Using a Hydraulic Conductivity Apparatus for Determination of the Permeability of Low Permeable Soils on the Example of Clay from Kleszczow

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Abstract. The paper presents results of the laboratory tests of the permeability coefficient of clay carried out in the originally constructed apparatus. This device is intended to test the permeability of low permeable soils. To verify the instrument and the reliability of the obtained results, tests on clay samples originating from Kleszczow Rift Valley were performed. In order to better identify the soil sample, its basic physical parameters and grain-size distribution curve were presented. The permeability tests were performed on three undisturbed samples of the same soil at four different pressure gradients. The diameter and the height of the sample were \( d = 40 \text{ mm} \), \( h = 30 \text{ mm} \), respectively. The hydraulic conductivity was determined based on the constant head tests results. During tests the penetrating liquid was distilled water. The full permeability test of a single sample was relatively short and lasted from 10 to 12 days. For tested clay the void ratio was equal to 0.53, and the permeability coefficient varied between \( 4.7 \times 10^{-10} \) to \( 6.2 \times 10^{-10} \) [m/s] in function of the hydraulic gradient. The values of the permeability coefficient obtained in this work correspond well with results presented in the literature. This shows that the constructed device proved itself for determining the permeability coefficient of clays. Thus, the constructed apparatus and the applied test method are good and simple tool for testing the permeability of low permeable soils.

1. Introduction

Determination and interpretation of hydraulic conductivity in very low permeable soils is a complicated process [1], [2]. There are many methods and different apparatuses and conditions to test permeability of low permeable soils such as clays. In the laboratory, the permeability of clays can be determined for example: in triaxial or in a modified triaxial apparatus [1], [3], [4] in measurement systems using “flow-pump” method [5], [6] directly or indirectly in oedometers [4], [7], [8], [9] in consolidometers [2], by using specially designed apparatuses [10], [11], [12] or even facilities [13].

It is obvious that each method has its own advantages and disadvantages. Disadvantages are often related to measurement errors or difficulties or ambiguities in the interpretation of measurement results (for example evaluation of the permeability from consolidation tests) [3], [8].

Due to the very low permeability of clays its measurement implies the observation of very small flows over extended periods of time. The identification and elimination (if possible) of errors on the observed flow is crucial for the accurate evaluation of the permeability of clays [3]. For example, list the most important sources of errors associated with a standard triaxial test installation: the mechanical leakage in the external fittings, the leakage in fittings within the cell, the osmosis and diffusion...
through the membrane and tubing within the cell, the lack of saturation of the rubber membrane [3]. Additionally, during some tests, the time of the measurements is very long: expressed in months or even years [10]. To overcome these difficulties new installations, improved measurements methods and more sophisticated equipment are still developed.

The paper presents results of the tests of permeability coefficient of clay samples obtained in the original hydraulic conductivity apparatus. This device, special type of permeameter, was constructed for testing the permeability of low permeable soils. But in this case the simplicity of the construction was the key. It was invented as a simple device, resistant to chemicals and ensuring a short time of tests. Additionally, to estimating the capability of this equipment and assessing the reliability of received outcomes, a comparison of the experimental results to results available in the literature was also performed.

2. Material and Methods

2.1. Materials

The samples of green clay originating from Kleszczów Rift Valley were selected for the investigations. It was decided to choose this soil because it had been well described and characterized earlier in the literature [14], [15], [16], [17]. These are the neogenic green clay from the Poznań series [14], [15]. It was found, i.a. that they are a very good material for use in insulation geo-barriers [17]. Samples for testing were taken from the Belchatów area. They contained about 30% of clay fractions. A dominant mineral in those clays is quartz and beidellite, and also there are minor quantities of kaolinite [14], [15]. These soils are characterized by significant swelling due to the high content of beidellite. The permeability of soils depends on many factors, including from the mineral composition, especially from the content of swelling minerals such as beidellite. Therefore, it should be assumed that the tested clays will be characterized by a very low permeability. For these clays, in the literature, the values of the permeability coefficient ranges from $3.5 \cdot 10^{-10}$ to $6.5 \cdot 10^{-10}$ [m/s] [17].

To better characterize the tested soil, its basic physical parameters (table 1) and grain-size distribution curve (‘figure 1’) were determined.

| $\rho$ [kg/m$^3$] | $\rho_s$ [kg/m$^3$] | $w$ [-] | $n$ [-] | $e$ [-] |
|-------------------|------------------|---------|--------|--------|
| 2090              | 2640             | 0.21    | 0.35   | 0.53   |

Soil particle density $\rho_s$, bulk density $\rho$ and water content $w$ were defined on the basis of PN-88/B-04481 standard. Moreover in (table 1) the porosity and the void ratio are denoted as $n$ and $e$, respectively. The grain-size distribution curve was drawn up in accordance to procedure described in PKN-CEN ISO/TS 17892-4 standard. The permeability tests were performed on three undisturbed samples of the same soil at four different pressure gradients (table 2). The dimensions of the sample were as follows: the diameter $d = 40$ mm, and the height $h = 30$ mm.
2.2. Apparatus

The hydraulic conductivity apparatus (‘figure 2’) constructed by a team from the Department of Geotechnics, Hydrotechnics, Underground and Water Engineering of Wroclaw University of Science and Technology is intended to test the permeability of low permeable soils as clays. It consists of several parts.

The internal diameter of the sample chamber \( d = 40 \text{ mm} \) and the samples height depends on the height of sample chamber and varies between 30 mm up to several hundred millimetres. In the permeameter (4) the soil sample is fixed between upper and lower rigid porous plates, in such a manner that the change of geometrical dimensions of the sample is not possible. The porous plates are retracted to the upper and lower chamber with the mounting rings (5a, 5b). In the chambers (5a and 5b) there are mounted valves. The entire column, composed of elements: 2-5b together with the apparatus frame (1), can be set up as presented in ‘figure 1’ or "upside down". It depends on the required direction of the flow. In ‘figure 1’ the flow should be from top to bottom (in accordance with the direction of gravity). In such a case the liquid is supplied continuously under constant pressure by the valve (3). The valve (2) should be slightly open so that the air and the excess of the liquid can outflow easily. The liquid moves in a closed circuit between valves (2) and (3). The liquid which passed through the permeameter outflows by another valve (6) and it is collected in the tank.

As we can see, the construction of the apparatus is simple. This is quite important because if necessary it is easy to change the elements already worn.

The sample chamber is made of glass or transparent plastic (second option) but most parts are made of stainless steel because of the assumption that the liquid percolating through the permeameter can be contaminated and not inert chemically.

To verify the capabilities of the device and the reliability of obtained results tests were needed. In case of satisfactory results this equipment could be an alternative to more sophisticated instruments.

Figure 1. The grain-size distribution curve of clay sample from Kleszczów Rift Valley.
2.3. Hydraulic conductivity test procedure

Initially undisturbed samples of soil were placed firmly in the sample chamber (4). They were pressed gently from cylindrical steel probe to the chamber by a special piston. Between the chamber and the piston a cutting ring was placed to give the proper diameter of samples. Next, the upper and lower sample surfaces were aligned using the other piston, the height of the sample was measured and finally a paper filter was placed on the top and the bottom of the sample. During tests the test column was composed (from top to bottom) of the following elements: chamber with the mounting ring and porous stone (5b) and one valve (6), permeameter (4), chamber with the mounting ring and porous stone (5a) with two valves (3, 2). The whole set was put together by a frame (1). The permeant fluid was distilled water and the flow direction was opposite to gravity.

Hydraulic conductivity testing began with saturating the sample of soil. The valve (2) was opened and water was flowing continuously from plumbing through this valve to the chamber (5a). The initial pressure difference between permeameter inlet and outlet was constant and equal to 200 kPa. The excess of water outflowed from chamber (5a) by valve (3). Manipulating the valve (3) allowed to change the pressure at the inlet of the permeameter (4) if necessary. After about 3 to 4 days water appeared in the valve (6) and was collected in the tank. On the surface of the collected water the film of oil was present, to prevent (or at least to decrease) evaporation of water from the tank. Every few hours the mass of water in the tank was controlled. When the increase in weight of water at the given interval of time was constant the proper measurement of hydraulic conductivity began. In the constant head test the mass of percolated water in time and water temperature were measured. Subsequently, the pressure difference was increased with the increment of 50 kPa and the measurement procedure

Figure 2. The constructed hydraulic conductivity apparatus.
started again. The test ended when pressure difference reached 350 kPa. Thus, for every sample the permeability coefficient \( k \) was determined at four different pressure gradients.

Every increase of pressure was applied in a gentle manner. During tests no leaks along the permeameter walls were observed, probably due to the swelling pressure which prevented this situation. The water temperature varied between 17 and 18.5 degrees Celsius. The mean value (17.8 °C) was adopted for further calculations.

The total testing time of one sample was about 10 to 12 days.

3. Results and Discussion
On the basis of the outcomes from the tests the values of permeability coefficient \( k \) [m/s] of the clay were calculated from Darcy's law expressed as follows:

\[
Q = \frac{m}{\rho \cdot t} = k \cdot \frac{p}{\rho g h} \cdot \frac{\pi d^2}{4}
\]

which after transformations takes the form:

\[
k = \frac{4m g h}{t \cdot p \cdot \pi d^2}
\]

where:
- \( m \) [kg] is the mass of the percolated water in time \( t \) [s],
- \( \rho \) [kg/m³] is the water density,
- \( g \) [m/s²] is the acceleration of gravity equal to 9.81,
- \( p \) [Pa] is the pressure difference between permeameter inlet and outlet and \( h \) and \( d \) are already mentioned height and diameter of clay sample, respectively. The mean values of \( k \) (of the three samples) for each hydraulic gradient are summarized in table 2.

| \( p \) [Pa] | 200 \( \times \) 10³ | 250 \( \times \) 10³ | 300 \( \times \) 10³ | 350 \( \times \) 10³ |
|-------------|-----------------|-----------------|-----------------|-----------------|
| \( i = p(\rho g h) \) [-] | 680.5 | 850.6 | 1020.7 | 1190.8 |
| \( k \) [m/s] | 4.7 \( \times \) 10⁻¹⁰ | 5.2 \( \times \) 10⁻¹⁰ | 5.6 \( \times \) 10⁻¹⁰ | 6.2 \( \times \) 10⁻¹⁰ |

To calculate hydraulic gradients it was assumed that the density of water is equal to 998.662 [kg/m³] (in the temperature \( T = 17.8 \) °C).

The comprehensive results of studies and tests for clays from Kleszczów Rift Valley were presented in [17]. Kowalczyk has carried out his tests in low-pressure consolidometer. In these tests the permeability coefficient depends on consolidation coefficient and clay bulk modulus. To determine the consolidation coefficient the reliable measurement of pore water pressure is needed, and the degree of saturation of the samples with water should be close to unity. On the basis of PN-88/B-04481 standard Kowalczyk also determined the physical parameters of tested clays. A good correspondence between physical parameters of clay tested by Kowalczyk and clay used in the present study (table 1) can be observed. For void ratio between 0.48 and 0.51 the permeability coefficient changes from 3.5 \( \times \) 10⁻¹⁰ to 6.5 \( \times \) 10⁻¹⁰ [m/s] [17]. In the present work the void ratio is a little bit higher and equal to 0.53, whereas the permeability coefficient varies between 4.7 \( \times \) 10⁻¹⁰ to 6.2 \( \times \) 10⁻¹⁰ [m/s] depending on the hydraulic gradient. So, it seems that these values are in good agreement.

It is difficult to carry out more extensive comparison to results of other researchers due to the lack of detailed data in available literature. For example, to make a fair comparison one should begin from
comparing the grain-size distribution curves for every kind of tested clay but these plots are not so often published.

About measurement errors, the presented equipment is insensitive to leakages. No leaks between sample chamber and chambers with the mounting ring were observed. Moreover, there is only one valve which carries the water which passed through the permeameter to the tank. The only loss of water can occur through evaporation form the tank. But to reduce this effect the film of oil was present on the water surface collected in the tank.

Other source of errors such as process of sample swelling was also reduced by the rigid apparatus construction. On the other hand, the apparatus construction, in the present form, does not allow for apply a given load during test.

However, the obtained results show that the constructed apparatus works well, and this first test encourages further research.

4. Conclusions

In this article a constructed hydraulic conductivity apparatus was presented. The simple and efficient construction of the equipment eliminates some of the measurement problems such as leaks of different origins or swelling of the sample, but also introduces some restrictions, for example lack of possibility of the measurement of k under a given load. Moreover, the full permeability test of a single sample is relatively short and lasts from 10 to 12 days.

To verify the apparatus possibilities, the tests on samples of clay from Kleszczów Rift Valley were made. For better identification of clay samples, the grain-size distribution curve was presented as well as the basic physical parameters of the clay. The values of the permeability coefficients were determined in the constant head tests. For the void ratio equal to 0.53 the permeability coefficient varies between $4.7 \times 10^{-10}$ to $6.2 \times 10^{-10}$ [m/s] in function of the hydraulic gradient. The obtained values of $k$ correspond well with results available in the literature [17]. This shows that the constructed device proved itself in determining the permeability coefficient of low permeable fine grained soils as clay.

However, to fully confirm the effectiveness of this device to determine $k$ of low permeable soils, and to define its range of applicability to test different kinds of soils additional research is required.

References

[1] G. Siemens, J.A. Blatz, “Development of a hydraulic conductivity apparatus for bentonite soils,” Can. Geotech. J. 44, pp. 997-1005, 2007.
[2] S. Kowalczyk, “Variability of permeability coefficient values of green clays from Belchatów in one-dimensional consolidation testing,” Geologija, 50, Supplement, pp. 16-19, 2008.
[3] F. Tavenas, P.J. Leblond, S. Leroueil, “The permeability of natural soft clays. Part I: Methods of laboratory measurement,” Can. Geotech. J. 20, pp. 629-644, 1983.
[4] M. Jaromińska, E. Dembicki, “Determination of the permeability coefficient of low permeable soils,” Inżynieria Morska i Geotechnika, 5, pp. 227-235, 1999 (in Polish).
[5] J. Herzig, J. Szczepańska, “Application of the ”flow-pump” method for testing the permeability coefficient in low permeable soils,” Współczesne Problemy Hydrogeologii VII, Kraków-Krynica, Wyd. AGH Kraków, 1995 (in Polish).
[6] M. Marciniak, J. Przybyłek, J. Herzig, J. Szczepańska, “Research on the permeability coefficient of semi-permeable soils,” Poznań: SORUS, 1999 (in Polish).
[7] A. Dueck, “Laboratory results from hydro-mechanical tests on a water unsaturated bentonite,” Engineering Geology, 97, pp. 15-24, 2008.
[8] V.V. Zhikhovich, “Determination of the permeability coefficient of saturated clay from the settlement curve in a compression test,” Gidrotekhnicheskoe Stroitels’tvo, No. 12, pp. 36-37, 1981.
[9] E. Sawicki, J. Stróżyk, “Determination of permeability coefficient of saturated clay based on linear segment of settlement curve,” Studia Geotechnica et Mechanica, vol. 31, No. 4, pp.
73-84, 2009.

[10] D.A. Dixon, J. Graham, M.N. Gray, “Hydraulic conductivity of clays in confined tests under low hydraulic gradients,” Can. Geotech. J., 36, pp. 815-825, 1999.

[11] C.C. Hird, S. Srisakthivel, “Laboratory investigation of permeability measurement in clay using outflow from unsupported cavities,” Géotechnique, 55, No.5, pp. 393-402, 2005.

[12] X. Wang, C.H. Benson, “Infiltration and saturated hydraulic conductivity of compacted clay,” Journal of Geotechnical Engineering, pp. 713-722, 1995.

[13] J.P. Britton, G.M. Filz, W.E. Herring, “Measuring the hydraulic conductivity of soil-bentonite backfill,” Journal of Geotechnical and Geoenvironmental Engineering, pp. 1250-1258, 2004.

[14] R. Wyrwicki, “The need to protect beidellite clays at KWB Belchatów,” Prz. Geol., 41, pp. 612–620, 1993 (in Polish).

[15] R. Wyrwicki, „Opinion on beidellite clays for the Belchatów Brown Coal Mine in Rogowiec,” Arch. KWB „Belchatów”, 1996 (in Polish).

[16] R. Wilczyński, „Previous results of basic research in the Poznań series in the light of geological-engineering problems of mining works in KWB Belchatów,” Pr. Geol.-Miner., 26, pp. 91–108, 1992 (in Polish).

[17] S. Kowalczyk, “Evaluation of beidellite clay insulation properties from brown coal mine “Belchatów” by using consolidation tests,” Przegląd Geologiczny, 53, No. 9, pp. 776-780, 2005.