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Permeability coefficient tests in non-cohesive soils

Key words: permeability coefficient, non-cohesive soil, pumping test, consolidation test, groundwater

Introduction

Permeability coefficient (k) is the basic parameter that characterizes the soil properties from the point of view of construction works (Matusiewicz & Wrzesiński, 2018; Wrzesiński, Kowalski & Miszkowska, 2018). This parameter characterizes the filtration ability of water in laminar movement through the soil and is a measure of the soil's hydraulic permeability. Filtration takes place through a network of channels formed from soil pores. The permeability coefficient depends on the soil properties, i.e.: soil type, porosity, grain size, soil structure, water viscosity (Todd, 1980). Approximate typical ranges of the permeability coefficient for cohesive and non-cohesive soils are presented in Table 1.

TABLE 1. Approximate typical ranges of the permeability coefficient for cohesive and non-cohesive soils (Wiłun, 2013)

Soil	Permeability coefficient (k) [m·s^{-1}]
Fine gravel	10^{-2}–10^{-3}
Coarse and medium sand	10^{-3}–10^{-4}
Fine sand	10^{-4}–10^{-5}
Silty sand	10^{-5}–10^{-6}
Silt	10^{-6}–10^{-8}
Clay with I_p = 10–20%	10^{-8}–10^{-10}
Clay with I_p = 20–30%	10^{-9}–10^{-11}
Clay with I_p > 30%	10^{-10}–10^{-12}

There are many methods for determining the permeability coefficient, ranging from uncomplicated calculations to complex field and laboratory methods (Wdowska & Lipiński, 2016). Each of the methods gives more or less similar value of the permeability coefficient to the real value. The choice of a method for determining the permeability coefficient depends largely on the soil type. Eurocode 7 distinguishes four methods of testing the permeability coefficient: empirical correlations, field tests, laboratory tests and estimation based on the oedometer test. In non-cohesive soils, the permeability coefficient is often determined based on empirical formulas. On the basis of empirical formulas, the value of the permeability coefficient is determined with regard to the grain size of the soil (most often the effective diameter of grain d_{10}), porosity and specific surface area (Twardowski & Drożdżak, 2006; Szymkiewicz & Kryczałło, 2011). On the other hand, empirical formulas do not take into account the influence of soil structure, anisotropy of permeability and the shape of soil grain. Research indicates that the permeability coefficient of the same material calculated on the basis of different empirical relationships may vary significantly (Parylak, Zięba, Bułdys & Witek, 2013). As a result, the approximate value of the permeability coefficient is often obtained on the basis of empirical formulas. Field tests that reflect the heterogeneity of the geological structure of the subsoil and anisotropy of hydraulic permeability are the most accurate way to determine the permeability coefficient. The most commonly used method of field tests is pumping test, which involves pumping water out of a well to obtain a hydrodynamic reaction of the subsoil (MacDonald, Barker & Davies, 2008; Polak, Kaznowska-Opala, Pawlecka & Klich, 2014). This reaction allows identification of permeability parameters of the subsoil, well performance parameters and inflow conditions. Pumping test can only be used to determine the permeability coefficient in well-permeable soils. In low-permeable soils, the BAT probe test is most often used. The BAT probe test involves combining a piezometer with a probe measuring part which has a glass water container. The test entails registration of the pressure changes inside the container. The permeability coefficient is calculated based on pressure changes as a function of time. In the laboratory constant or variable gradient methods are used to measure the permeability coefficient. Constant gradient methods are applied to measure the permeability coefficient in well-permeable soils. The most common constant-gradient tests are the ones in the Rowe chamber, ZW-K2 apparatus or Trautwein system (Head & Epps, 2011). Variable-gradient methods are only used to determine the permeable parameters of low-permeable soils. The most common are tests in a modified oedometer supplemented with a burette, test using a Kamieński tube and flow-pump method. Of the above mentioned variable-gradient methods in laboratory conditions, the most common is the flow-pump method. This method involves setting a constant speed of water flow through the sample and measuring the pressure difference at the bottom and top of the soil sample. The test continues until the pressure difference between the bottom and the top of the sample stabilizes.

Laboratory tests for determining the permeability coefficient are less accurate compared to field tests, especially for non-cohesive soils. In laboratory tests, the value of permeable parameter is mainly affected by the change in geological structure in relation to field conditions.

The purpose of the research presented in the paper is to determine and compare the values of the permeability coefficient in non-cohesive soils determined in selected laboratory and field tests.

Materials and methods

Permeability coefficient tests were carried out by the pumping method and in a consolidometer. Pumping tests were started by selecting sites in the field where the subsoil has homogeneous permeable soils and it is possible to carry out the tests. A total of 18 sites were selected for testing. Pumping tests were performed according to the standard method (Driscoll, 1986; Krusemann & de Ridder, 1994; Dąbrowski & Przybyłek, 2005; ICRC, 2011). In each test site one well and two piezometers were installed. Field tests began with the installation of a well with a diameter of 400 mm at designated test sites. Depending on the borehole, the wells were installed to a depth of 1.20–1.80 m. Piezometers with a diameter of 140 mm were installed near each well. One at a distance of 2.0 m from the edge of the well, while the other at a distance of 5.0 m. Installation was carried out excluding the causes and effects of adverse events (Rybka, Bondar-Nowakowska & Połoński 2016). Wells and piezometers were made of ready-made PVC materials. The wells and piezometers used in the research are shown in Figures 1 and 2. A typical schematic of the test pumping system is shown in Figure 3.

FIGURE 1. Well with a diameter of 400 mm made of PVC material used in pumping tests

FIGURE 2. Piezometer with a diameter of 140 mm made of PVC material used in pumping tests

Before pumping test, a dynamic light probe SL tests were performed near the well to determine the density index of the tested soils. Simultaneously, soil samples for laboratory tests were taken from the subsoil. Pumping tests consisted of pumping water out of the well and measuring the changes of the water table in piezometer. In each well the tests were performed several times to verify

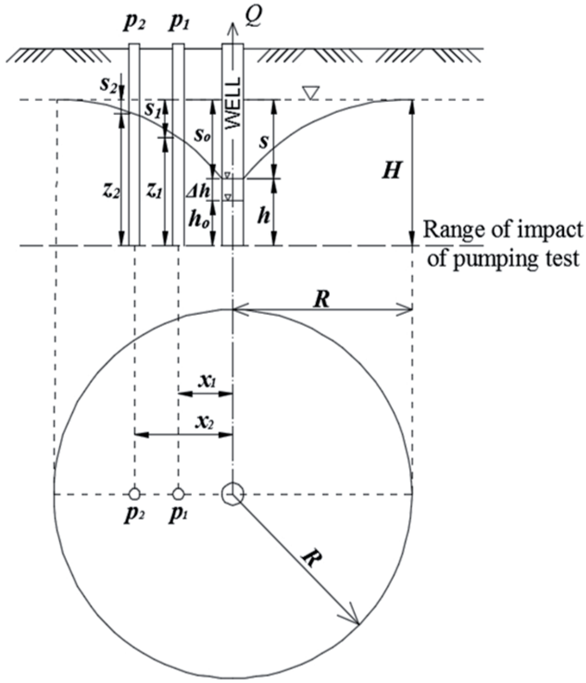

FIGURE 3. Typical schematic of the pumping test system: p_1 – piezometer 1, p_2 – piezometer 2, h – water table outside the well, h_0 – water table inside the well, Δh – difference in water table inside and outside the well, s – lowering the water table at the well, s_0 – lowering the water table inside the well, s_1 – lowering the water table in the piezometer 1, s_2 – lowering the water table in the piezometer 2, z_1 – water table in the piezometer 1, z_2 – water table in the piezometer 2, R – distance of lowering the water table around the well

the obtained results. The differences between the values of permeability coefficients obtained at the same test site did not exceed 5%. Measurements in the piezometers were also carried out for 30 days after the finish of the pumping tests. The permeability coefficient (k) was determined according to the equation:

$$k = \frac{\frac{Q}{\Pi\left(z_2^2 - z_1^2\right)} \ln x_2}{x_1}$$

where:
Q – flow of pumped water,
z_1 – water table in piezometer 1,
z_2 – water table in piezometer 2,
x_1 – distance between piezometer 1 and well,
x_2 – distance between piezometer 2 and well.

The following tests were carried out in the laboratory: tests on soil grain size, tests on a scanning electron microscope and tests on a permeability coefficient. Tests on soil grain size were performed to determine soil type according to EN ISO 14688-1:2002 and EN ISO 14688-2:2004. Photos in a scanning electron microscope (XL series, QUANTA 200) were taken to determine the shape of particles of the tested soil. Some photos for the same soil type and similar density index from two different test sites are shown in Figure 4. Permeability coefficient tests were carried out in a laboratory using consolidometer (Fig. 5). Testing of the permeability coefficient in the consolidometer began with the compaction of soil samples in the Proctor apparatus to the density index determined in the field tests with a light dynamic probe SL (Head, 1980; Tymosiak & Sulewska, 2016).

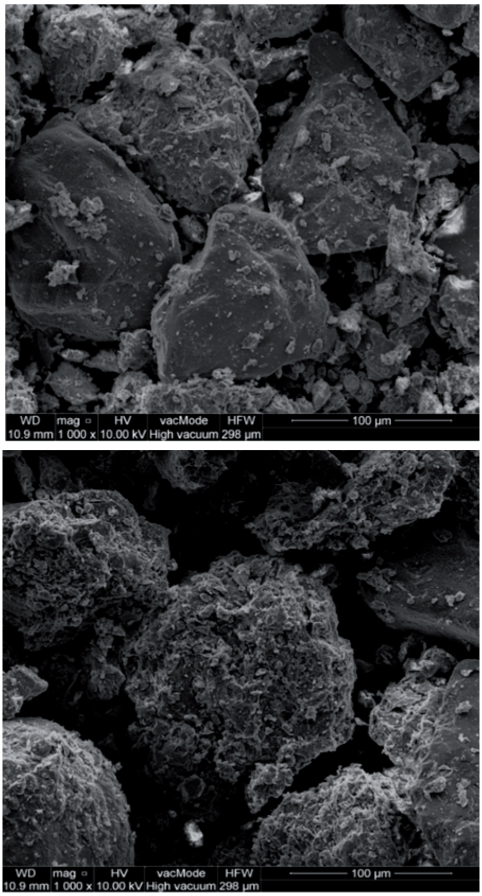

FIGURE 4. Photos of fine sand (FSa) with similar density index (I_D) from two different test sites (wells 1 and 6)

FIGURE 5. Consolidometer used in tests

After compaction, the sample with a diameter of 150 mm and a height of 60 mm, was placed in a consolidometer. The tests were carried out with a continuous inflow of water from below with constant gradients of 0.50. The differences between the values of filtration permeability obtained with the same gradients did not exceed 5% for each soil. Summary of grain size distribution and density indexes of analysed soils are presented in Table 2.

Results and discussion

The performed tests allowed to determine the permeability coefficient of selected non-cohesive soils by two methods: pumping test and consolidometer test. The values of obtained permeability coefficients for the tested soils are presented in Table 3.

TABLE 2. Grain size distribution and density indexes of analysed soils

Well	Soil	Fraction* [%]				Density index (I_D) [-]
		Gr	Sa	Si	Cl	0.55
1	FSa	0	91	9	0	0.49
2	FSa	1	90	9	0	0.67
3	FSa	0	92	8	0	0.61
4	FSa	1	92	7	0	0.64
5	FSa	2	90	8	0	0.41
6	FSa	0	94	6	0	0.54
7	FSa	1	93	6	0	0.51
8	FSa	0	97	3	0	0.56
9	FSa	0	95	3	2	0.39
10	FSa	0	95	5	0	0.50
11	MSa	0	99	1	0	0.48
12	MSa	0	98	1	1	0.41
13	MSa	1	96	3	0	0.58
14	MSa	2	97	3	0	0.52
15	MSa	0	98	2	0	0.61
16	CSa	8	92	0	0	0.71
17	CSa	12	87	1	0	0.68
18	CSa	19	81	0	0	0.59

*According to EN ISO 14688-1:2002 and EN ISO 14688-2:2004.

The performed research indicates that lower permeability coefficients were obtained in laboratory tests compared to field tests. The impact of the density index on the obtained permeability coefficients are important in the tested non-cohesive soils. Generally, lower permeability coefficients were obtained in soils that were characterized by a higher density index.

It should be noted that the value of the permeability coefficient is influenced by the shape of soil particles and their mutual arrangement. Irregularly shaped sand grains hold more water bound in the micro-cavities compared to more regular ones which was confirmed in the performed tests. In the cases of the same soil type and similar density index, the differences in the values of the permeability coefficient are significant. For instance, in the case of fine sand (FSa) from wells 1 and 6, the difference in the values of the permeability coefficient is two times. The influence of grain shape and density index on the value of the permeability coefficient is greatest in fine sands (FSa).

Differences in the values of tested parameter obtained in field and laboratory tests indicate that only field tests reflect actual field conditions. The value of permeability coefficient in non-cohesive

TABLE 3. Values of permeability coefficient from pumping test and consolidometer test

Well	Soil	Permeability coefficient (k) [m·s^{-1}]	
		pumping test	consolidometer test
1	FSa	$2.31 \cdot 10^{-5}$	$2.19 \cdot 10^{-5}$
2	FSa	$3.70 \cdot 10^{-5}$	$3.41 \cdot 10^{-5}$
3	FSa	$2.08 \cdot 10^{-5}$	$1.99 \cdot 10^{-5}$
4	FSa	$1.25 \cdot 10^{-5}$	$1.34 \cdot 10^{-5}$
5	FSa	$5.76 \cdot 10^{-5}$	$5.65 \cdot 10^{-5}$
6	FSa	$4.67 \cdot 10^{-5}$	$4.44 \cdot 10^{-5}$
7	FSa	$3.78 \cdot 10^{-5}$	$3.65 \cdot 10^{-5}$
8	FSa	$4.39 \cdot 10^{-5}$	$3.98 \cdot 10^{-5}$
9	FSa	$4.79 \cdot 10^{-5}$	$4.65 \cdot 10^{-5}$
10	FSa	$5.60 \cdot 10^{-5}$	$5.28 \cdot 10^{-5}$
11	MSa	$1.68 \cdot 10^{-4}$	$1.57 \cdot 10^{-4}$
12	MSa	$2.98 \cdot 10^{-4}$	$2.93 \cdot 10^{-4}$
13	MSa	$2.27 \cdot 10^{-4}$	$2.12 \cdot 10^{-4}$
14	MSa	$1.50 \cdot 10^{-4}$	$1.45 \cdot 10^{-4}$
15	MSa	$1.31 \cdot 10^{-4}$	$1.32 \cdot 10^{-4}$
16	CSa	$3.72 \cdot 10^{-4}$	$3.68 \cdot 10^{-4}$
17	CSa	$4.12 \cdot 10^{-4}$	$3.84 \cdot 10^{-4}$
18	CSa	$4.86 \cdot 10^{-4}$	$4.78 \cdot 10^{-4}$

soils is largely influenced by the heterogeneity of the subsoil and the geological structure, which is very difficult to reflect in laboratory tests.

Conclusions

The paper aims to comparison the permeability coefficient in non-cohesive soils by the method of pumping test and based on tests in a consolidometer. The performed research indicates that lower permeability coefficients were obtained in laboratory tests compared to field tests. The impact of the density index and the shape of soil grains on the obtained permeability coefficients are significant in the tested non-cohesive soils. For the same soils but with different density indexes, the permeability coefficient differs even several times. Studies have shown that also large differences in the values of the permeability coefficient are in the case of the same soils with a similar density index but with different grain shapes. Permeability coefficient tests are often carried out only for large construction projects, while in smaller investments the values of permeability coefficients are calculated with empirical formulas. Using empirical formulas to determine permeability coefficients results in approximate values often several times smaller or larger than the real ones in the field. Field tests are costly, which is why permeability coefficient are often determined based on laboratory tests or empirical formulas. In laboratory tests, the value of permeability parameter is often affected by the changed geological structure in relation to field conditions. Empirical formulas give only approximate values of the permeability coefficient, because they do not embrace real field conditions. In the case of non-cohesive soils, it is difficult to reproduce the appropriate compaction and mutual arrangement of soil particles, which can immensely affect test results. Field tests allow to determine reliable results since they reflect the real heterogeneity of the geological structure of the subsoil and anisotropy of hydraulic permeability. This is due to the representation of a larger soil surface in field studies compared to laboratory tests and occurrence of natural conditions in the subsoil.

It is hard to carry out the pumping test in densely built-up areas due to their impact on neighbouring buildings and if the change of the water table goes beyond the plot area, the additional water and legal permits are required. Therefore, laboratory tests, both the test methodology and apparatus, should be improved to best reflect the real conditions that occur in the field.

References

Dąbrowski, S. & Przybyłek, J. (2005). *Metodyka próbnych pompowań w dokumentowaniu zasobów wód podziemnych. Poradnik metodyczny* [Methods of test pumping in documenting groundwater resources. A methodological guide]. Poznań: Bogucki Wydawnictwo Naukowe.

Driscoll, F. (1986). *Groundwater and Wells*. St Paul, MN: Johnson Filtration Systems.

EN ISO 14688-1:2002. Geotechnical Investigation and Testing. Identification and Classification of Soil. Part 1: Identification and Description.

EN ISO 14688-2:2004. Geotechnical Investigation and Testing. Identification and Classification of Soil. Part 2: Principles for a Classification.

Head, K. & Epps, R. (2011). *Manual of soil laboratory testing*. Vol. 2. *Permeability, shear strength and compressibility test*. Dunbeath Mill: Whittles Publishing.

Head, K. (1980). *Manual of soil laboratory testing*. Vol. 1. *Soil classification and compaction test*. London: Pentech Press.

International Committee of the Red Cross [ICRC] (2011). *Technical review. Practical guidelines for test pumping in water wells*. Geneva.

Kruseman, G.P. & Ridder, N.A. de (1994). *Analysis and Evaluation of Pumping Test Data*. Wageningen: International Institute for Land Reclamation and Improvement.

MacDonald, A., Barker, J. & Davies, J. (2008). The bailer test: A simple effective pumping test for assessing borehole success. *Hydrogeology Journal*, *16*(6), 1065-1075.

Matusiewicz, W. & Wrzesiński, G. (2018). Odwodnienie stref bezodpływowych małej zlewni miejskiej [Drainage of the depression area in a small urban catchment]. *Acta Scientiarum Polonorum Architectura*, *17*(3), 131-144. https://doi.org/10.22630/ASPA.2018.17.3.35

Parylak, K., Zięba, Z., Bułdys, A. & Witek, K. (2013). Weryfikacja wyznaczania współczynnika filtracji gruntów niespoistych za pomocą wzorów empirycznych w ujęciu ich mikrostruktury [The verification of determining a permeability coefficient of noncohesive soil based on empirical formulas including its microstructure]. *Acta Scientiarum Polonorum Architectura*, *12*(2), 43-51.

Polak, K., Kaznowska-Opala, K., Pawlecka, K. & Klich, J. (2014). Analiza przebiegu próbnych pompowań na przykładzie studni badawczej AGH-1 [Interpretation of pumping tests results on the basis of examination of AGH-1 well]. *Przegląd Górniczy*, *10*, 106-111.

Rybka, I., Bondar-Nowakowska, E. & Połoński, M. (2016). Causes and effects of adverse events during water supply and sewerage system constructions. *Archives of Civil Engineering*, *62*(1), 173-184.

Szymkiewicz, A. & Kryczałło, A. (2011). Obliczanie współczynnika filtracji piasków i żwirów na podstawie krzywej uziarnienia: przegląd wzorów empirycznych [Calculation of permeability coefficient of sands and gravel based on grain size distribution curve: review of empirical relations]. *Inżynieria Morska i Geotechnika*, *2*, 110-121.

Todd, D. (1980). *Groundwater Hydrology*. Chichester: John Wiley & Sons.

Twardowski, K. & Drożdżak, R. (2006). Pośrednie metody oceny właściwości filtracyjnych gruntów [Indirect methods for assessing soil filtration properties]. *Wiertnictwo, Nafta, Gaz*, *23*(1), 477-486.

Tymosiak, D. & Sulewska, M.J. (2016). Badania parametrów zagęszczalności gruntów niespoistych metodą Proctora [The study of compactibility parameters in non-cohesive soils by Proctor compaction test]. *Acta Scientiarum Polonorum Architectura*, *15*(3), 43-54.

Wdowska, M.K. & Lipiński, M.J. (2016). Ocena efektywności wyznaczania współczynnika filtracji metodami pośrednimi w różnych gruntach drobnoziarnistych [Effectivness of indirect approach of determination of coefficient of permeability in fine grained soils]. *Acta Scientiarum Polonorum Architectura*, *15*(4), 79-89.

Wiłun, Z. (2013). *Zarys geotechniki*. Warszawa: Wydawnictwa Komunikacji i Łączności.

Wrzesiński, G., Kowalski, J. & Miszkowska, A. (2018). Numerical analysis of dewatering process of deep excavation. *International Multidisciplinary Scientific GeoConference SGEM*, *18*(1.2), 497-504. https://www.doi.org/10.5593/sgem2018/1.2/S02.063

Summary

Permeability coefficient tests in non-cohesive soils. The paper aims to comparison the permeability coefficient in non-cohesive soils by the method of test pumping and based on tests in a consolidometer. The tests were carried out on 18 types of non-cohesive soils with different fraction. Pumping tests were carried out according to the standard method i.e. by making one well with a diameter of 400 mm and installing two piezometers at different distances from the well. The water table change was measured in piezometers during water pumping from the well. Tests in the consolidometer were carried out on soil samples that were first compacted to the same density index as in the test site. The tests were carried out with a continuous inflow of water from below with constant gradients of 0.50. The tests presented in the paper allow to verify and compare the values of the permeability coefficient in non-cohesive soils determined in the field and laboratory tests.

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