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Research of hydraulic conductivity coefficient of aquitadrs in cylinders

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Abstract: Results of field and laboratory research on the hydraulic conductivity coefficient of near-surface aquitards are presented in the article. The research was conducted for Quaternary tills and Tertiary clays occurring in the area of the Wielkopolski National Park. Special cylinders equipped with a sealing device and a contact sensor of the water level position each were designed. The cylinders were sunk into the examined aquitards and then injected with water. After sealing the cylinder the air inside was compressed which caused water injection from the cylinder into the examined aquitards. The rate of the injection was observed by measuring the water level depression in the cylinder. Theoretical consideration has been carried out and an own algorithm enabling computation of the hydraulic conductivity coefficient value on the basis of measurements of: depression s, time t, pressure in the cylinder ΔH and effective porosity of the examined bodies n_e has been developed. During the field research a methodology of determination of the hydraulic conductivity coefficient k of near-surface aquitards was developed. 25 values for the tills and 12 values for the clays were determined.

Laboratory research on the hydraulic conductivity coefficient of till and clay samples taken from the sites of the field examinations has been conducted. The results obtained during the field research have been compared to those of the laboratory research. The hydraulic conductivity coefficient values resulting from the laboratory research are by two orders of magnitude lower than those of the field research. It has been found that sample consolidation, essential for conducting the laboratory research, leads to the destruction of the system of microcracks and fractures occurring in natural conditions. As a result the hydraulic conductivity coefficient values obtained in laboratory conditions are lower than those obtained through field research. Field and laboratory research carried out according to the proposed methodology permit determining the variability range of the hydraulic conductivity coefficient of the examined aquitards. The upper limit of this range is constituted by the transmissivity of the system of microcracks and fractures and the lower limit by the transmissivity of the consolidated bodies. In this sense field and laboratory research can complement each other, which in effect can lead to experimental determination of the variability range of the hydraulic conductivity coefficient of the examined aquitards.

Key words: hydraulic conductivity coefficient, aquitards, field and laboratory research.

1. Introduction

Aquitards occurring close to the soil surface play an important role in the hydrological cycle. On one hand these bodies make recharge of the first level of groundwaters more difficult by infiltration of precipitation waters. On the other hand near-surface aquitards are not always an effective barrier to the migration of pollutants into the groundwaters. It is also worth noticing that examination of near-surface bodies may, by analogy, provide information on hydrogeological parameters of deeper occurring bodies of similar origin (Daniel 1984). For this reason experimental determination of the hydraulic conductivity coefficient of aquitards occurring near the soil surface is of substantial practical importance.

2. Theoretical background

Theoretical assumptions of identification experiments aiming at the *in situ* determination of filtration parameters of near-surface aquitards are analogous to those of the cylinder injection method developed by Maag. Additionally, in the methodology developed by the authors and described in this article, higher pressure in the cylinder, necessary to force filtration through the examined bodies, is taken into consideration. The experiment consists in sinking a cylinder of height d into the examined aquitards to a depth of g (Fig. 1). The cylinder should then be injected with water to about 2/3 of its height. Then the top opening of the cylinder is sealed with a special plug with a culvert for supplying compressed air. The air is compressed to a pressure ΔH. After time t, the depression s of the water level in the cylinder is measured. For the sake of theoretical analysis of the water level change in the cylinder it is assumed that water is filtered from the cylinder into the aquitards under examination according to Darcy's law; this assumption is justified when the pressure, and thus the gradient, is justifiable (Sai, Anderson 1990). Additionally, it is necessary to assume that the sinking of the cylinder into the aquitards under examination has been carried out without harming their structure and that the influence of the "skin effects" is negligibly small. The last two assumptions turn out to be difficult to satisfy in practice.

2.1. Water injection in the cylinder

The diagram of the station for near-surface aquitards' of hydraulic conductivity coefficient examination is shown in Fig. 1. The analysis of the water level motion has been carried out analogically to the Maag method of borehole injection through the bottom. In addition to that, the higher pressure value forcing the filtration has been taken into consideration (Marciniak et al 1999).

The volume V_w of water injected from the cylinder into the examined bodies can be computed using the formula:

$$V_w = \pi r^2 s \tag{1}$$

The injected water will saturate the volume V_s of the examined bodies, which is much greater because of the effective porosity n_e:

$$V_s = \frac{V_w}{n_e} = \frac{\pi r^2 s}{n_e} \tag{2}$$

Water injection range L can be determined from the equation:

$$V_s = \pi r^2 L = \frac{\pi r^2 s}{n_e} \tag{3}$$

hence

$$L = \frac{s}{n_e} \tag{4}$$

Water seepage can in turn be calculated as:

$$Q = \frac{V_w}{t} = \frac{\pi r^2 s}{t} \tag{5}$$

Filtration area F and the average filtration distance Δl are defined by the equations:

$$F = \pi r^2 \tag{6}$$

$$\Delta l = \frac{L}{2} = \frac{s}{2n_e} \tag{7}$$

According to Darcy's law the filtration discharge Q is directly proportional to the filtration area F and hydraulic head ΔH and inversely proportional to the filtration distance Δl:

$$Q = kF = \frac{\Delta H}{\Delta l} \tag{8}$$

Hence the hydraulic conductivity coefficient k can be calculated as:

$$k = \frac{Q \Delta l}{F \Delta H} \tag{9}$$

After substituting formula (5) for Q, expression (7) for Δl, equation (6) for F and applying simple transformations one finally obtains:

$$k = \frac{s^2}{2n_e t \Delta H} \tag{10}$$

Formula (10) permits the calculation of the hydraulic conductivity coefficient of aquitards on the basis of field experiments in a cylinder of diameter $2r$, sunk into the examined bodies whose effective porosity equals n_e, in which, after water injection, sealing and compressing the air inside to the pressure ΔH over time t, the depression s of the water level has been obtained. All the data necessary for computation can be measured during the identification experiment in field. The only exception is the effective porosity n_e, which can be estimated on the basis of literature or determined experimentally in laboratory conditions.

3. Field station equipment

The cylinder is a steel tube, 2 inches (approximately 52 mm) in diameter and 1 m in height (Fig. 1). In the bottom part of the cylinder, three symmetrically placed cylinder sinking stoppers have been welded. The cylinder sinking depth has to be planned so that:

- after sinking the cylinder and compressing the air inside, the cylinder would not be pulled out of the examined bodies,
- well entry loss would be negligible,
- sinking the cylinder would not be too difficult (the best thing to do $L < g$).

After a series of field tests it has been found that a sinking depth of about 10 cm permits to keep the cylinder in the ground during the air compression and eliminating water flow out at the bottom part of the cylinder.

Water injection from the cylinder sunk into the near-surface aquitards can be carried out using a sealing device and a compressor. A manometer is used to keep a check on the pressure value in the cylinder while a contact water level sensor is used to measure the water level depression after finishing the injection.

The measurement of the water level depression in the cylinder is not easy due to the fact that the values of the obtained depressions are very low (in the order of several millimeters after an hour of water injection). A special contact water level sensor has been used to solve this difficulty; its principle of operation is explained in Fig. 1. The sensor (4) is made up of two insulated ends of electric wire put tightly through tube (3). The space in the cylinder is sealed by means of valves (5). After installing the sealing device in the cylinder and twisting plug (7) tight, device (8) permitting detection of electric current passage should be connected to the outer ends of the electric wire projecting from tube (3). Then, slowly shifting and twisting down tube (3), one has to capture the moment when the wire ends touch the water level. It is important to do this only during the downward movement of the tube, because owing to the meniscus around the wire ends, water level would turn out to be somewhat higher during an upward movement of tube (3); the value of hysteresis can amount even to 3 mm. At the beginning the distance between the top end of tube (3) and the reference level (e.g., the top edge of the cylinder) should be measured by means of a vernier calliper.

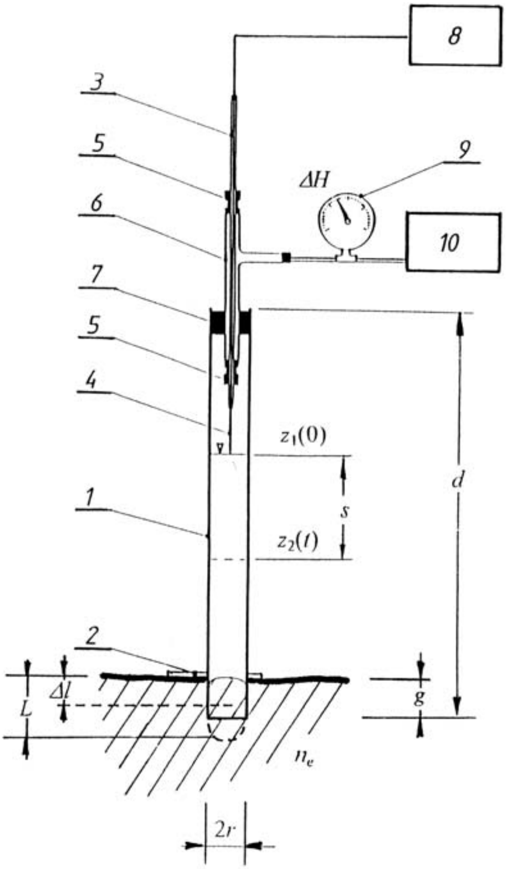

Fig. 1. Diagram of a station for examination of filtration parameters of near–surface aquitards using the cylinder injection method.

Explanations: **Structural components:** 1 – cylinder, 2 – sinking stop, 3 – copper tube with a double electric wire tightly fixed inside, 4 – contact water level sensor, 5 – valve for tightly passing the tube, 6 – corps, 7 – rubber plug, 8 – water level indicator, 9 – manometer, 10 – compressor. **Mathematical symbols:** $z_1(0)$ – position of the initial water level, $z_2(t)$ – position of the final water level, s – water level depression in the cylinder, t – water injection time, r – cylinder radius, d – cylinder height, g – depth of the cylinder sinking into the examined grounds, L – range of water injection from the cylinder into the examined aquitards, Δl – average water filtration distance, ΔH – pressure value in the cylinder, n_e – effective porosity of the examined aquitards.

Schemat stanowiska do badania parametrów filtracyjnych przypowierzchniowych utworów półprzepuszczalnych metodą zalewania cylindra

Objaśnienia: **Elementy konstrukcyjne:** 1 – cylinder, 2 – ogranicznik wbijania, 3 – rurka miedziana ze szczelnie zatopionym w środku dwużyłowym przewodem elektrycznym, 4 – stykowy czujnik poziomu wody, 5 – dławik do szczelnego przeprowadzenia rurki, 6 – korpus, 7 – korek gumowy, 8 – sygnalizator poziomu wody, 9 – manometr, 10 – kompresor. **Symbole matematyczne:** $z_1(0)$ – położenie zwierciadła wody w chwili początkowej, $z_2(t)$ – położenie zwierciadła wody po czasie t, s – depresja zwierciadła wody w cylindrze, t – czas zatłaczania wody, r – promień cylindra, d – wysokość cylindra, g – głębokość wbicia cylindra w badane utwory, L – zasięg zatłaczania wody z cylindra do badanych utworów półprzepuszczalnych, Δl – średnia droga filtracji wody, ΔH – wysokość ciśnienia w cylindrze, n_e – porowatość efektywna badanych utworów.

After compressing the air in the cylinder valve (5) should be loosened and tube (3) lowered (slowly, with a twisting downward movement) to capture again the moment of touching the water level by the sensor (4). Another measurement of the distance between the top end of tube (3) and the reference level enables the calculation of the value of the water level depression in the cylinder.

4. Field research

4.1. Site of the field research

The field research was carried out in the region of the Wielkopolski National Park (WNP) situated south of Poznań (fig. 2). The main features of the relief of the WNP area are associated with the latest glaciation–the Vistulian. Approximately 80% of the WNP's area is undulating, wavy, upland moraine partially hilly (80–120 m above sea level), where the examined outcrops are situated. Tertiary bodies occur here under the cover of Quaternary bodies, but locally Tertiary – Neogene clays of the Poznań series are exposed in the neighborhood of Quaternary bodies (glacitectonic), forming isolated geological bodies. Quite continuos level of till of thickness reaching 25 m survived from the Central Polish glaciation. Detached blocks of this till can, however, be built into younger, Pleistocene sediments, as at the JP-5 station in Puszczykowo. Detached blocks of Tertiary clays of the Poznań series occurring in Wał Pożegowski, which can be seen near the soil surface at the JP-1 and JP-2 stations in Stare Dymaczewo, are of similar origin. From the Northern Polish glaciation of the Leszno phase tills sampled at the JP-3 and JP-4 stations in Stare Puszczykowo retained.

Stare Dymaczewo (samples JP-1, JP-2)

This is a inoperative clay mine close to the local brickyard. In Dymaczewo village Tertiary clays of the middle level of the Poznań series, glacitectonically raised to 80 m above sea level, strongly undulating and cracked were exploited. These bodies are covered (or in places mixed) with Quaternary sediments (moraine till, fluwoglacial sands).

Stare Puszczykowo (samples JP-3, JP-4)

The JP-3 and JP-4 stations in Stare Puszczykowo are situated in the central-east part of the WNP, within a distance of about 200 m. The JP-4 station (Stare Puszczykowo) is situated in a closed gravel pit, the walls of which reach, in places, more than ten meters in height. At present access to the outcrops is limited, as the heading is used as a waste dump. The profile of the sediments in the gravel pit includes dark brown and yellow till (most probably from the Leszno phase of the Vistulian) and lower occurring, structurally diverse glacifluwial sands and gravels,

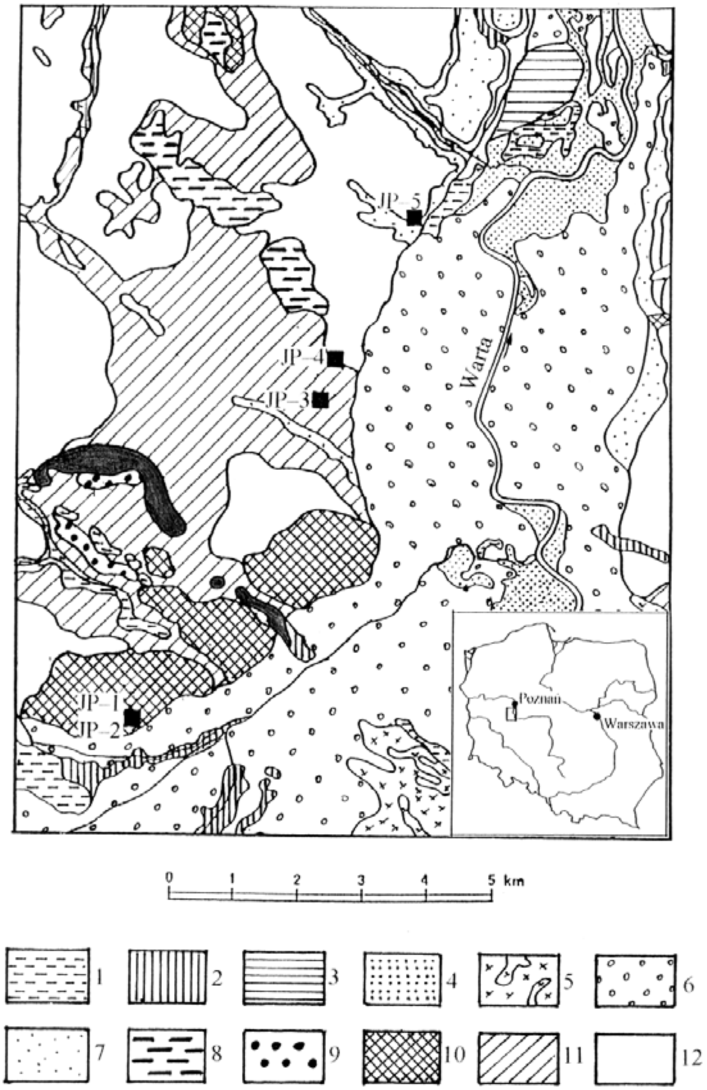

Fig. 2. Geological map of the Poznań area, on the basic of Mojski (1980), with the sites of the field examination stations marked

Explanations: 1 – peat, 2 – slime, 3 – mud, 4 – silt, sand and river gravel, 5 – sand and dune, 6 – sand and river gravel, 7 – sand and gravel water–glaciers, 8 – sand, silt and glacilacustrine clay, 9 – sand and gravel eskers, 10 – sand, gravel and stones moraines local occurrence detched block of Tertiary clay, 11 – sand, gravel and stones glaciers, 12 – glacial till.

Mapa geologiczna okolic Poznania, na podstawie Mojskiego (1980), z zaznaczoną lokalizacją terenowych stanowiska badawczych

Objaśnienia: 1 – torfy, 2 – namuły, 3 – mady rzeczne, 4 – mułki, piaski i żwiry rzeczne, 5 – piaski eoliczne z wydmami, 6 – piaski i żwiry rzeczne, 7 – piaski i żwiry wodnolodowcowe, 8 – piaski, mułki i iły zastoiskowe, 9 – piaski i żwiry ozów, 10 – piaski, żwiry i głazy moren czołowych z lokalnie występującymi porwakami iłów trzeciorzędowych, 11 – piaski, żwiry i głazy lodowcowe, 12 – gliny zwałowe.

cemented with calcite in the ceiling part. The moraine till occurring in the ceiling forms a bed of thickness ranging from 2 to 3 meters and has joint like cracks. As far as the texture is concerned, the sediment in question is homogeneous. The JP-3 station (Stare Puszczykowo) is situated in the woods, where in a 2.5-meter slope the same bed of till as in the profile ceiling in the gravel pit is exposed.

Puszczykowo (sample JP-5)

This is a natural outcrop of till in the woods, on a slope of about 2 m, exploited by local inhabitants. This till has a very interesting structure. Three kinds of cracks occur in it: horizontal, vertical and oblique, crossing at different angles. This till can, while occurring in the area of Baltic glaciation, date from the Central Polish glaciation; the characteristic structure is claimed to be the result of a strong compaction of the continental glacier. The age of this till isn't, however, precisely known.

4.2. Measurement methodology

In the beginning of the field research preliminary series of measurements was carried out with the aim of recognizing the conditions of running the experiment, developing the methodology of the research and mastering the technique of realization the measurements. During the preliminary series difficulties associated with satisfying the requirements formulated in the theoretical assumptions of the experiment were encountered. At first the cylinders were sunk into the examined bodies, injected with water and sealed and filtration was forced by compressing the air to the pressure height planned in advance. When the pressure values were low, no significant depression could be obtained. When the pressure was higher, often a piping of water through the examined bodies followed; sometimes even the cylinder to fall over. After many trials a methodology of gradual increase of the pressure in the cylinder was successfully developed.

The field research was carried out in the following order:

1. Preparing a fragment of the examined bodies by cleaning it and removing the humus and weathered fragments of the layer. The structure of the examined bodies must not be damaged during the cleaning.
2. Sinking the cylinder into the examined bodies, paying special attention to keeping the sinking direction vertical in order to minimize the damage done to the natural structure of the examined sample.
3. Driving additional steel pins into the holes in the stops so that the cylinder is better fixed to the ground.
4. Injecting water into the cylinder to about 2/3 of its height.
5. Installing the device used for sealing the cylinder and for injecting the water.
6. Performing the initial measurement of the water level position by means of the water level sensor and a vernier calliper rule.

7. Sealing the cylinder by twisting the top valve tight and compressing the air to a low pressure value of 3 m H_2O (3 kPa) for one hour's time.

8. Unsealing the cylinder by twisting the top valve loose and performing the measurement of the water level position after an hour of air compression.

9. Sealing the cylinder once again by twisting the top valve tight and compressing the air to a higher pressure value of 6 m H_2O (6 kPa) for another hour, then reading the water level position in the cylinder.

10. Repeating subsequent air compressions for pressure values of 9 m H_2O (9 kPa) and 12 m H_2O (12 kPa); the subsequent compression stages should last an hour each.

11. Performing the measurement of the water level position for the subsequent stages of air compression in the cylinder.

The second, final measurement series was conducted according to this scheme.

At each station cylinders were sunk into the examined bodies several times, which is indicated by the subsequent lower case letters in the description of the results (e.g., at the JP-1 station the cylinder was sunk six times: a, b, c, d, e and f). Multiple-stage compressions are additionally indicated as subsequent measurements by numbers (e.g., JP-1f1, JP-1f2, …).

4.3. Results of the measurements and computations of hydraulic conductivity coefficient of the aquitards'

Research aiming at the determination, in field conditions, of the hydraulic conductivity coefficient of near-surface aquitards was conducted for two lithological types of these bodies: Quaternary tills and Tertiary clays. In the tables the most important source data and computed results for the tills (Table 1) and for the clays (Table 2) are presented. The numerical values of the effective porosity n_e, obtained on the basis of porosimetric examinations of till and clay samples amount to: $n_e = 11{,}24\%$ for till and $n_e = 2{,}52\%$ for clay.

5. Laboratory research

Laboratory research on the hydraulic conductivity coefficient *k* using the flow-pump method (Olsen et al 1985; Aiban, Znidarcić 1989; Herzig, Szczepańska 1995) was carried out for seven samples taken in the area of the WNP at the sites of the field research. The laboratory research was conducted for three different values of the infusion pump discharge Q:

- for till: $Q_1 = 1{,}6 \cdot 10^{-11}$ m^3/s $Q_2 = 4{,}5 \cdot 10^{-11}$ m^3/s $Q_3 = 8{,}5 \cdot 10^{-11}$ m^3/s
- for clay: $Q_1 = 1{,}6 \cdot 10^{-12}$ m^3/s $Q_2 = 4{,}5 \cdot 10^{-12}$ m^3/s $Q_3 = 8{,}5 \cdot 10^{-12}$ m^3/s

The results of the laboratory research are presented in Table 3.

Table 1. Breakdown of the results of measurements conducted in the region of The Wielkopolski National Park and the hydraulic conductivity coefficient computations for the tills.

Zestawienie wyników pomiarów wykonanych na terenie Wielkopolskiego Parku Narodowego i obliczeń współczynnika filtracji dla glin.

Position	Measurement	Pressure ΔH	Depression s	Time t	Water volume V_w	Discharge Q	Water range L	Filtration way Δl	Gradient $\Delta H/l\Delta$	Hydraulic cond. coefficient k
		m H_2O	$\cdot 10^{-3}$ m	s	$\cdot 10^{-6}$ m	m^3/s	$\cdot 10^{-3}$ m	$\cdot 10^{-3}$ m	$\cdot 10^{-3}$ m/m	m/s
tills – initial series										
JP–4a	1	2,0	16	1200	31,4	$2{,}6\cdot 10^{-8}$	123	62	0,033	$4{,}10\cdot 10^{-7}$
	2	5,0	6	840	11,8	$1{,}4\cdot 10^{-8}$	46	23	0,216	$3{,}30\cdot 10^{-8}$
	3	10,0	3	780	5,9	$7{,}6\cdot 10^{-9}$	23	12	0,870	$4{,}44\cdot 10^{-9}$
	4	15,0	5	900	9,8	$1{,}1\cdot 10^{-8}$	39	19	0,781	$7{,}12\cdot 10^{-9}$
JP–4b	1	5,0	2	900	3,9	$4{,}4\cdot 10^{-9}$	15	8	0,650	$3{,}42\cdot 10^{-9}$
	2	10,0	1	900	2,0	$2{,}2\cdot 10^{-9}$	8	4	2,597	$4{,}27\cdot 10^{-10}$
	3	15,0	2	900	3,9	$4{,}4\cdot 10^{-9}$	15	8	1,951	$1{,}14\cdot 10^{-9}$
	4	20,0	2	900	3,9	$4{,}4\cdot 10^{-9}$	15	8	2,601	$8{,}55\cdot 10^{-10}$
JP–5a	1	5,0	114	1530	224,0	$1{,}5\cdot 10^{-7}$	877	438	0,011	$6{,}53\cdot 10^{-6}$
JP–5b	1	5,0	14	1740	27,5	$1{,}6\cdot 10^{-8}$	108	54	0,093	$8{,}66\cdot 10^{-8}$
JP–5c	1	2,5	76	290	149,0	$5{,}2\cdot 10^{-7}$	585	292	0,009	$3{,}06\cdot 10^{-5}$
JP–5d	1	2,5	1	960	2,0	$2{,}1\cdot 10^{-9}$	8	4	0,649	$1{,}60\cdot 10^{-9}$
	2	5,0	1	1320	2,0	$1{,}5\cdot 10^{-9}$	8	4	1,299	$5{,}83\cdot 10^{-10}$
	3	12,5	3	900	5,9	$6{,}5\cdot 10^{-9}$	23	12	1,087	$3{,}08\cdot 10^{-9}$
	4	15,0	1	900	2,0	$2{,}2\cdot 10^{-9}$	8	4	3,896	$2{,}85\cdot 10^{-10}$
JP–5e	1	3,0	3	600	5,9	$9{,}8\cdot 10^{-9}$	23	12	0,261	$1{,}92\cdot 10^{-8}$
	2	5,0	14	900	27,5	$3{,}1\cdot 10^{-8}$	108	54	0,093	$1{,}68\cdot 10^{-7}$
tills – final series										
JP–4f	1	3,0	24	3600	47,1	$1{,}3\cdot 10^{-8}$	185	92	0,033	$2{,}05\cdot 10^{-7}$
	2	6,0	37	3600	72,6	$2{,}0\cdot 10^{-8}$	285	142	0,042	$2{,}44\cdot 10^{-7}$
	3	9,0	51	3600	100,0	$2{,}8\cdot 10^{-8}$	392	196	0,046	$3{,}09\cdot 10^{-7}$
	4	12,0	67	3600	132,0	$3{,}7\cdot 10^{-8}$	515	258	0,047	$4{,}00\cdot 10^{-7}$
JP–5f	1	3,0	12	3600	23,6	$6{,}5\cdot 10^{-9}$	92	46	0,065	$5{,}13\cdot 10^{-8}$
	2	6,0	14	3600	27,5	$7{,}6\cdot 10^{-9}$	108	54	0,112	$3{,}49\cdot 10^{-8}$
	3	9,0	28	3600	55,0	$1{,}5\cdot 10^{-8}$	215	108	0,083	$9{,}31\cdot 10^{-8}$
	4	12,0	44	3600	86,4	$2{,}4\cdot 10^{-8}$	338	169	0,071	$1{,}72\cdot 10^{-7}$

Table 2. Breakdown of the results of measurements conducted in the region of the Wielkopolski National Park and the hydraulic conductivity coefficient computations for the clays.

Zestawienie wyników pomiarów wykonanych na terenie Wielkopolskiego Parku Narodowego i obliczeń współczynnika filtracji dla iłów.

Position	Measurement	Pressure ΔH	Depression s	Time t	Water volume V_w	Discharge Q	Water range L	Filtration way Δl	Gradient $\Delta H/l\Delta$	Hydraulic cond. coefficient k
		m H_2O	$\cdot 10^{-3}$ m	s	$\cdot 10^{-6}$ m	m^3/s	$\cdot 10^{-3}$ m	$\cdot 10^{-3}$ m	$\cdot 10^{-3}$ m/m	m/s
clays – initial series										
JP–1a	1	2,5	4	1980	7,9	$4{,}0\cdot 10^{-9}$	133	67	0,037	$5{,}3\cdot 10^{-8}$
JP–1b	1	escape of water trough crack								
JP–1c	1	7,5	17	5460	33,4	$6{,}1\cdot 10^{-9}$	567	283	0,027	$1{,}18\cdot 10^{-7}$
JP–1d	1	10,0	171	3300	336,0	$1{,}0\cdot 10^{-7}$	5700	2850	0,004	$1{,}48\cdot 10^{-5}$
JP–2a	1	10,0	30	4560	58,9	$1{,}3\cdot 10^{-8}$	1000	500	0,020	$3{,}29\cdot 10^{-7}$
clays – final series										
JP–1f	1	3	2	3600	3,9	$1{,}1\cdot 10^{-9}$	67	33	0,090	$6{,}17\cdot 10^{-9}$
	2	6	2	3600	3,9	$1{,}1\cdot 10^{-9}$	67	33	0,180	$3{,}09\cdot 10^{-9}$
	3	9	4	3600	7,9	$2{,}2\cdot 10^{-9}$	133	67	0,135	$8{,}23\cdot 10^{-9}$
	4	12	6	3600	11,8	$3{,}3\cdot 10^{-9}$	200	100	0,120	$1{,}39\cdot 10^{-8}$
JP–2f	1	3	1	3600	2,0	$5{,}5\cdot 10^{-10}$	33	17	0,180	$1{,}54\cdot 10^{-9}$
	2	6	2	3600	3,9	$1{,}1\cdot 10^{-9}$	67	33	0,180	$3{,}09\cdot 10^{-9}$
	3	9	4	3600	7,9	$2{,}2\cdot 10^{-9}$	133	67	0,135	$8{,}23\cdot 10^{-9}$
	4	12	5	3600	9,8	$2{,}7\cdot 10^{-9}$	167	83	0,144	$9{,}65\cdot 10^{-9}$

Table 3. Breakdown of the results of the laboratory research on the hydraulic conductivity coefficient of till and clay samples taken in the area of the Wielkopolski National Park using the flow-pump method.

Zestawienie wyników badań laboratoryjnych współczynnika filtracji metodą *flow–pump* próbek gliny i iłu pobranych na terenie Wielkopolskiego Parku Narodowego.

Number of sample	Hydraulic conductivity coefficient *k*				
	Q_1	Q_2	Q_3	average value	average value
	m/s	m/s	m/s	m/s	m/s
			tills		
JP–3	$8,80\cdot10^{-10}$	$1,30\cdot10^{-9}$	$1,60\cdot10^{-9}$	$1,26\cdot10^{-9}$	$9,36\cdot10^{-10}$
JP–4	$2,50\cdot10^{-10}$	$5,30\cdot10^{-10}$	$6,40\cdot10^{-10}$	$4,73\cdot10^{-10}$	
JP–5.1	$8,40\cdot10^{-10}$	$1,20\cdot10^{-9}$	$1,40\cdot10^{-9}$	$1,15\cdot10^{-9}$	
JP–5.2	$6,10\cdot10^{-10}$	$8,80\cdot10^{-10}$	$1,10\cdot10^{-9}$	$8,63\cdot10^{-10}$	
			clays		
JP–1.1	$1,50\cdot10^{-11}$	$2,80\cdot10^{-11}$	$3,80\cdot10^{-11}$	$2,70\cdot10^{-11}$	$2,83\cdot10^{-11}$
JP–1.2	$1,40\cdot10^{-11}$	$1,60\cdot10^{-11}$	$2,50\cdot10^{-11}$	$1,83\cdot10^{-11}$	
JP–2.1	$2,50\cdot10^{-11}$	$3,20\cdot10^{-11}$	$3,70\cdot10^{-11}$	$3,13\cdot10^{-11}$	
JP–2.2	$2,50\cdot10^{-11}$	$3,90\cdot10^{-11}$	$4,60\cdot10^{-11}$	$3,67\cdot10^{-11}$	

6. Comparison of the results of the field and laboratory research

The comparison of the results obtained during the field research of the examined aquitards (Tables 1 and 2) with the results of the laboratory research conducted using the flow-pump method (Table 3) has been carried out for the tills and the clays.

In Fig. 3 all the values of the hydraulic conductivity coefficient for the tills are presented in the form of a bar chart: 25 field measurements (lighter bars) and 4 results of the laboratory research (darker bars). It is noticeable that the values of the hydraulic conductivity coefficient obtained during the field research are widely dispersed, ranging from $2,85\cdot10^{-10}$ to $3,06\cdot10^{-5}$ m/s. During the laboratory research similar values of the hydraulic conductivity coefficient for the four examined samples were obtained. The average value for these four samples is $9,36\cdot10^{-10}$, which is close to the lower limit of hydraulic conductivity coefficient variability range determined from the field research. It can also be noticed that the hydraulic conductivity coefficient values obtained on the basis of the field research have approximately a bimodal distribution around the values of 10^{-7} m/s and 10^{-9} m/s. Statistical confirmation of this observation would require, however, collecting a larger amount of data.

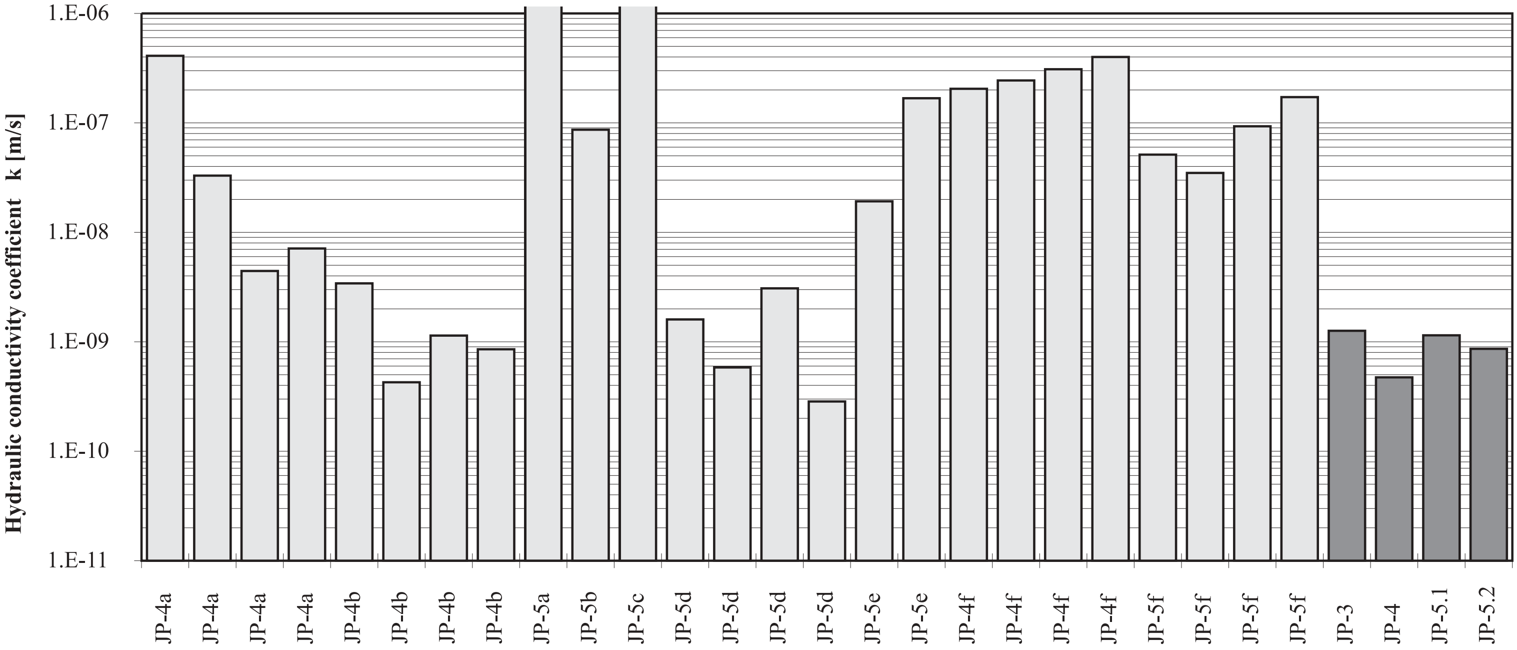

Fig. 3. Comparison of the hydraulic conductivity coefficient values of the tills, obtained on the basis of field research in cylinders in the area of the Wielkopolski National Park (lighter bars) and the laboratory research using the flow–pump method (darker bars).

Porównanie wartości współczynnika filtracji dla glin, uzyskanych na podstawie badań terenowych w cylindrach na terenie Wielkopolskiego Parku Narodowego (barwy jaśniejsze) oraz na podstawie badań laboratoryjnych metodą *flow-pump* (barwy ciemniejsze).

An analogous comparison has been drawn for the clays (fig. 4). In this case 12 values obtained through the field research and 4 results of the laboratory research using the flow-pump method were available. The hydraulic conductivity coefficient values obtained through the field research range from $1{,}54 \cdot 10^{-9}$ to $1{,}48 \cdot 10^{-5}$ m/s. The distribution of the hydraulic conductivity coefficient values for the clays resulting from the field research is single modal with the *k* values concentrating around 10^{-8} m/s. The results of the laboratory research are not very dispersed; the average value is $2{,}83 \cdot 10^{-11}$ m/s. The results obtained in laboratory conditions are therefore by more than two orders of magnitude lower than the results of the field research.

When assessing the obtained results, one has to point out the reasons for the aforementioned discrepancies:

- During the laboratory research the sample is consolidated before being placed in the flow-pump station. During the sample consolidation microcracks of the examined structure are destroyed, which leads to understating of the hydraulic conductivity coefficient values obtained in the laboratory.

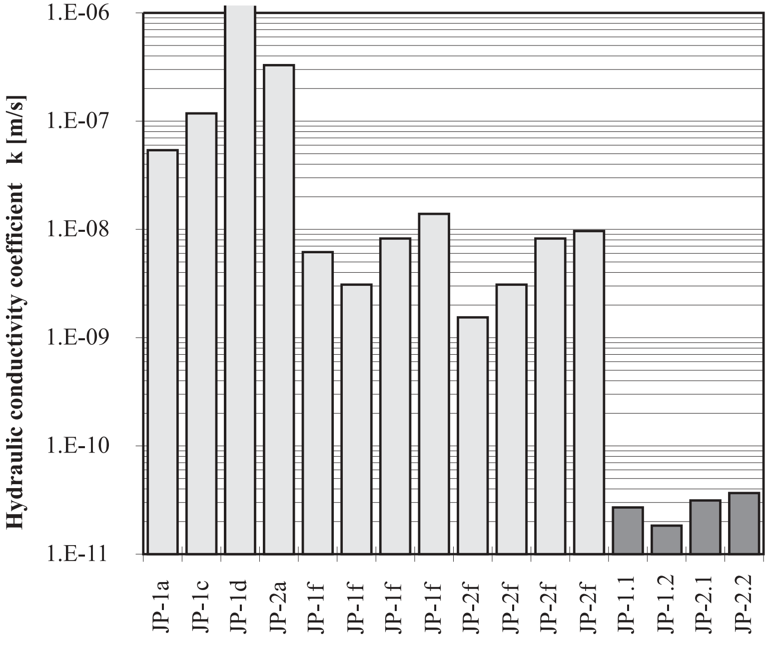

Fig. 4. Comparison of the hydraulic conductivity coefficient values of the clays, obtained on the basis of field research in cylinders in the area of the Wielkopolski National Park (lighter bars) and the laboratory research using the flow-pump method (darker bars).

Porównanie wartości współczynnika filtracji dla iłów, uzyskanych na podstawie badań terenowych w cylindrach na terenie Wielkopolskiego Parku Narodowego (barwy jaśniejsze) oraz na podstawie badań laboratoryjnych metodą flow–pump (barwy ciemniejsze).

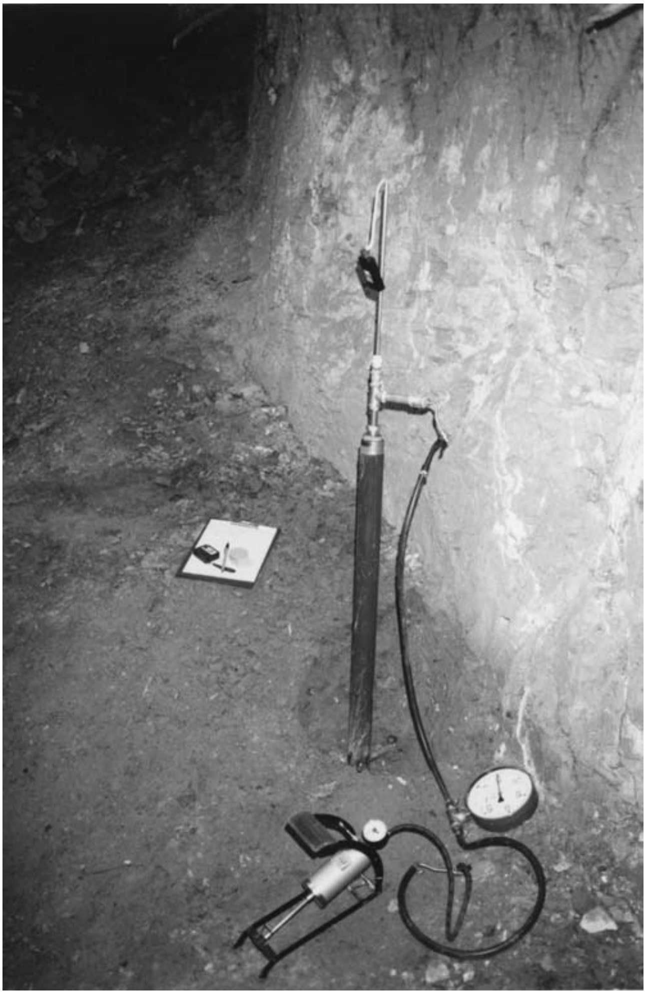

Photo 1. The JP–5 measuring station in the Wielkopolski National Park.

The cylinder is sunk in glacial till. The sealing device projects from the cylinder. A manometer and a compressor lie nearby. In the vertical wall of the till outcrop the microcracks (lighter lines) can be seen.

Stanowisko pomiarowe JP-5 w Wielkopolskim Parku Narodowym.

Cylinder zagłębiony w glinie zwałowej. Z cylindra wystaje urządzenie uszczelniające. Obok leżą manometr i kompresor. Na pionowej ścianie odsłonięcia glinowego widać mikroszczeliny, w formie jaśniejszych linii.

• The result of a field experiment depends on the place of sinking of the cylinder into the examined bodies, especially when cracks and microcracks occur in these bodies. In phot. 1, where the station JP-5 is shown, it can be easily seen that the examined tills have a network of small cracks. An extreme example of this phenomenon is the JP-1b experiment, during which the cylinder was accidentally sunk in a large crack in the fractured near surface clays, which resulted in very fast leakage of the water injected into the cylinder. In such a case it was impossible to determine the hydraulic conductivity coefficient using the proposed method. Summing up, the natural system of cracks and microcracks is conducive to obtaining higher hydraulic conductivity coefficient values on the basis of field research.

In the case of aquitards a variability range rather than an exact value of the hydraulic conductivity coefficient of the given structure should therefore be considered, since a system of cracks and fractures will have better filtration properties than consolidated fragments of the bodies in question. For experimental determination of such a variability range of the hydraulic conductivity coefficient both laboratory and field research are essential.

7. Summary

Comparison of the results of field measurements conducted according to the proposed methodology with the results of laboratory research carried out using the flow-pump method leads to the conclusion that the results of laboratory research on the aquitards' hydraulic conductivity coefficient are understated. This applies not only to the flow-pump method, but also to other methods of laboratory determination of aquitards' filtration parameters. The initial sample consolidation in laboratory conditions leads to destruction of the natural microcrack system. In consequence of this the hydraulic conductivity coefficient value obtained on the basis of laboratory research is lower than the corresponding result from field research.

Field and laboratory research performed in accordance with the proposed methodology permit determining the variability range of the hydraulic conductivity coefficient of the examined aquitards. The upper limit of this range is constituted by the transmissivity of the system of microcracks and fractures and the lower limit by the transmissivity of the consolidated bodies. In this sense field and laboratory research can complement each other, which in effect can lead to experimental determination of the variability range of the hydraulic conductivity coefficient of the examined aquitards.

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Badania wspczynnika filtracji utworów półprzepuszczalnych w cylindrach

Streszczenie: W artykule przedstawiono wyniki badań terenowych i laboratoryjnych współczynnika filtracji przypowierzchniowych utworów półprzepuszczalnych. Badania przeprowadzono dla glin czwartorzędowych oraz iłów trzeciorzędowych występujących na terenie Wielkopolskiego Parku Narodowego. Zaprojektowano specjalne cylindry, które wyposażono w urządzenie uszczelniające oraz stykowy czujnik położenia zwierciadła wody. Cylindry zagłębiano w badane utwory półprzepuszczalne, a następnie zalewano je wodą. Po uszczelnieniu cylindra sprężano powietrze, co spowodowało zatłoczenie wody z cylindra do badanych utworów półprzepuszczalnych. Obserwowano tempo zatłaczania wody poprzez pomiary depresji zwierciadła wody w cylindrze. Przeprowadzono rozważania teoretyczne i opracowano własny algorytm umożliwiający obliczenie wartości współczynnika filtracji na podstawie pomiaru depresji s, czasu t, wysokości ciśnienia w cylindrze ΔH oraz porowatości efektywnej badanych utworów $n_{e.}$ Podczas badań terenowych wypracowano metodykę oznaczania współczynnika filtracji k przypowierzchniowych utworów półprzepuszczalnych, a także przeprowadzono 25 oznaczeń k dla glin oraz 12 oznaczeń dla iłów. Wykonano badania laboratoryjne współczynnika filtracji metodą *flow–pump* dla próbek glin oraz iłów pobranych z tych samych miejsc, gdzie realizowano badania *in situ*. Wyniki uzyskane podczas badań terenowych porównano z wynikami badań laboratoryjnych. Na podstawie badań laboratoryjnych uzyskano o dwa rzędy wielkości niższe wartości współczynnika filtracji w stosunku do wyników badań *in situ*. Stwierdzono, że konsolidacja próbki, konieczna dla zrealizowania badań laboratoryjnych, prowadzi do zniszczenia systemu mikroszczelin i spękań występującego w warunkach naturalnych. Skutkuje to niższymi wartościami współczynnika filtracji uzyskiwanymi w warunkach laboratoryjnych.

Badania terenowe i laboratoryjne wykonane według zaproponowanej metodyki, pozwalają określić zakres zmienności współczynnika filtracji badanych utworów półprzepuszczalnych. Górną granicę tego zakresu stanowi przewodność systemu szczelin i spękań, a dolną przewodność utworów skonsolidowanych. W tym znaczeniu badania terenowe i laboratoryjne mogą się wzajemnie uzupełniać, co w efekcie może doprowadzić do doświadczalnego oznaczenia zakresu zmienności współczynnika filtracji badanych utworów półprzepuszczalnych.

Słowa kluczowe: współczynnik filtracji, utwory półprzepuszczalne, badania terenowe i laboratoryjne.