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# Variability of permeability coefficient values of green clays from Bełchatów in one-dimensional consolidation testing*

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The article discusses the values of the permeability coefficient obtained in the consolidometric tests with continuous loading (CL) on samples of green clay from the Bełchatów lignite mine. A wide range of differences in the coefficient value was compared to the values of pore water pressure with regard to total stress (the pore water pressure parameter $C_{CL}$). On the basis of the obtained test results we present the possibility of an effective determination of the permeability coefficient for low permeability soils in consolidation tests conducted in the conditions of continuous loading.

**Key words:** consolidation, CL consolidation test, coefficient of permeability, pore water pressure parameter $C_{CL}$

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Evaluation of the permeability properties of cohesive soils, clays in particular, is a complex issue. It is a consequence of the specific nature of permeability process taking place in low permeability soils and the need to readjust the testing procedures to such conditions.

Tests with a variable hydraulic gradient are commonly used in the case of cohesive soils with the permeability coefficient lower than $10^{-5}$ m/s. Among them, indirect methods based on Terzaghie's consolidation theory and assumption of two-phase medium can be distinguished. Such tests are conducted in tri-axial compression apparatuses, oedometers, consolidometers. The values of the consolidation coefficient gained in those tests significantly differ from the values obtained by other laboratory methods, which are considered as estimated values (Krogulec, 1994; Żak, Ossowski, 1996; Kaczyński et. al., 1997, 2000; Dobak, 2007).

The comparison of permeability parameters was conducted on green clay samples from the Bełchatów open pit (Central Poland).

To verify the coefficient of permeability obtained by the consolidation method, the TRAUTWEIN measuring system was applied. This system enables saturating samples with water and forcing water movement in the soil by a permometer. Thus, the indirect (consolidation testing) and the direct (Trautwein measuring system) methods were compared for soil permeability protection.

The conducted verification of permeability has one more aspect. Namely, it is a different method of forcing the seepage process. Tests in the Trautwein system are based on water flowing through the sample. Such a way of permeability testing, without loss or increase in water volume is classified as "sourceless". The consolidometer tests (CL tests), which are referred to in the article, represent an alternative. The permeability parameters determined by indirect methods may be based on consolidation theory. Water is forced to flow by external loading resulting in water extraction from a porous space. Only water from pores flows through the sample during consolidometer tests and that's why it represents the "source" field of permeability.

The tests were conducted on clay samples with a non-disturbed structure, drawn in May 2005 from the "Bełchatów Field" in a lignite mine. The soils were of dark green colour with white irregular aggregates. Soil consistency expressed by the liquidity index $I_L < 0$. The total content of $CaCO_3$ was below 1%, but in the white aggregates it exceeded 5%. The grain size analysis of the samples indicated that the soils can be classified as clay ($f_i$ 90÷93%; $f_\pi$ 7÷10%). In terms of mineral composition, the soils are mostly composed of beidellite and quartz. The percentage share of these minerals, determined by thermal analysis, is 91.3% and 8.7%, respectively. The parameters of physical features of the soils are presented in Table 1 (Kowalczyk, 2007).

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Table 1. **Physical properties of green clays**

| Density of solid particles $\rho_s$, Mg/m³ | Bulk density of soil ρ , Mg/m³ | Dry density of solid particles $\rho_d$, Mg/m³ | Natural moisture content $w_n$, % | Plastic limit $w_p$, % | Liquid limit $w_L$, % *Casagrandea **penetrometer ELE | Liquidity index $I_L$ [–] | Plasticity index $I_p$, % | Consistency | Porosity n [–] | Void ratio e [–] |
|---|---|---|---|---|---|---|---|---|---|---|
| 2.80–2.82 | 1.84–1.93 | 1.41–1.47 | 28.9–35.0 | 36.4–38.0 | *106.6–110.6<br>**105.4 | (–0.07)÷(–0.09) | 70.2–72.6 | semi–solid | 0.48–0.50 | 0.92–1.00 |

It follows from the theoretical assumptions that a correct determination of the permeability coefficient by the method of consolidation testing requires a full saturation of pores with water (two-phase medium). Reliable results by this method can be obtained if the degree of saturation is close to unity. For the analysed soils, $S_{r0}$ ranged between 0.85 and 0.97. The average value of degree of saturation was 0.91.

Determination of soil permeability by the consolidometric method (CL tests) requires a continuous increase of pore water pressure. The character of pore water pressure increase depends on the rate of loading and on the changes of the soil structure. Therefore, first of all a reliable measurement of pore water pressure to determine permeability parameters is required. So it is necessary to fill the consolidometer with water before testing and to exclude any possible leakage in the measuring system so that the overpressure could not dissipate. It is also crucial that the water in the measuring system is deaerated.

The values of pore water pressure in one-dimensional consolidation tests can be considered with reference to the total stress as the so-called pore water pressure parameter $C_{CL}$. It indicates the ratio of pore water pressure ($u$) to the total axial stress (σ) in the soil at a given point of time $C_{CL} = \frac{u}{\sigma}$. Considering the soil behaviour during consolidation tests, according to the Terzaghi's one-dimensional consolidation theory, immediately after application of stress the pore water pressure $u$ should be equal to the value of the initial stress and then $C_{CL} = 1$. As soon as seepage is started up, the soil skeleton plays an increasing role in shaping the effective stress, and the $C_{CL}$ value decreases.

The results of experimental tests show an significant inconsistency of the soil behaviour with the theoretical model (Dobak, 1999), so he distinguished four types of $C_{CL}$ – σ diagrams:

- QT (quasi-theoretical) – the variability most approximate to the theoretical one; it demonstrates the highest values of $C_{CL}$ at the beginning of the tests, then they decrease. The discrepancies in relation to the model theoretical solutions consist in obtaining the value $C_{CL\,max} < 1$;
- PT (quasi-theoretical with the maximum shift) – the highest value of $C_{CL}$ does not occur at the beginning of the tests, but it is obtained after some time which is defined as the response time, when mobilization of pore water pressure is observed (Kowalczyk, 2005);

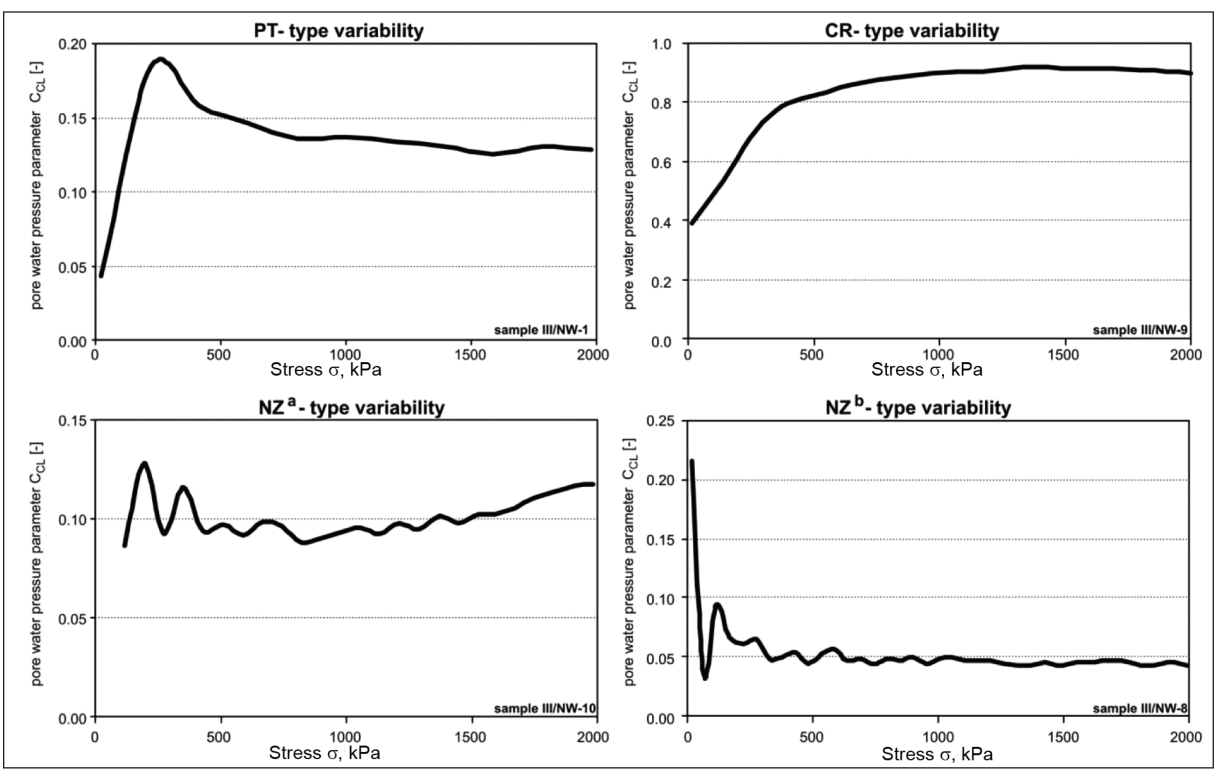



**Figure.** Experimental types of pore water pressure variability obtained in green clay tests

- NZ (irregular, variable) – characterized by an alternate increase and decrease in the $C_{CL}$ parameter. The NZ-type variability can be divided into two subtypes (Kowalczyk, 2005). Distinct repeating maxima and minima can be perceived in subtype *a*. After one of the maxima is reached, the $C_{CL}$ diagram generally starts to decline, though not always (see Figure), and it reaches the next local maximum. The subtype *b* is characterized by a rapid reaching of the $C_{CL}$ maximum value and then the quasi-linear course which proves a nearly constant participation of the liquid phase in the overtaking of stress;
- CR (continuously growing) – the $C_{CL}$ value rises concurrently with the consolidation stress without reaching a distinct maximum, and then its declines.

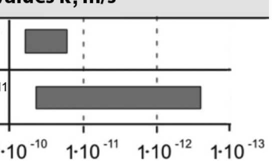
The consolidation tests presented in the article were conducted for the constant rate of loading (CRL). Three loading velocities were used: 0.05 kN/min, 0.10 kN/min, 0.15 kN/min. Three types of the variability of pore water pressure mentioned above were observed: PT, NZ, CR (Figure).

The green clay permeability coefficient tests determined on the basis of the consolidation coefficient show a wide range of results (Table 2). The values of the permeability coefficient *k* obtained by the direct method correspond to the upper range of the *k* values determined in the CRL tests. The permeability coefficient values obtained by the consolidometric method are generally lower than those gained in the Trautwein system. These results can lead to an incorrect evaluation of the insulating properties of the tested soils.

The diversity of the permeability coefficient values obtained in the CL tests is a consequence of a wide range of pore water pressures generated during the tests. The rate of loading has an insignificant influence on those differences, so it can be neglected in the further considerations. The changes of the permeability coefficient values in the CL tests are related to the above-mentioned types of variability of pore water pressure (Table 3).

Table 2. **The permeability coefficient values obtained by different methods**

| Testing equipment | Permeability coefficient values k, m/s |
|---|---|
| Trautwein | $(1.7 \div 6.4) \cdot 10^{-11}$ |
| Consolidometer | $2.5 \cdot 10^{-13} \div 4.5 \cdot 10^{-11}$ |




Of all the analysed tests, PT-type ones give the best approximate variability to the theoretical solution. For this type, the obtained permeability coefficient values correlate with the values obtained by the direct method. In the case of NZ[a] and NZ[b] types, the *k* values were slightly lower. It should be pointed out that the hydraulic gradients obtained in the CL tests were 10–30 times higher (for PT and NZ types) than those used during the tests in the Trautwein measuring system.

The widest discrepancies were stated for the CR variability type. The values of the permeability coefficient in those tests significantly (100 times) differed from the other results and were under estimated.

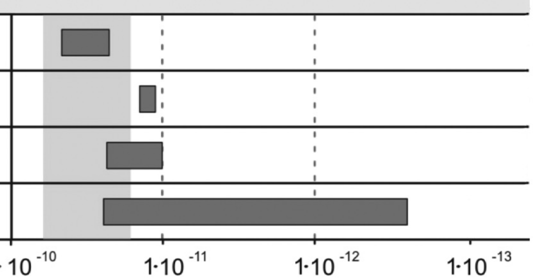
The CR-type variability tests demonstrate discrepancies between the experimental and theoretical characteristics. The consolidation coefficient values for this type of variability of pore water pressure are not reliable (Kowalczyk, 2007). Therefore, data on the permeability coefficient are considered incorrect.

## CONCLUSIONS

- The above analyses show that the discrepancy of the permeability coefficient values obtained by the consolidation tests and the tests in the Trautwein measuring system is conditioned mainly by the type of variability of pore water pressure in the CL tests.
- For soil permeability assessment, the results of CL tests concerning the variability of pore water pressure with a good approximate variability to the theoretical solution (PT type) should be recommended. The values of the permeability coefficient are similar to those obtained by the direct method.
- Tests in which an increase in pore water pressure of CR and NZ type occurs should be excluded from the evaluation process of soil permeability properties because of a wide range of the results and a discrepancy between experimental and theoretical characteristics.
- When the samples of CR-type variability are omitted, tests based on the "source" and "sourceless" permeability field give similar values of the permeability coefficient.

Table 3. **The values of the permeability coefficient obtained in CL tests divided into pore water pressure types**

| Parameter type of variability of pore water pressure | Permeability coefficient values k [m/s] for NNS samples of green clay at a stress of 2 MPa |
|---|---|
| PT | $(2.2 \div 4.5) \cdot 10^{-11}$ |
| NZ [a] | $(1.1 \div 1.4) \cdot 10^{-11}$ |
| NZ [b] | $(1.0 \div 2.3) \cdot 10^{-11}$ |
| CR | $2.5 \cdot 10^{-13} \div 2.4 \cdot 10^{-11}$ |




– range of values recommended on the basis of direct method tests.

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### FILTRACIJOS KOEFICIENTO KAITA TIRIANT BELCHATOVO ŽALIĄJĮ MOLĮ

*S a n t r a u k a*

Remiantis molio konsolidacijos tyrimais, analizuojamos molio filtracijos koeficiento vertės. Natūralios drėgmės ir sandaros žaliojo molio bandiniai buvo paimti iš 100 m gylio. Didelis kiekis molio dalelių, tarp kurių vyrauja beidelitas, nulemia dideles šio molio plastiškumo vertes. Konsolidacijos tyrimai atlikti nuolat didėjančios apkrovos sąlygomis (CL metodas). Gauti rezultatai patikrinti TRAUTWEIN matavimo sistema, kuria tiesiogiai įvertinama filtracijos koeficiento vertė. Gautas platus filtracijos koeficiento verčių kaitos intervalas, susijęs su porų slėgiu bei per laiką didėjančiu įtempiu. PT tipo tyrimų rezultatai gerai koreliuojasi su tiesioginių tyrimų rezultatais. Tyrimų analizė ir palyginimas leido pateikti metodines išvadas apie galimybę naudoti netiesioginį metodą tiriant molio konsolidacijos laidumą.

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### ZMIENNOŚĆ WARTOŚCI WSPÓŁCZYNNIKA FILTRACJI IŁÓW ZIELONYCH Z BEŁCHATOWA W BADANIACH KONSOLIDACJI

*S t r e s z c z e n i e*

W artykule przeanalizowano wyniki oznaczeń współczynnika filtracji iłów, uzyskane metodą pośrednią z badań konsolidometrycznych w warunkach ciągłego wzrostu obciążenia (badania typu CL). W celach weryfikacji tak uzyskanych wyników przeprowadzono także badania przepuszczalności gruntu za pomocą systemu pomiarowego TRAUTWEIN, będącego bezpośrednią metodą określania wartości współczynnika filtracji. Badaniom poddano próbki iłów zielonych o nienaruszonej strukturze i naturalnej wilgotności, pobrane z głębokości 100 m poniżej powierzchni terenu, z nadkładu złoża węgla brunatnego „Bełchatów". Próbki te posiadają wysokie wartości wskaźnika plastyczności (tab. 1), co jest związane ze znacznym udziałem frakcji ilastej, w której dominuje beidellit. Otrzymany z badań CL szeroki zakres zmienności wartości współczynnika filtracji wynika ze zróżnicowanego charakteru dystrybucji ciśnienia porowego, kształtującego się w toku wzrastającego naprężenia konsolidacyjnego. Wyraża się to różnymi typami zmian parametru ciśnienia wody w porach $C_{CL}$ (rysunek). Dla typu PT, czyli najbliższego rozwiązaniu teoretycznym, uzyskane wartości współczynnika filtracji dobrze korelują się z rezultatami metody bezpośredniej. Przeprowadzone analizy przebiegu badań i porównanie ich wyników pozwoliły na sformułowanie metodycznych wniosków dotyczących miarodajności i warunków stosowalności pośredniej metody określania przepuszczalności iłów z badań konsolidometrycznych.

**Себастиан Ковальчик**

### ИЗМЕНЧИВОСТЬ КОЭФФИЦИЕНТА ФИЛЬТРАЦИИ ПРИ ИССЛЕДОВАНИИ БЕЛХАТОВСКИХ ЗЕЛЕНЫХ ГЛИН

*Р е з ю м е*

Рассмотрены значения коэффициента фильтрации по данным консолидационных испытаний. Образцы зеленых глин отбирались с глубины 100 м. Большое количество глинистых частиц, среди которых преобладает бейделит, определяет высокие значения показателя пластичности глин. Консолидационные испытания проводились при постепенном увеличении нагрузки методом CL. Полученные результаты проверялись измерительной системой TRAUTWEIN, с помощью которой можно оценить непосредственно значение коэффициента фильтрации. Получен широкий диапазон изменения значений коэффициента фильтрации в зависимости от порового давления и увеличивающегося напряжения. Результаты, полученные при исследовании типа PT, хорошо коррелируют с результатами прямых испытаний. Сравнение и анализ полученных результатов позволили представить методические выводы о возможности применить косвенный метод при исследовании водопроводимости глин по данным консолидационных испытаний.