressed by specific time of consolidation related with the maximum C_{CL} value are marked in the c_v–σ diagrams (Fig. 3a, b). Usually they are situated in the rectilinear quasi-stabilized section of the diagram. This confirms the correctness of the c_v value in this phase of the CL test.

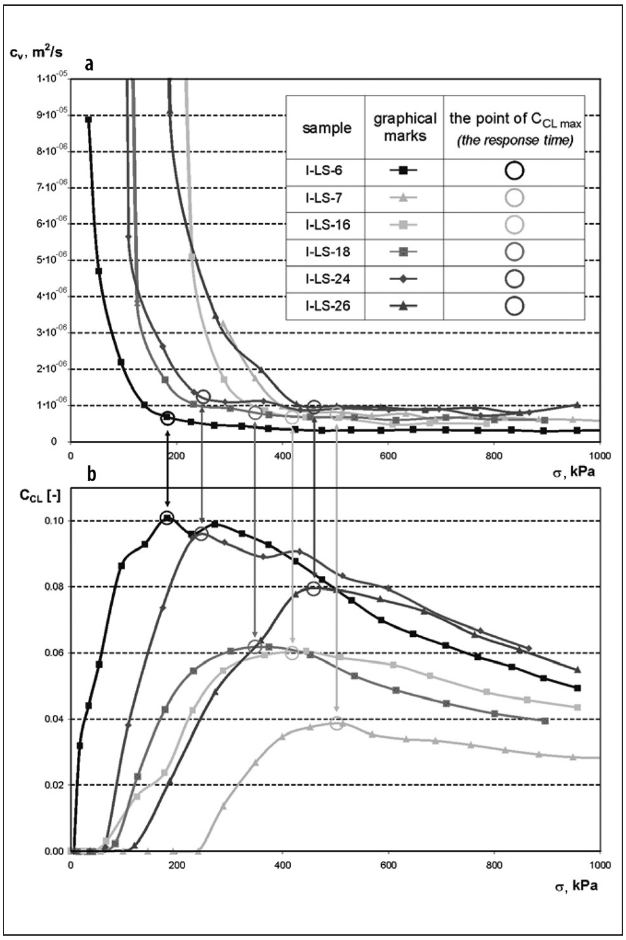


Fig. 3a. Quasi-hyperbolic changes of c_v during CL tests

Fig. 3b. Distribution of pore water pressure parameter C_{CL} and translation of maximum C_{CL} value

COMPARISON OF EXPERIMENTAL DATA WITH THEORETICAL SOLUTION OF CL TEST

Theoretical relations mentioned at the beginning of this article, expressed using non-dimensional C_{CL} and T_{CL} parameters, constitute the best possible criterion of indicating a continuous reliable phase of the CL test.

Figure 4 presents changes of the C_{CL} parameter in the T_{CL} function for the constant rate of loading (CRL) tests.

The value of the relative time of consolidation $T_{CL} = 2$ divides the unsteady and the steady phases. From the point of view of mathematics, this value is consistent with the end of consolidation caused by the initial increase of $\Delta\sigma_v \to 0$.

When $T_{CL} > 2$, the test enters the steady phase. It is confirmed by comparing the theoretical C_{CL} distribution with the results of tests. In Fig. 4, the continuous line illustrates theoretical solutions C_{CL}–T_{CL}, while the points mark the results of CRL tests conducted in a consolidometer using an MTS press. The results of experimental tests significantly differ from the theoretical diagram in the non-steady phase and are more similar to the theoretical solution in the steady phase. Location of experimental points in the non-steady phase in the diagram indicates that these T_{CL} values are too high. Modification of their location can be based only on the correction of c_v values because the t_{CL}, C_{CL} and H values come from direct measurements and are correct. Therefore, moving the experimental point with coordinates (T_{CL}, C_{CL}) to the left, to the theoretical curve, a decrease of T_{CL} values requires a consequential decrease of c_v (see the formula in Fig. 5).

The above analysis indicates that the c_v value is overestimated in the non-steady phase. In order to improve this value, the non-linear formula from Wissa et al. (1971) or the α_{cv} correction factor suggested by Janbu et al. (1981) can be used. Another way of correcting c_v is interpretation of the theoretical diagram C_{CL}–T_{CL}. Then, as the initial data we take C_{CL} parameters and the relevant values of the t_{CL} time. These data come directly from measurements and do not depend on the consequences of theoretical assumptions of the consolidation process. In the analysed tests results, this interpretation is most similar to Wissa's

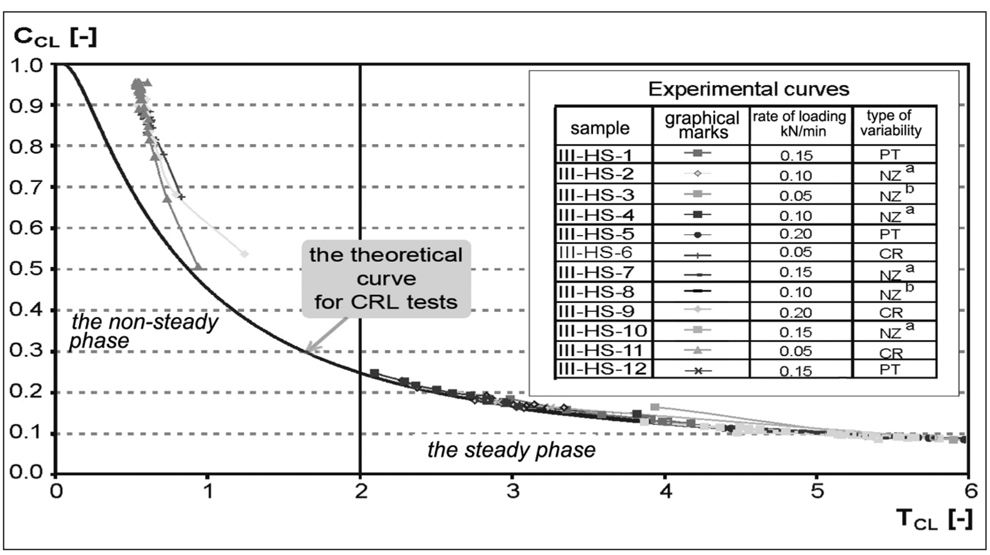
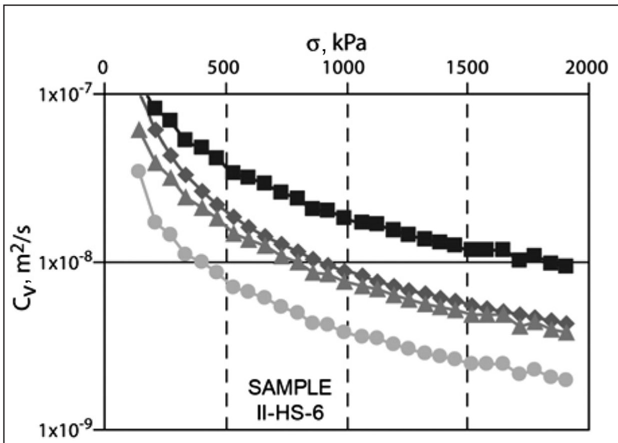


Fig. 4. Experimental test results compared with the theoretical relation C_{CL}–T_{CL}



MARKS		FORMULA	SOURCE
■	linear	$C_{v\,linear} = \frac{H^2}{2u_b}\left(\frac{\Delta\sigma_v}{\Delta t}\right)$	Wissa (1971)
◆	relation C_{CL}-T_{CL} (vide fig.4)	$C_v = T_{CL}\frac{H^2}{t_{CL}}$	Dobak (1999)
▲	non-linear	$C_v = -\frac{0{,}434\left(\frac{u_b}{\sigma_v}\right)}{\log\left(1-\frac{u_b}{\sigma_v}\right)}C_{v\,linear}$	Wissa (1971)
●	correction α_{cv}	$C_v = \alpha_{Cv}\;C_{v\,linear}$ $\alpha_{Cv} = f\left(\frac{\Delta u_b}{\Delta\sigma_v}\right)$	Janbu (1981)

Fig. 5. Comparison of c_v values from non-steady phase calculated by different formula

non-linear solution. This confirms the consistence of Wissa's formula with the theory of consolidation applied to continuous loading. Correction of c_v values from the non-steady phase is justified from the physical point of view after the end of mobilization of the pore water pressure phase (exceeding the C_{CL} maximum value in the course of the test). This requirement is impossible to meet when the CR or NZ diagram is obtained for C_{CL}–σ_v. In the case of tests with a variable loading velocity (for example, CRS tests), it is necessary to calculate the C_{CL}–T_{CL} theoretical diagram according to an individual loading program. It limits the common use of this referential method for correcting the c_v value.

CONCLUSIONS

1. Analyses of the consolidation process in the test green clays show that distinguishing the unsteady and steady phases of the tests is necessary for a proper interpretation of test results.

2. In every test, a significant decrease of soil permeability was stated, which also causes a decrease of the consolidation coefficient. In such conditions, stabilization of pore water pressure cannot be obtained and this criterion cannot be used for assessing the steady phase in the tests under analysis.

3. On the hyperbolical c_v–σ_v diagram, a quasi-linear rectilinear section asymptotic to the σ axis can be distinguished. The values of c_v in this section are consistent with the phase where the $C_{CL\,\max}$ value was exceeded and the distribution of pore pressure typical of seepage consolidation occurs. Data from this section of the diagram may be recommended as reliable c_v values from CL tests.

4. C_{CL} and T_{CL} values obtained from the CRL tests show a general consistence with the theoretical curve at an advanced stage of the tests. Therefore, it is correct to assume the steady phase ($T_{CL} > 2$) as a reliability criterion for CL test results.

5. In CRL tests, we can recommend an easy method of correcting $\mathbf{c}_v$ by means of reference to the theoretical curve C_{CL}–T_{CL}. The results of this method of CL test interpretation are most similar to the calculation of $c_{v\,\text{nonlinear}}$ formula presented by Wissa. The linear formula and the Janbu correction give higher and lower values, respectively.

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NEOGENO BELCHATOVO ŽALIOJO MOLIO KONSOLIDACIJOS PARAMETRAI – CL BANDYMŲ INTERPRETACIJOS TYRINĖJIMAI

S a n t r a u k a

Patikimas konsolidacijos koeficiento vertės nustatymas yra būtinas prognozuojant statinių nusėdimą bei vertinant grunto izoliacines savybes. Tyrinėtas neogeno žaliasis molis, slūgsantis virš rudosios anglies klodo Belchatovo telkinyje (Centrinė Lenkija). Gilios Kleščevo tektoninės įdubos sąlygomis molis įgavo specifinių savybių. Tyrimai atlikti didėjančios apkrovos CL metodu. Klasikinis patikimumo kriterijus, pagrįstas stabilizuotu porų slėgiu, yra nepatikimas, nes didėjant apkrovai ženkliai kinta grunto filtracinės ir konsolidacinės savybės. Patikimumo kriterijumi siūloma pasirinkti kvazistabilizuotą konsolidacijos koeficiento vertę C_v. Eksperimentiniai duomenys palyginti su teoriniais sprendiniais apibrėžta funkcija, t. y. porų slėgis (parametras C_{CL}) ir reliatyvus konsolidacijos laikas (T_{CL}). Stabilizuota fazė prasideda, kai $T_{CL} > 2$. Geriausiai tyrimų rezultatai atitinka teorinius sprendimus, kai konsolidacijos koeficientas skaičiuojamas pagal Wisso nelinijinį sprendinį. Gautų rezultatų analizė rodo, kad būtina išskirti CL tyrimo fazes – stabilizuotą ir nestabilizuotą ir gautus rezultatus palyginti su teoriniais sprendimais.

Paweł Dobak, Sebastian Kowalczyk

PARAMETRY KONSOLIDACJI NEOGEŃSKICH ZIELONYCH IŁÓW Z BEŁCHATOWA – ANALIZA METOD INTERPRETACJI BADAŃ CL

Streszczenie

W artykule przedstawiono zagadnienia metodyczne związane z interpretacją wyników badań konsolidacji prowadzonych w warunkach ciągłego wzrostu obciążenia (system CL). Uzyskiwanie miarodajnych wartości współczynnika konsolidacji jest niezbędne w prognozowaniu osiadań i może być także wykorzystane przy ocenie właściwości izolacyjnych gruntów spoistych. Badaniom poddano neogeńskie iły zielone występujące w nadkładzie największego w Polsce Centralnej złoża węgla brunatnego „Bełchatów". Grunty te reprezentują szeroko rozpowszechnioną w Polsce formację jeziornych iłów neogeńskich. W warunkach głębokiego rowu tektonicznego Kleszczowa posiadają jednak specyficzne wykształcenie i właściwości (tab. 1). Jako podstawowe kryterium miarodajności wyników badań CL przyjmuje się osiągnięcie fazy ustalonej konsolidacji. Klasyczne kryterium oparte na stabilizacji ciśnienia porowego jest tu nieprzydatne, gdyż wraz z rosnącym obciążeniem znacząco zmieniają się właściwości filtracyjne i konsolidacyjne gruntu wyrażone przez parametr $t_{(T=1)}$ (rys. 1 i 2). Jako zalecane kryterium miarodajności należy przyjmować quasi-stabilizację wartości współczynnika konsolidacji c_v, której początek jest w analizowanych badaniach dobrze skorelowany z osiągnięciem maksymalnej wartości parametru ciśnienia wody w porach $C_{CL\,max}$ (rys. 3).

Użyteczne jest też porównywanie danych doświadczalnych z teoretycznym rozwiązaniem określonym przez zależność parametru ciśnienia wody w porach C_{CL} od względnego czasu konsolidacji T_{CL}. W rozwiązaniu tym faza ustalona zaczyna się, gdy $T_{CL} > 2$ (rys. 4). W fazie nieustalonej obserwuje się natomiast znaczące zawyżenie parametrów konsolidacji. Przeanalizowano różne metody korekty wyników z fazy nieustalonej. Najlepsza zgodność z rozwiązaniami teoretycznymi występuje, gdy współczynnik konsolidacji c_v obliczany jest na podstawie nieliniowego rozwiązania przedstawionego przez Wissa i in. (1971). W przeprowadzonych badaniach obliczenia oparte na rozwiązaniu liniowym oraz poprawce zaproponowanej przez Janbu (1981) dały odpowiednio wartości c_v zawyżone lub zaniżone. (rys. 5). Analizy wyników badań wskazują na potrzebę wydzielania faz badania CL: nieustalonej i ustalonej, oraz porównywania uzyskiwanych wyników z rozwiązaniami teoretycznymi, na których oparte jest pojęcie współczynnika konsolidacji.

Павел Добак, Себастиан Ковальчик

КОНСОЛИДАЦИОННЫЕ ПАРАМЕТРЫ НЕОГЕНОВЫХ БЕЛХАТОВСКИХ ЗЕЛЁНЫХ ГЛИН – ИССЛЕДОВАНИЯ ИНТЕРПРЕТАЦИИ ИСПЫТАНИЙ CL

Резюме

Определение достоверного значения коэффициента консолидации является обязательным при прогнозировании осадки сооружений и оценке изоляционных свойств грунтов. Исследовались неогеновые зеленые глины, залегающие над толщей коричневого угля в месторождении Белхатово (Центральная Польша). В глубокой тектонической впадине Клещего глины приобрели специфические свойства. Исследования проведены в условиях увеличивающейся нагрузки методом CL. Классический критерий достоверности, определяемый по поровым давлениям, не является достаточно достоверным, кроме того, при увеличении нагрузки значительно изменяются условия фильтрации консолидации. Экспериментальные результаты сравнены с теоретическими, полученными с помощью параметра порового давления C_{CL} и релятивного времени консолидации T_{CL}. Фаза стабилизации консолидации начинается при $T_{CL} > 2$. Наилучшее соответствие экспериментальных и теоретических данных получено в тех случаях, когда коэффициент консолидации рассчитывался по нелинейному решению Висса. Анализ полученных результатов показывает, что следует выделить отдельные фазы испытаний по методу CL: стабилизированную и нестабилизированную, кроме того, полученные результаты следует сопоставлять с теоретическими данными.