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PERMEABILITY OF COVER DEPOSITS OF CRYSTALLINE ROCKS IN THE SUDETY MOUNTAINS (SW POLAND) BASED ON A FIELD STUDY

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Abstract: Article presents a study on the permeability of weathering covers formed on crystalline rocks, which was conducted in south-western Poland (Sudety Mountains). Evaluation of the infiltration capacity was performed based on field measurements of the vertical hydraulic conductivity carried out by using the Porschet method and the ETC Pask Constant Head Permeameter. During the field investigations conducted in sixteen sites, 28 determinations of the hydraulic conductivity k were made, 16 by the Porschet method and 12 using the ETC Pask Permeameter**.** Ten sites represent weathering covers of metamorphic rocks (amphibolites, eclogites, mica-schists, crystalline limestones, gneisses) and the next six sites represent covers of igneous rocks (granites). The values of the vertical hydraulic conductivity k determined by the Porschet method ranged between 0.053 and 2.19 m/d, while those obtained using the ETC Pask Permeamet erranged between 0.012 and 0.76 m/d. In the first place, it should be noticed that the results determined during the field investigations conducted according to the Porschet method are generally 3-4 times higher than those obtained using the ETC Pask Permeameter**.** The results for the vertical hydraulic conductivity allow us to classify weathering sediments of metamorphic and igneous rocks, as semi-permeable to medium permeable rocks. Weathered gneisses were distinctly characterized by the worst capacity to conduct water (semi-permeable) among all types of weathering covers of crystalline rocks. Higher values (0,08-0,8 m/d) of the vertical hydraulic conductivity were found for the weathering covers of the other metamorphic rocks (low permeable). The best conditions to conduct water were found in the weathering covers of granite rocks, which in most cases are classified as medium permeable rocks (more than 0.8 m/d) and exhibit distinctly better permeability coefficients.

Keywords: weathering covers, field studies, hydraulic conductivity, Sudety Mts.

1. INTRODUCTION

One of the main factors determining groundwater recharge is the permeability of the zone of cover deposits, depending on the lithological development of bedrock. Groundwater recharge is a significant element representing the status of groundwater. It directly affects the amount of renewable groundwater resources and largely determines groundwater vulnerability to pollution (Duda et al., 2011, Staśko et al., 2012, Tarka et al., 2017). With the development of hydrogeological research, it was noticed that the weathering cover deposits of crystalline rocks played an important role as an element of the water cycle system, being an environment for infiltration water or to the formation of an aquifer (Scanlon et al., 2002, Maréchal et al., 2003, Cascini et al., 2006, Staśko et al., 2010). Under favorable conditions, the covers of weathered crystalline rocks can be a good groundwater collector where the flow occurs in an unsaturated rock matrix, which results in the formation of a discontinuous piezometric surface (Kowalski, 1987, Marszałek, 1996, Tarka, 1997). Therefore, the knowledge of the basic hydrogeological parameters of these layers is very important to understand the water cycle issues (Staśko & Chodacki, 2014).

This article presents a study on the permeability of cover deposits of crystalline rocks, which was conducted using field methods in south-western Poland within the area of the Sudety Mountains. Due to high precipitation and low surface evaporation, mountainous areas are characterized by significant groundwater recharge. Almost 50% of the Sudetes area is composed of crystalline rocks, which include igneous and metamorphic rocks. An almost continuous cover of surface deposits formed of weathering cover and rock debris overlies crystalline rocks. Apart from high precipitation and favorable thermal conditions, groundwater recharge in areas of weathering covers of crystalline rocks should be directly linked to the hydrogeological properties of weathered deposits (Staśko & Tarka, 1993, 2001).

The weathered rock layer with a thickness of several to a dozen or so meters, which extends almost continuously across the entire area of crystalline rocks, forms fine-grained weathering crust, frequently sandy, which passes with increasing depth into coarser-grained material with rock blocks. The deeper, the smaller the ratio between the fine- and coarse-particle material becomes (Staśko, 2002). The hydrogeological properties of weathered rock found in the Sudetes area have been discussed many times in multiple scientific publications (Kryza & Kryza, 1983, Marszałek, 1996, Tarka, 1997, Staśko & Tarka, 1993, 2001, Wąsik & Wąsowski, 2015), in which the vertical hydraulic conductivity k for weathered metamorphic rocks, for example, among others gneisses, mica slates, amphibolites, and crystalline limestones, ranged from 0.05 to 30 m/d. In the case of weathered gneisses of various types and mica slates, the dominant values of the vertical hydraulic conductivity range between 0.1 m/d and about 5 m/d. Weathering covers of marbles, for which the k was several m/d, were characterized by higher permeability properties. In the case of other lithological types, there is no clear variation in the hydraulic conductivity. In spite of large structural differences in cover deposits, a relatively low variation in the hydraulic conductivity is observed. Besides, no relationship is noted between the hydraulic conductivity and the place of location (altitude, height above the valley bottom, slope inclination, and slope exposure). In the predominant area where crystalline rocks occur in the Sudety Mountains, apart from the summit parts of the mountains and outcrops of marble lens, the permeability properties of weathering covers are similar (Tarka, 1997). The aim of this article is to expand the numerical characteristics describing the permeability of weathering covers formed on crystalline rocks of the Sudetes. Evaluation of the infiltration capacity was performed based on field measurements of the vertical hydraulic conductivity carried out by the Porschet method and using the ETC Pask Constant Head Permeameter. An additional goal of this study was also to test the ETC Pask Permeameter and refer the obtained results to the values derived by applying the Porschet method, which is commonly used in Poland.

2. STUDY AREA

The study area, which comprised the Sudety Mountains, is located in the south-western part of Poland. In terms of physico-geographical regionalization, the Sudetes are part of the edge of the Czech Massif province.

The topography of the study area is diverse due to the occurrence of mountain massifs. The elevations in the study area range from around 300 m a.s.l. in the valleys of the mountain rivers up to a maximum elevation of 1603 m a.s.l., which is the peak of Śnieżka Mountain, in the Karkonosze Mountains, on the Polish-Czech border. The entire study area is intersected with numerous valleys and mountain passes.

In geological terms, the Sudety Mountains are an elevation fold and block structure whose basement is composed of Paleozoic crystalline rocks belonging to the West European Platform. Within the basement, there are irregular synclinorial structures that have the character of Permian-Mesozoic sedimentary basins. These basins separate outcrops of the crystalline basement into several separate units. The boundaries between the individual elements of the geological structure of the Sudetes are frequently tectonic in nature (Żelaźniewicz & Aleksandrowski, 2008) (Fig. 1).

Cover deposits overlie crystalline and sedimentary rocks. They consist of rock blocks, rock debris, or more frequently sandy deposits, loamy sands, and weathered loams. Weathering covers in the Sudetes exhibit significant variations in their thickness, from several centimeters to twenty meters. In most formations, exposed bare rock make up a small part of them, accounting for one percent or less. Thin covers are often found in the upper parts of steep slopes and their thickness increases downward (Staśko, 2002).

The covers of crystalline rocks are predominantly composed of weathered deposits formed in site or translocated down the slope. These are crusts with different fractions, frequently with a substantial proportion of stones and boulders. In most mountainous areas, the weathering crusts are loamy and therefore they contain a rather large percentage of the silt and clay fractions. This means that their capacity to conduct and accumulate gravitational water is limited. Cover deposits of mountainous areas composed of crystalline rocks sometimes form the so-called granular weathering cover, with a more even grain-size distribution and a predominance of the sand and gravel fractions (Fig. 2A). They are primarily found in the summit zones of mountains and on slope flattenings. Some areas of the Sudetes have in their upper parts loose covers in the form of rock debris.

Figure1. General geological map of the Sudetes (Zuchiewicz et al., 2007) with location of field works.

Debris covers are characterized by very high permeability since gravitational water does not have conditions to accumulate. It moves in the bottom parts of debris practically as freely as on ground surface.

Weathering processes leading to the formation of weathered deposits are active in the so-called weathering zone, that is, from ground surface to about 20 m b.g.l., as a result of which the rock is enriched with components such as clay minerals, quartz, or mica. Their formation is dependent, among others, on substrate lithology or the degree of maturity of weathered deposits (Staśko, 2002). Such weathering covers can predominantly be found on mountain slopes in the form of rock debris mixed most frequently with cohesive soil (Staśko, 2002).

Similarly, to the entire Sudetes crystalline massif, two basic types of covers occur within the study area: granular weathering cover deposited in situ on the bedrock and loamy-sandy weathering covers overlying it (Fig. 2). The latter, due to sometimes a substantial amount of the silt and clay fractions, have the character of weathered slope loams. The entire profile is closed with a soil layer. The granular weathering cover corresponds to saprolite not translocated down the slope, while the upper weathering cover corresponds to diluvial slope deposits moved as a result of solifluction (Jahn, 1968, Marszałek, 1996, Tarka, 1997).

As reported by Staśko (2002), weathered deposits of the subsurface zone (zones 2 and 3 in Fig. 2), i.e. loamy sands or sandy loams, are characterized by a porosity ranging from 12% to more than 30%, a water absorbability at a level of 50%, and a gravity drainage capacity of more than 20%. In the study area, the thickness of weathering covers is about 5-7 m (Kryza, 1983, Tarka, 1997).

In hydrogeological terms, three main aquifer zones can be distinguished in the areas where crystalline rocks occur in the Sudetes (Staśko, 2002).

Zone I (the shallowest one) is the most widespread zone. The water circulation environment is usually a lithologically varied weathering cover with a variable thickness, overlying a fissured substrate in which weathering processes also occur.

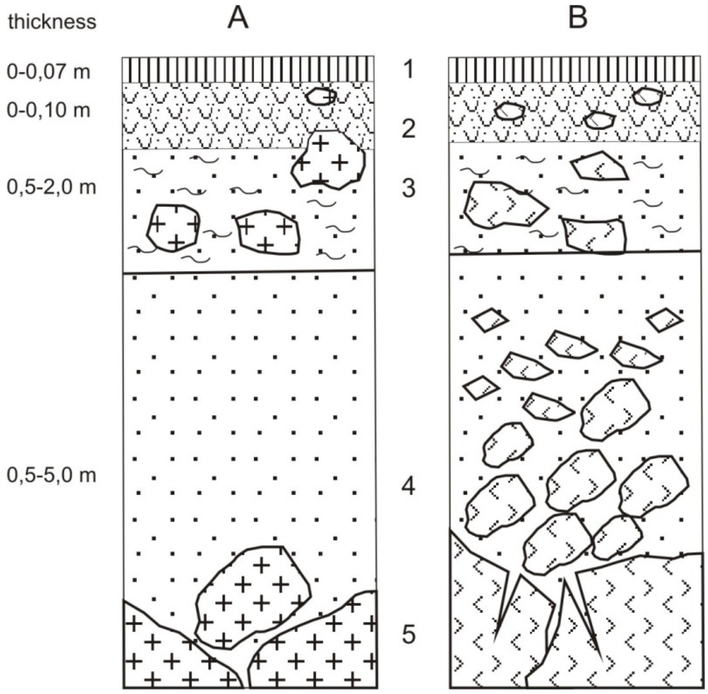

Figure 2. Schematic profiles of weathering covers formed on granite (A) and metamorphic rocks (B) (via Jahn, 1968, Tarka, 1997). 1 - soil, 2 - loamy and sandy deposits, 3 - loamy and sandy deposits with debris, 4A - granular rock waste, 4B - debris, 5 - cracked solid rock

The piezometric groundwater surface is formed according to the land morphology, which means that it is gravitational in nature (Kryza & Kryza, 1983, Staśko, 2002).

Zone II is represented by waters found at greater depths. These waters are recharged by local infiltration, but their circulation occurs within a network of syngenetic or tectonic fissures. This is an area of densely fractured rock massif with high conductivity and low capacity (Kryza H. & Kryza J., 1983).

The deepest zone (III) is made up of single occurrences of water in deep tectonic fractures of local nature. This is an area of deep circulation paths with the lowest capacity and hydraulic conductivity (Staśko, 2002). Generally, these are hydrogeodynamic and hydrogeochemical anomalies, which are manifested in an ascending outflow, high water mineralization, and also temperature resulting from the geothermal gradient (Kryza & Kryza , 1983).

The total thickness of the zone available for penetration of groundwater in crystalline rocks ranges from 8 to 10 m in the summit zones and up to more than 70 m in valleys and the lower part of slopes. This volume changes with changes in the character of the particular zones and it decreases with increasing depth (Staśko, 2002).

3. METHODS

A field study was conducted in the autumn of 2019. The vertical hydraulic conductivity of weathering covers was determined at 16 study sites, which were designated based on the Detailed Geological Map of the Sudetes at a scale of 1: 25 000 and based on a field reconnaissance. The study sites represented the weathering cover formed on metamorphic and igneous rocks in 7 different lithological units (Table 1).

Sites P1-P10 representing weathering covers of metamorphic rocks are located within the geological structure of the Lądek-Śnieżnik Metamorphic Unit (Fig. 1). Sites P11-P16 represent weathering covers of igneous rocks and are located in three geological units of the Sudetes: Karkonosze Granitoids Massif (P11, P12), Kudowa Granitoids Massif (P13, P14), and Kłodzko-Złoty Stok Granitoids Massif (P15, P16).
Evaluation of the permeability of weathering covers of crystalline rocks in the area of the Sudety Mountains was performed based on field measurements of the vertical hydraulic conductivity k made according to the Porschet method (sites P1-P16), which is commonly used with respect to poorly permeable deposits in Poland (Pleczyński, 1981). Moreover, comparative test studies were carried out in relation to the Porschet method, by using the ETC Pask Constant Head Permeameter (sites P1, P2, P4, P6, P8, P9, P11-P16). A total of 28 permeability results were obtained for the weathering covers of crystalline rocks of the Sudetes. The field methods allow reliable values of the hydraulic conductivity of subsurface deposits to be obtained because weathering crust with an intact structure is investigated.

Table 1. Characteristics of study sites.

Site	Location	Coordinates WGS 84		Basement rock	Type of weathering cover
		x	y		
P1	Stronie Śląskie	16.868606	50.281497	amphibolite	silty sand
P2	Strachocin	16.891823	50.308912	eclogite	silty sand
P3	Strachocin	16.892080	50.309680	eclogite	silty sand
P4	Kletno	16.842513	50.237050	mica-schist	silty sand
P5	Kletno	16.842170	50.236556	mica-schist	silty sand
P6	Kletno	16.843801	50.234415	crystalline limestone	silty sand
P7	Idzików	16.773033	50.268030	gneiss coarse-grained	sandy loam
P8	Idzików	16.773205	50.268441	gneiss coarse-grained	sandy loam
P9	Międzygórze	16.766939	50.230242	gneiss fine-grained	sandy loam
P10	Międzygórze	16.766918	50.230091	gneiss fine-grained	sandy loam
P11	Maciejowa	15.314721	50.894064	granite	fine sand
P12	Bukowiec	15.827315	50.829447	granite	medium sand
P13	Jakubowice	16.273229	50.459813	granite	medium sand
P14	Kudowa-Zdrój	16.256898	50.441326	granite	loamy sand
P15	Ołdrzychowice Kłodzkie	16.718259	50.368996	granite	loamy sand
P16	Rogówek	16.743442	50.378649	granite	loamy sand

Macroscopic identification was also performed and laboratory grain size tests were conducted in order to determine the type of the weathering cover (results in last column of table 1). Furthermore, the results obtained from the field investigations were classified according to the permeability properties of the rock environment (Pazdro & Kozerski, 1990).

Preparatory field work for measurements was carried out using a hand auger with a diameter of 7 cm. The depth of boreholes, which were made after first removing the top layer composed of leaves and the humus layer (about 5-10 cm), was from 40 cm to 60 cm. All borehole locations were situated in the weathering cover on slopes within zones 2 and 3, as shown in Figure 2.

3.1. Porschet Method

The Porschet method involves observation of the rate of water table lowering in a borehole with a specific diameter *r* (Fig. 3), ponded with water. A hole (pit) with a diameter of about 10 cm and a depth of H=40-50 cm is made and it is filled with water. At specific time intervals Δt, the height of the water table above the bottom of the hole $x_{1,2}$ is measured and the vertical hydraulic conductivity k is calculated according to the below formulas (Pleczyński, 1981):

$$k = \frac{\varphi(x_1)-\varphi(x_2)}{\Delta t}\ [cm/min] \quad [1]$$

$$\varphi(x_1) = \frac{r}{2}\lg\left(x_1 + \frac{r}{2}\right) \quad [2]$$

$$\varphi(x_2) = \frac{r}{2}\lg\left(x_2 + \frac{r}{2}\right) \quad [3]$$

$$\Delta t = t_2 - t_1 \quad [4]$$

where:
k – vertical hydraulic conductivity [cm/min];
x_1, x_2 – height of the water table above the bottom of the hole[cm];
t_1, t_2 – time of the water table lowering from x_1 to x_2 [min];
r – hole radius[cm].

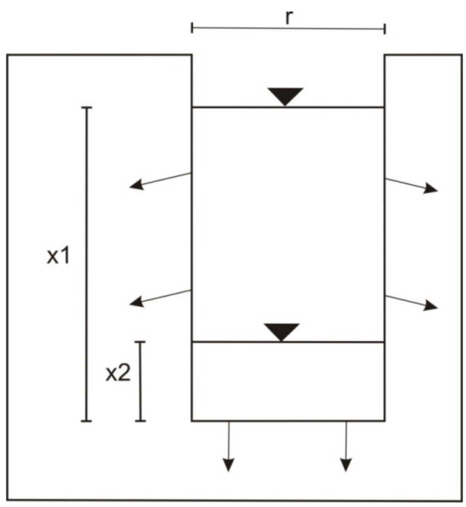

Figure 3. Measurement scheme using the Porschet method.

This is a method for determining infiltration with a variable pressure head. The Porschet method, in which at least three successive pondings are used, provides reliable baseline data regarding the infiltration capacity of the soil tested (Pleczyński, 1981).

3.2. Method Using the ETC Pask Constant Head Permeameter

This is a method for determining the vertical hydraulic conductivity k at a constant pressure head. In situ measurement of k using the ETC Pask Permeameter applies the "*Constant Head Well Permeameter*" (CHWP) method (Reynolds & Elrick, 1986, Reynolds, 1993). The CHWP method is based on producing constant water pressure in a borehole augered into unsaturated rock (Fig. 4), where a zone of water-saturated soil is gradually established. When a fully water-saturated zone is established, the outflow of water from the hole into the rock approaches a constant velocity. After this steady flow rate has been reached, the vertical hydraulic conductivity k of the soils composing the weathered deposit surrounding the hole can be determined using the constant water flow rate, the radius of the well, and the head of ponded water in the well (Fig. 4).

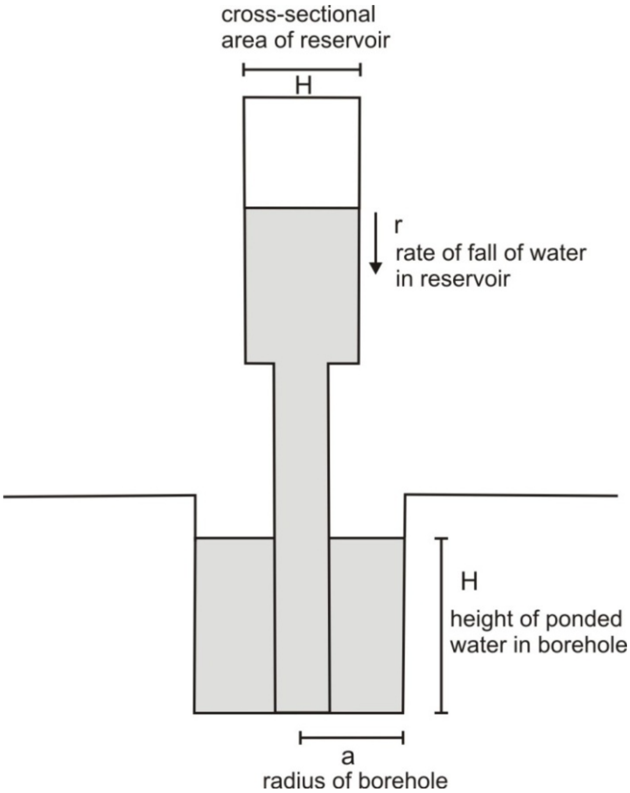

Figure 4. Measurement scheme using the ETC Pask Constant Head Permeameter.

During the initial stage, the water spills at a very fast rate into the borehole from the container with water put into it until the height of water in the borehole reaches the level of the outlet hole of the container. Monitoring of the water fall rate in the permeameter (container) continues until an air bubble appears, which shows that the pressure in the borehole has stabilized.

At the place of measurements, more than one permeametric test should be carried out to make sure that test results are representative. If there are no extreme differences in measurements of the

hydraulic conductivity, it can be appropriate to use the average value. The last step is to calculate the measured rate of fall of the water level according to formula 5.

$$k = CQ/[2\pi H^2+\pi a^2 C+(2\pi H/\alpha^*)] \quad [5]$$ (Reynolds, 1993)

where:

k– hydraulic conductivity [cm/min];
C – a shape factor selected from Fig. 5;
Q – flow rate [cm^3/min]; Q = X r
X – reservoir cross-sectional area[cm^2];
r – rate of fall of the water level in the permeameter reservoir[cm/min];
a – radius of borehole [cm];
H – water ponding head in the borehole[cm];
α^* -crust texture-structure parameter selected from the appropriate category in Table 2[cm^{-1}]

The determination of k at a specific study site begins from calculating the volume of infiltration water (Q) from the permeameter. The next step is to use the graph (Fig. 5) to determine the parameter C. The calculated value of H/a is referred to the crust type. The last element is to determine the value of the coefficient α^* using Table 2, which makes the value of this parameter dependent on the type of crust.

4. RESULTS

During the field investigations conducted at the sixteen sites, 28 determinations of the hydraulic conductivity k were made, 16 by the Porschet method and 12 using the ETC Pask Permeameter. Table 3 compares the results obtained using both methods.

The values of the vertical hydraulic conductivity k determined by the Porschet method ranged 0.053-2.19 m/d, while those obtained using the ETC Pask Permeameter ranged 0.012-0.76 m/d. In the first place, it should be noticed that the results determined during the field investigations conducted according to the Porschet method are generally 3-4 times higher than those obtained using the ETC Pask Permeameter. At site P14 a difference by even one order of magnitude can be seen.

The Porschet method is characterized by hydraulic conductivity values between 0.053 and 2.19 m/d, with an average of 0.49 m/d. The lowest hydraulic conductivity was found at site P9, where

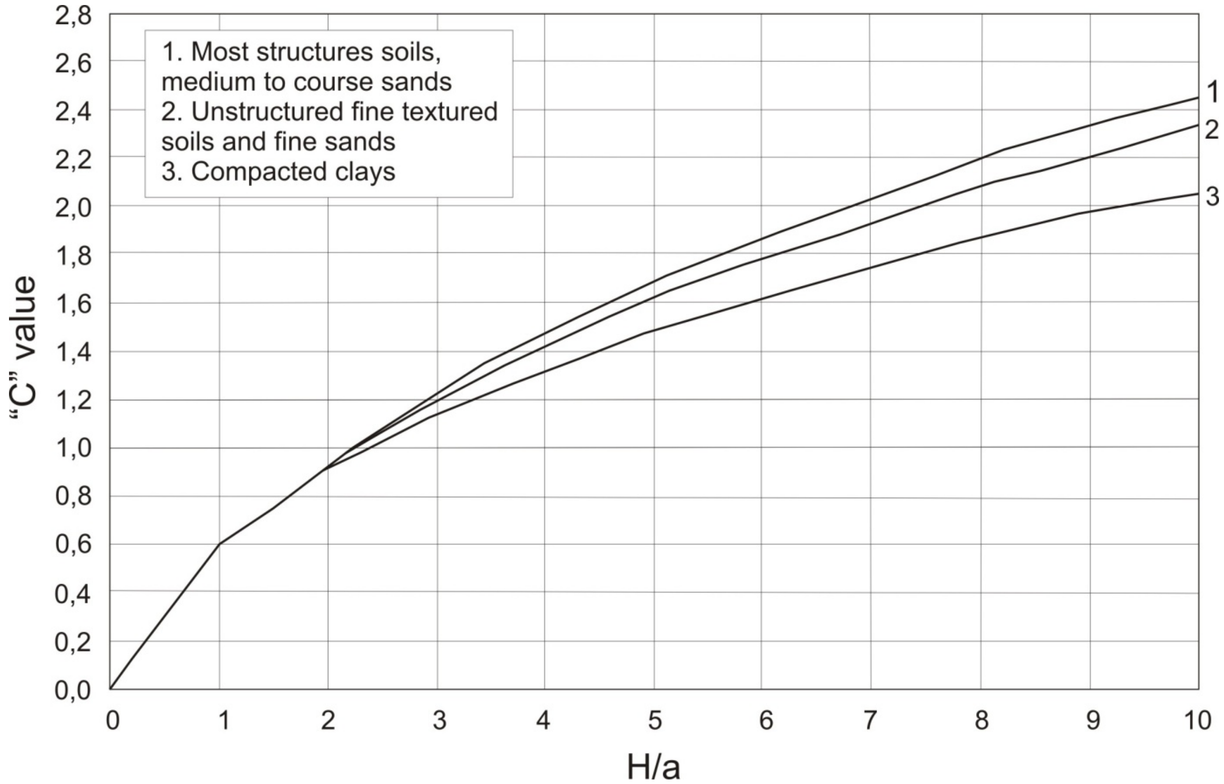

Figure 5. Determination of C values (Reynolds, 1993).

Table 2. Suggested α* values (Reynolds, 1993).

α* [cm^{-1}]	Cust structure and texture
0.36	Coarse sands and highly structured crusts
0.12	Most structured crusts and medium sands
0.04	Unstructured fine textured crusts and fine sands
0.001	Compacted clays (e.g. clay liners)

Table 3. Permeability results of weathering covers of the study area.

Site	Basement rock	Type of weathering cover	k [m/d]	
			Porschet	Pask
P1	amphibolite	silty sand	0.28	0.09
P2	eclogite	silty sand	0.13	0.05
P3	eclogite	silty sand	0.14	-
P4	mica-schist	silty sand	0.46	0.14
P5	mica-schist	silty sand	0.3	-
P6	crystalline limestone	silty sand	0.35	0.1
P7	gneiss, coarse-grained	sandy loam	0.06	-
P8	gneiss, coarse grained	sandy loam	0.055	0.012
P9	gneiss, fine grained	sandy loam	0.053	0.015
P10	gneiss, fine grained	sandy loam	0.071	-
P11	granite	fine sand	0.362	0.15
P12	granite	medium sand	1.21	0.14
P13	granite	medium sand	2.19	0.76
P14	granite	loamy sand	0.39	0.036
P15	granite	loamy sand	1.02	0.12
P16	granite	loamy sand	0.78	0.11

sandy loam formed on gneisses with a fine-grained structure was observed. Site P13, where the weathering cover formed on granite was composed of medium sand, exhibited the best permeability.

The measurement of the conductivity of subsurface deposits using the ETC Pask Permeameter produced hydraulic conductivity results ranging 0.012-0.76 m/d. The average value obtained from all measurements is 0.14 m/d, which gives a 3.5 times lower average value than in the case of the Porschet method. The lowest measurement value k=0.012 m/d was found at site P8 where sandy loam had formed on augen gneisses (coarse-grained). The highest value k=0.76 m/d was recorded at site P13, similarly as in the case of the Porschet method. The analysis of the results shows that the hydraulic conductivity range of 0.1 - 1 m/d is dominant.

When analyzing the data regarding the k coefficient, a larger difference can be seen between the highest and lowest values in the case of application of the Porschet method (2.14 m/d). For the ETC Pask Permeameter, it is 0.75 m/d. As far as the division between igneous and metamorphic rocks is concerned, a greater difference in the results is found in the case of the Porschet method. As regards granites, the differences are 1.83 m/d (Porschet) and 0.72 m/d (ETC PASK), respectively, whereas for metamorphic rocks they are 0.41 m/d (Porschet) and 0.13 m/d (ETC Pask Permeameter). Moreover, it was noted that the better the permeability properties of the cover deposits, the greater the differences in k values between both methods. For sandy loams and silty sands, the differences are 3 or 4 times, whereas in the case of medium sands and loamy sands they reach even one order of magnitude. To sum up, it can be concluded that the ETC Pask Permeameter is more suitable for determining the k of poorly permeable weathering covers. Given the better capacity of weathered rock to conduct water, the results derived using this method should be treated with reservation and other field methods should be employed to check the correctness of the obtained results.

Taking into account the larger variations in the hydraulic conductivity results obtained by the Porschet method and its multiple applications in the investigations carried out in the area of the Sudetes, it was decided that the results determined based on this method would be included in the discussion. Thus far, the ETC Pask Permeameter has not been used to determine the permeability of weathering covers in mountain areas in Poland and therefore there are no data with which the results presented in this article could be compared. Also, there are no results concerning the use of the ETC Pask Permeameter in foreign literature. This article presents a pioneer application of the ETC Pask Permeameter to characterize the permeability of weathering covers of crystalline rocks not only in the Sudety Mountains, but also across Poland.

5. DISCUSSION

Determinations of the conductivity of cover deposits, as expressed by the hydraulic conductivity, made by applying field methods were performed many times within the area of the Sudety Mountains already in the 1990's (Tarka, 1997, Bocheńska et al., 2002, Marszałek et al., 2011, Chudy & Sulima, 2011, Wąsik & Wąsowski, 2015). These studies were conducted not only on weathered igneous and metamorphic rocks, but also with regard to weathering covers on sedimentary rocks (Marszałek et al., 2011, Chudy & Sulima, 2011). Table 4 shows the differences in the infiltration capacity of cover deposits located in the area of the Sudetes based on archival data and the present study.

The results for the vertical hydraulic conductivity derived based on the present field study (Table 3, Fig. 6) allow us to classify weathering covers of metamorphic and igneous rocks, according to the classification of Pazdro & Kozerski (1990), as semi-permeable to medium permeable rocks. The graph in figure 6 shows the graphical variations in the hydraulic conductivity for the weathering crusts covering crystalline rocks in the Sudetes.

In the first place, sandy loam resulting from weathering gneisses (Table 3), can be classified as semi-permeable crust (below 0.086 m/d). Their hydraulic conductivity was below 0.1 m/d and ranged 0.053 - 0.071 m/d. Weathered gneisses were distinctly characterized by the worst capacity to conduct water among all types of weathering covers of crystalline rocks.

The other weathering covers of metamorphic rocks in the Eastern Sudetes investigated within the study area should be considered to be poorly permeable. The crusts formed as a result of weathering of eclogite exhibited an almost twice higher hydraulic conductivity than weathered gneisses, which was 0.13 m/d – 0.14 m/d.

Even higher values of the vertical hydraulic conductivity were found for the weathering covers of the other distinguished lithological units. For weathered amphibolite, this coefficient was 0.28 m/d, whereas for crystalline limestone 0.35 m/d.

Weathered mica schist achieved the highest coefficient, even if its average is taken into account. The average from two sites was 0.38 m/d. At site P4, the result was 0.46 m/d, whereas for site P5 it was 0.3 m/d.

Table 4. Permeability results of weathering covers of Sudetes.

Location	Type of rocks		k [m/d]
Western, Middle and Eastern Sudetes (present study)	Igneous	weathering covers of granites	0.3-2.19
	Metamorphic	weathering covers of gneisses, mica-schists, crystalline limestones, eclogites, amphibolites	0.053-0.46
Middle Sudetes (Marszałek et al., 2011)	Sedimentary	fluvial deposits	0.4-0.5
	Metamorphic	weathering covers of granite-gneisses	0.11-1.15
	Metamorphic	weathering covers of gneisses	0.29-0.9
	Metamorphic	weathering covers of migmatites	0.06-0.5
Middle Sudetes (Chudy & Sulima, 2011)	Igneous	weathering covers of rhyoliyes	0.13-0.81
	Sedimentary	loams	0.38-0.56
	Sedimentary	fluvial deposits	0.35-3.74
Western Sudetes (Kryza H. & Kryza J., 1983, Marszałek, 1996)	Igneous	grained granites	0.57-20.30
	Sedimentary	fluvial deposits	0.18-18.29
	Metamorphic	weathering covers of hornfels	0.18-0.24
Western Sudetes (Marszałek, 1996)	Igneous	granite rubbles	1-49
Western Sudetes (Wąsik & Wąsowski, 2015)	Igneous	weathering covers of granites	0.009-0.175
	Metamorphic	weathering covers of greens tones	0.033-0.034
	Metamorphic	weathering covers of amphibolites	0.011-0.406
	Metamorphic	weathering covers of hornfels	0.160-0.408
Eastern Sudetes (Kryza, 1983)	Metamorphic	rumbbles of gneisses, mica-schits	12
	Sedimentary	loams	0.7
	Sedimentary	fluvial deposits	11.6

A previous study conducted in the Lądek-Śnieżnik Metamorphic Unit confirms the rather low permeability of weathering covers of metamorphic rocks (Kryza, 1983). Laboratory tests were performed for weathered rocks such as gneisses, mica schist, and crystalline limestones. The weathering cover of these rocks was represented by slope loams and the average hydraulic conductivity was 0.7 m/d. When averaging the k results determined in the present study, an average of 0.19 m/d was obtained. Taking into consideration a number of factors, such as the different locations of the study boreholes and the differences in grain-size distribution, it can be accepted that the results are similar and that the characteristics of a poorly permeable environment can be attributed to the weathering covers of metamorphic rocks (k = 0.08-0.8 m/d).

Similar ranges for the permeability of cover deposits of metamorphic rocks were found in the area of the Western Sudetes (Wąsik & Wąsowski, 2015). The study in question was conducted using the Porschet method. In the area of weathering covers of amphibolites, the values of the hydraulic conductivity were found to range between 0.16 and 0.79 m/d, while for weathered hornfels they were 0.35 – 0.89 m/d. The hydraulic conductivity for weathered greenstones was 0.16 – 1.02 m/d.

The Central Sudetes area does not differ in permeability values of weathered metamorphic rocks, either. The vertical hydraulic conductivity of weathered metamorphic rocks, among others gneisses (k = 0.18–0.9 m/d), granite gneisses (k = 0.11–1.15 m/d), or paragneisses and migmatites (k = 0.06–0.5 m/d), reveal that these weathered deposits are poorly to very poorly permeable (Marszałek et al., 2011). In the case of weathered crystalline limestones and dolomites, the permeability coefficient ranged 0.4 – 1.09 m/d (Bocheńska et al., 2002).

The weathering covers of granite rocks, which in most cases are classified as medium permeability rocks (0.8 – 8 m/d) according to the division by Pazdro & Kozerski (1990), exhibit distinctly better permeability coefficients. The weathering covers of Kudowa granite, formed as medium sands, rank first since they reach permeability values of more than 2 m/d. The average value of k for weathered granite reaches 1 m/d. In the area of the Western Sudetes, among all weathering covers of crystalline rocks the best results were also shown by weathered granites 0.091 – 8.08 m/d and their permeability can be classified as medium or even good (Wąsik & Wąsowski, 2015).

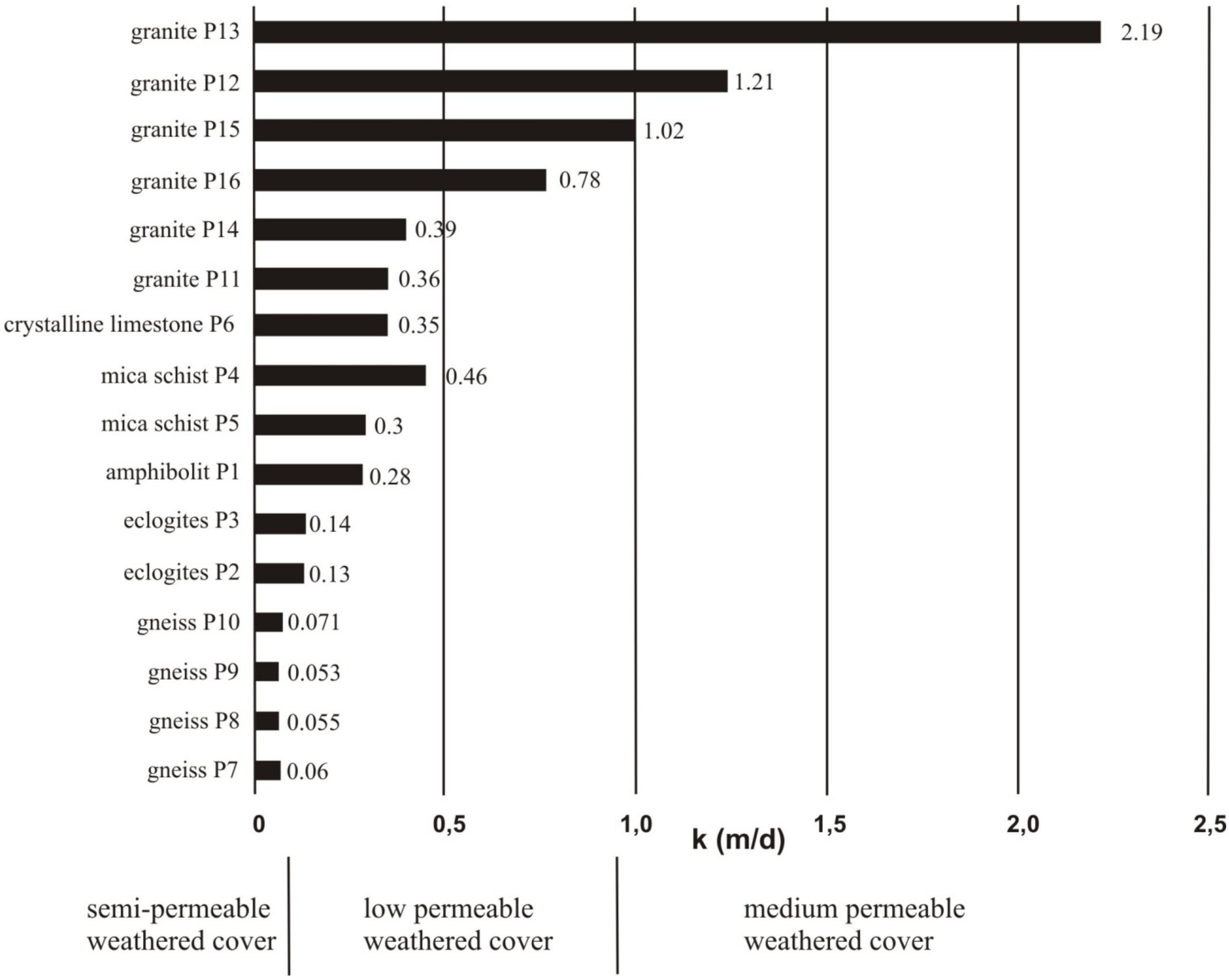

Figure 6. Differences in the hydraulic conductivity of weathering covers of crystalline rocks in the Sudetes.

In the Central Sudetes, the permeability of weathered igneous rocks determined by the Porschet method (Chudy & Sulima, 2011) was k= 0.13 - 0.81 m/d for weathered rhyolite, while for trachybasalts and latites k=0.13-2.69 m/d. Locally in the area of the Sudety Mountains (particularly in the Central and Western Sudetes), weathered igneous rocks can be characterized by very high permeability. In the Sudetes, granular weathered granite (the so-called granite grus) is distinguished by the best conductivity since the hydraulic conductivity reach values in the order of several dozen to even several hundred m/d (Wąsik & Wąsowski, 2015).

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