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Constant head permeameter tests for hydraulic conductivity of unconsolidated sediments and associated terminology

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Abstract

Laboratory tests for hydraulic conductivity of unconsolidated sediments are presented and associated terminology used in groundwater literature and practice is discussed. Samples of unconsolidated sediments, i.e. gravels and sands deposited at two sites, Zagreb alluvial aquifer (Sava basin, Croatia) and Virovitica alluvial aquifer (Drava basin, Croatia) were tested in the laboratory using a constant head permeameter. Main features of the tests are presented and the results at two sites are compared. Discussion on terminology used to denote the capacity of a medium to transmit water in groundwater literature and practice is presented, referring to the ambiguity of terms most often used to its denotation. Today's most often denotations in groundwater literature and practice are hydraulic conductivity, K [L/T] (m/s in SI system) or coefficient of permeability, k [L/T] (m/s in SI system), the terms being used specifically for the flow of a single water phase through a porous media. In addition, discussion is broadened with the relation to the notation permeability, k [L^2] (m^2 in SI system) i.e. intrinsic or absolute or specific permeability, also denoted as k [L^2] (m^2 in SI system) when porous medium is 100% saturated with a single-phase fluid, i.e. water in considered case, and which are the property of the porous media only, not the fluid.

Keywords: hydraulic conductivity, permeability, intrinsic permeability, permeameter, terminology

1. Introduction

Test for hydraulic conductivity of unconsolidated sediments dates back to 1856, when Henry Darcy conducted the first documented test to determine the laws of the water flow through sands (**Darcy, 1856**). The parameter to which we today most commonly refer to as hydraulic conductivity, usually denoted as capital K [L/T] (m/s in SI system), Darcy denoted with the small letter k and termed as a coefficient dependent on the permeability of the layer in his work on the public fountains of the city of Dijon (**Darcy, 1856**). Today's terminology and notation has slightly changed with respect to Darcy's in majority of groundwater literature, naming parameter as hydraulic conductivity specifically for the flow of water through a porous media when dealing with the single water phase and symbolizing it as capital letter K. Hydraulic conductivity controls flow and transport processes in aquifers and is one of the most important sediment properties. It is a tensor, which means that its properties change with direction, i.e. they vary in space, usually having smaller values in vertical than in horizontal direction. The hydraulic conductivity characterizes the capacity of a medium to transmit water.

Laboratory tests of hydraulic conductivity most commonly encompass grain size analysis (**Hazen, 1892; Terzaghi, 1925; Carman, 1937; Kozeny, 1953; Vuković and Soro, 1992; Roscoe Moss Company, 2008**) and permeameter tests (**Freeze and Cherry, 1979; Todd and Mays, 2005; Malama and Revil, 2014**). Although grain size analysis is more often applied, permeameter tests are also in use. With respect to gravel and sand samples, constant head permeameter test is widely applied. Numerous tests of hydraulic conductivity have been obtained in both laboratory and the field in the past. One of the most comprehensive summary is given by **Davis, 1969**. Namely, gravels and clean sands with hydraulic conductivity larger than 10^{-5} m/s are tested in constant head cells while finer deposits like very fine or silty sands, silts and clays are tested in falling head cells and oedometers. Tests of hydraulic conductivity of unconsolidated deposits of Zagreb aquifer using constant head permeameter were applied in previous studies by **Ban, A. (2011)**, **Ivačić, V. (2014)**, **Gelo, N. (2014)**, **Peršić, S. (2014)** and **Čambala, M. (2017)**. Ban tested samples of unconsolidated material taken in the near vicinity of the river Sava and obtained hydraulic conductivities in the range of 10^{-4} m/s. Ivačić determined the hydraulic conductivity of the samples taken from the 50 m borehole in the area of the future well field Črnkovec and obtained the values in the range of 10^{-3} to 10^{-5} m/s. Gelo and Peršić studied the samples taken from 100 m borehole in the

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eastern part of the Zagreb aquifer and also obtained hydraulic conductivities in the range of 10^{-3} to 10^{-5} m/s while Čambala determined hydraulic conductivities in the range of 10^{-3} to 10^{-4} m/s in the central part of the Zagreb aquifer.

In presented research, samples of unconsolidated sediments, i.e. gravels and sands were collected at two sites, Zagreb alluvial aquifer (Sava basin, Croatia) and Virovitica alluvial aquifer (Drava basin, Croatia). Hydraulic conductivity of samples was tested in laboratory using constant head permeameter tests. Constant head test of the sediment taken from the shallow zone of the central part of the Zagreb aquifer near wellfield Velika Gorica contained about 60% of gravel and some 40% of sand size grains and showed hydraulic conductivities in the range of 10^{-5} m/s which was in line with the tests from previous authors. On the other hand, constant head test of the sediment taken from the Virovitica aquifer which contained more than 90% of gravel and less than 10% of sand size grains, showed higher values of hydraulic conductivity in the range of 10^{-2} m/s.

In addition, discussion on terminology used in groundwater literature and practice is presented in a separate section, referring to unambiguity of terms most often used to its denotation. Terms hydraulic conductivity, K [L/T] (m/s in SI system), coefficient of permeability, k [L/T] (m/s in SI system), permeability, k (L^2) (m^2 in SI system) and intrinsic or absolute or specific permeability, k [L^2] (m^2 in SI system) are discussed, pointing to denotations that often cause misunderstandings both in groundwater literature and practice.

2. Materials and methods

2.1. Theoretical background

John Cherry and Allan Freeze (**Freeze and Cherry, 1979**) wrote in their textbook and later Freeze repeated it in an article about the Henry Darcy and the Fountains of Dijon (**Freeze, 1994**): "The birth of groundwater hydrology as a quantitative science can be traced to the year 1856. It was in that year that a French hydraulic engineer named Henry Darcy published his report on the water supply of the city of Dijon, France. In the report, Darcy described a laboratory experiment that he had carried out to analyze the flow of water through sands. The result of his experiment can be generalized into the empirical law that now bears his name." Darcy's law for anisotropic porous media is later derived from the Navier-Stokes equation by using a formal averaging procedure (Neuman, 1975).

Darcy's law (**Darcy, 1856**) is empirical since it is based on results observed from a set of laboratory experiments conducted in an apparatus shown in **Figure 2.1**. Darcy conducted the experiment in October 1855 and February 1856 in a local hospital of the city of Dijon, France together with the engineer Charles Ritter with the aim to determine the law for the flow of water through sand. Apparatus consisted of vertical column with the height of 2.5 m built of a pipe of a 0.35 m in diameter, sealed with the plate on both ends. The column was connected to the hospital water supply system. The valve at the end of the inflow pipe enabled control of the water inflow while the valve on the outflow pipe enabled the control of the water outflow into the reservoir of known volume. The pressure in both ends of the column was measured in mercury manometers. The column had the vent installed, enabling removal of the air entrapped in the apparatus. The experiment was conducted in a number of series using the quartz sand from the river Saône which flows through the east of France.

Darcy's law can be written as:

$$Q = -KA\frac{h_2 - h_1}{l} \tag{1}$$

where
Q – flowrate [m^3/s],
K – hydraulic conductivity, proportionality factor which Darcy describes as a coefficient dependent on the permeability of the layer [m/s],
A – cross-section area of the sand column perpendicular to the flow direction [m^2],
l – the length of the sand column in Darcy apparatus [m],
h_1 *and* h_2 – heights in manometer tubes above the reference level measured below and above the sand column [m],

Hydraulic conductivity, K, proportionality factor which Darcy describes as a coefficient dependent on the permeability of the layer can be expressed as:

$$K = Cd^2\frac{\delta g}{\mu} = k\frac{\delta g}{\mu} \tag{2}$$

where
C – dimensionless coefficient [-],
d – representative grain diameter [m],
k – intrinsic permeability [m^2]
δ – water density [kg/m^3],
g – acceleration due to gravity [m^2/s],
μ – dynamic viscosity of water [Pa s],

Hydraulic conductivity, K denotes the capacity of a medium to transmit water and intrinsic permeability, k denotes the property of the porous media only, not the fluid, when dealing with the porous medium 100% saturated with a single water phase.

If equation 1 is written in differential form it becomes:

$$q = K\frac{dh}{dl} = Ki \tag{3}$$

where
q – specific discharge [m/s],
i – hydraulic gradient [-],

Darcy's law is linear since the plot of experimental observations of the specific discharge q versus the hydraulic gradient i indicate a straight line (**Figure 2.2**). If we consider the linear equation in one variable in a slope intercept form $y = ax$, where a is the slope of the line and intercept is equal to zero, i.e. the line crosses the y axis in the y coordinate equal to zero, i.e. in the origin, we can see that in Darcy's law K is the slope of the line which passes through the origin of a coordinate system (see **Figure 2.2**). As long as the plotted data of q versus i stay on the straight line, the flow is considered to be laminar, and Darcy's law valid. When deviation of the plotted data of q versus i from the straight line occurs, the flow is considered to be nonlinear and Darcy's law no longer valid. The lower limit of the validity of Darcy's law is connected with the existence of the threshold hydraulic gradient. The law does not hold at a very low head gradients in some fine-textured materials such as compacted clays due to electrostatic forces which exist in clayey soils (Yeh et al., 2015). The validity of Darcy's law is also described with the Reynolds number, Re [-]:

$$Re = \frac{(\delta q d)}{\mu} \tag{4}$$

where
d – characteristic length, generally considered as the effective grain size, or d_{10} (i.e. the grain size for which 10 percent of the sample by weight is finer) [m],

For the Reynolds number less than one, the flow is considered to be laminar and Darcy's law valid. For the Reynolds number in a range from 1 to 10, experimental tests have shown that Darcy's law may still be valid, as this is the case for groundwater flow. At large hydraulic gradient values (i.e. at $10 \leq Re < 100$) flow deviates from the linear relationship and the relation between q and i is no longer linear, although the flow can still be in the laminar flow regime or in transition regime. At $Re << 100$, turbulent flow takes place. The upper boundary of Re equal to 10 is though not strict. There are cases where the value of Reynolds number is somewhat above 10 and the specific discharge q versus hydraulic gradient i still plots on a straight line, indicating that the Darcy's law is linear and though valid. Therefore the validity of Darcy's law when conducting an experiment in a laboratory test is best checked by a specific discharge q versus hydraulic gradient i plots. But generally, suggested boundaries of Reynolds number apply in practice.

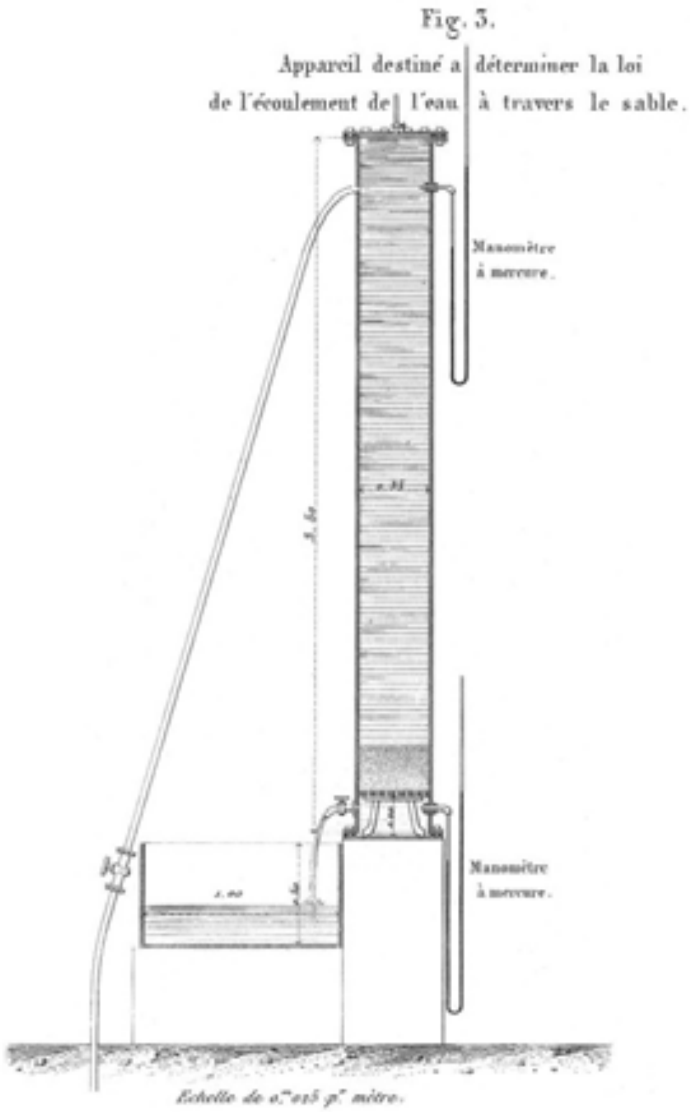

Figure 2.1: Darcy apparatus used in the development of Darcy's law (taken from **Darcy, 1856**, translation by **Glenn Brown and Bruno Cateni, 1999**, https://bae.okstate.edu/faculty-sites/Darcy/English/index.htm, accessed 8. 8. 2018)

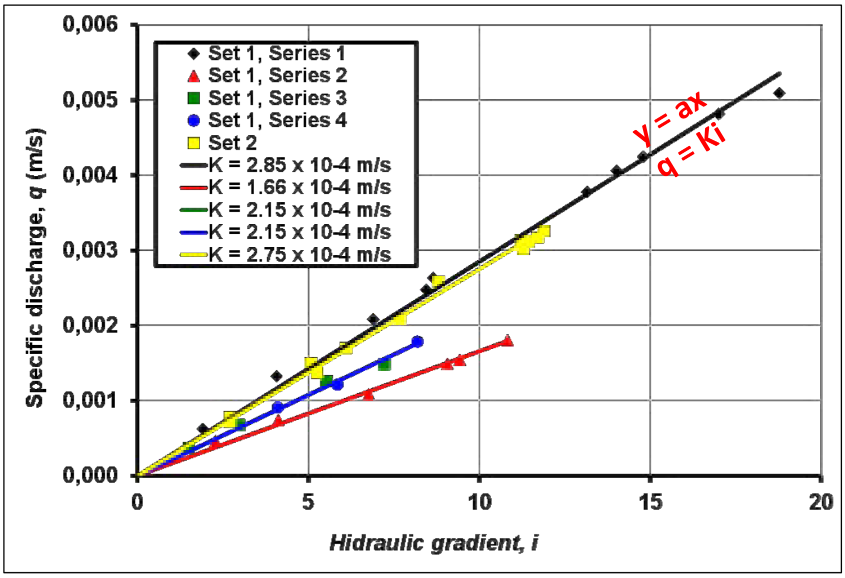

Figure 2.2: Darcy's data plotted as q versus i (taken and modified from **Darcy, 1856**, translation by **Glenn Brown, 2000**, https://bae.okstate.edu/faculty-sites/Darcy/Summary.htm, accessed 8. 8. 2018,)

2.2. Constant head permeameter test

Constant head permeameter tests are being conducted in an apparatus which is basically a modification of Darcy's apparatus (see **Figure 2.1**), retaining the same apparatus concept as Darcy's (**Figure 2.3**). The tests are regularly being conducted using standards (for example ASTM standard: D 2434 – 68 or ISO standard: CEN ISO/TS 17892-11:2004/AC). In order to obtain valid results, some prerequisites need to be satisfied for the laminar flow of water through granular soils under constant-head conditions (ASTM standard: D 2434 – 68): (1) continuity of flow with no soil volume change during a test; (2) flow with the soil voids saturated with water and no air bubbles in the soil voids; (3) flow in the steady state with no changes in hydraulic gradient, and (4) direct proportionality of velocity of flow with hydraulic gradients below certain values, at which turbulent flow starts. Samples should contain less than 10% of the material passing the 75-µm (No. 200) sieve and they should be selected by the method of quartering. Furthermore, any particles larger than 19 mm should be separated by sieving. Specimen should be compacted in a cell in successive layers to a height of about 2 cm above the upper manometer outlet. Entrapped air should be evacuated from the specimen using a vacuum pump under 50 cm Hg minimum for 15 min before the specimen is saturated. Air evacuation should be followed by a slow saturation of the specimen from the bottom upward under full vacuum in order to free any remaining air in the specimen. Adequate air removal from the specimen, flow system and manometer system is vital for the success of the permeameter test.

After preparation of specimen and apparatus, procedure is followed with a series of measurements of volume of water, V [L^3] (m^3 in SI system) discharged in time, t [T] (s in SI system) from which flow rate, Q [L^3/T] (m^3/s in SI system) is calculated. Specific discharge q is calculated as the ratio of the calculated flowrate, Q and the cell area, A [L^2] (m^2 in SI system) perpendicular to the flow direction. Hydraulic gradient, i is calculated as a ratio of the measured head difference, H [L] (m in SI system) in manometers and the distance between manometers, L [L] (m in SI system). After each measurement, specific discharge q versus hydraulic gradient i is plotted on the graph which enables insight into the current state of the flow, i.e. linear or nonlinear. Hydraulic conductivity, K is calculated based on Darcy's law and can be read out from the equation on the chart as the slope of the line which passes through the q versus i data set and origin of a coordinate system (see also section 2.1). Head differences between manometer outlets are increased by 0.5 cm for each measurement until departure of specific discharge q versus hydraulic gradient i becomes apparent, which means that flow had become nonlinear. As described in section 2.1, the validity of Darcy's law can also be tested by Reynolds number. In order to ensure laminar flow conditions, suggested values of initial hydraulic gradient, i for loose compactness ratings are from i = 0.2 to 0.3 which corresponds to the initial head differences between manometer outlets of 3 to 4 cm, and dense compactness ratings from i = 0.3 to 0.5, which corresponds to the initial head differences between manometer outlets of 5 to 7 cm. The lower values of i are applied to coarser soils and the higher values to finer soils.

Figure 2.3: Example of the constant head permeameter apparatus (manufacturer: ELE, United Kingdom; Laboratory of the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Croatia)

2.3. Samples of unconsolidated sediments for constant head tests

Samples of unconsolidated sediments, i.e. gravels and sands were taken at two sites.

The first site was Zagreb alluvial aquifer which is situated in the Sava river basin and characterized with its alluvial deposits. Aquifer is composed mainly of Quaternary sediments. This area was during the Pleistocene age covered with lakes and marshes while neighbouring mountains, Mt. Medvednica and Vukomeričke gorice hills, was land susceptible to intensive erosion. Weathered material was carried along the streams and deposited in lakes and marshes (Velić and Saftić, 1991). In beginning of the Holocene, climate and tectonic processes enabled river Sava to cut its course. With this event, transport of material from the Alps began (Velić and Durn, 1993). Transport of materials was of varying intensity due to frequent changes of climate conditions. During warm and wet periods, it was intensive while its intensity reduced during dry and cold periods. Beside climate changes, tectonic movements also influenced the deposition processes (Velić et al., 1999). Consequence of such deposition conditions was pronounced heterogeneity and anisotropy of the aquifer sediments as well as unequal distribution of the aquifer thicknesses. The composition of the lower Pleistocene deposits is predominantly yellowish-red, yellowish-orange and yellowish-brown, clayey silts/silty clays with sporadic lenses and interbeds of gravelly-sands. The lower and middle part of the Middle Pleistocene unit is predominantly composed of grey coloured sands while the upper part comprises grey coloured or red to yellowish-brown mottled silt and clay sized material (Velić and Durn, 1993). Frequent lateral changes of gravels, sands, silts and clays occur in the Upper Pleistocene unit. The Holocene is composed of pale, yellowish- grey coloured gravels and sands in which limestone cobbles prevail. Quaternary deposits are generally divided into three basic units: (1) aquifer system overburden built of clay and silt, (2) shallow Holocene aquifer built of alluvial deposits i.e. medium-grain gravel mixed with sands and (3) deeper aquifer from Middle and Upper Pleistocene built of lacustrine-marshy deposits, with frequent lateral and vertical alterations of gravel, sand and clay. Differentiation between shallow and deeper aquifers is stratigraphic since they are hydraulically connected and form a single aquifer from hydrogeological point of view. The sample of gravels and sands for the constant head test (**Figure 2.4**) was taken from shallow Holocene Zagreb aquifer, i.e. its central part near Velika Gorica wellfield. It contained about 60% of gravel and some 40% of sand size grains (**Figure 2.5**).

Figure 2.4: Gravel and sand sample for constant head test taken from shallow Holocene Zagreb aquifer

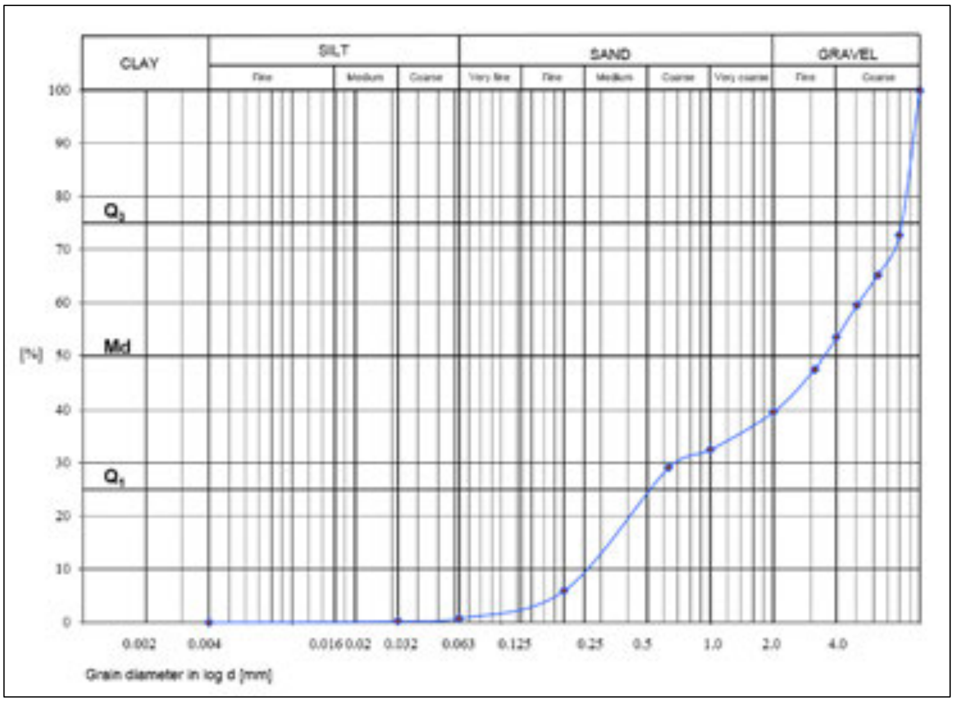

Figure 2.5: Grain size distribution of sample for constant head test taken from Zagreb aquifer

The second site was Virovitica alluvial aquifer, situated in the Drava river basin also characterized with alluvial deposits of Quaternary age. During the Pleistocene age deposition of aeolian sediments, i.e. loess sediments occurred in alteration with fluvial deposits. Denudation processes and tectonic processes enabled deposition of diluvia and pluvial sediments as well as alluvial sediments deposited by the river Drava. Quaternary deposits are characterized with the thick coarse-grained clastic deposits interlayered with thin fine-grained and clayey layers which enabled formation of thick aquifers, with thickness ranging up to 100 m and more (**„Službeni glasnik" of Virovitičko – podravska County No. 7A/00., 1/04., 5/07., 1/10., 2/12., 4/12., 2/13., 3/13**, http://zpuvpz.hr/prostorni-planovi-viroviticko-podravske-zupanije/, accessed 10.8.2018.). The sample of gravels and sands for the constant head test (**Figure 2.6**) taken from the shallow part of Virovitica aquifer contained more than 90% of gravel and less than 10% of sand size grains (**Figure 2.7**).

Figure 2.6: Gravel and sand sample for constant head test taken from shallow part of Virovitica aquifer

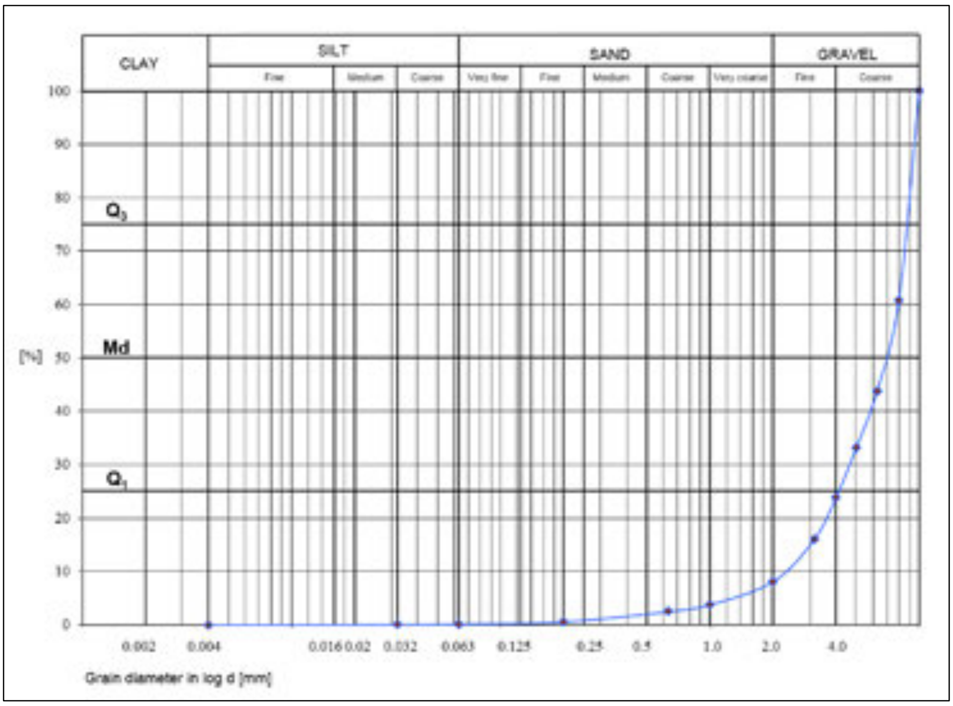

Figure 2.7: Grain size distribution of sample for constant head test taken from Virovitica aquifer

3. Results and discussion

3.1. Hydraulic conductivity of unconsolidated sediments

Results of the constant head permeameter tests for hydraulic conductivity of samples taken from Zagreb and Virovitica alluvial aquifer, i.e. from Sava and Drava river basins, are presented on **Figures 3.1** and **3.2**, plotted on charts as specific discharge, q versus hydraulic gradient, i. Hydraulic conductivity, K can readily be seen on the charts in presented trendline equations. Namely, as discussed in section 2.1, hydraulic conductivity, K is the slope of the trendline which passes through the q versus i data set and the origin of a coordinate system, i.e. in the y coordinate equal to zero.

Hydraulic conductivity of the sample taken from the Zagreb aquifer showed the value of K equal to 8.2×10^{-5} m/s. Series of 9 measurements were conducted. It can be seen that flow for applied hydraulic gradients in the final stage, i.e. for the final 2 measurements, became nonlinear. Therefore only the first 7 measurements were considered in the calculation of the K value during which the flow was still laminar. Obtained K value is within the range of the values expected for Zagreb aquifer. Namely, eastern parts of the Zagreb aquifer tend to have hydraulic conductivities in the range from 10^{-3} to 10^{-5} m/s while western parts have somewhat higher values of K, ranging up to 10^{-2} m/s.

The obtained hydraulic conductivity of the sample taken from Virovitica aquifer showed higher values of hydraulic conductivity, i.e. 1.8×10^{-2} m/s. The obtained value should though be taken with care since difficulties in measurements of the volume of water, V discharged in time, t were present due to high discharge rates, which affected the precision of measurements. Nevertheless, it is evident that a sample with a high share of the gravel size particles, i.e. around 90% (see **Figure 2.7**), is bound to yield high hydraulic conductivities as well. Furthermore, taking into account high discharge rates during testing, obtained high hydraulic value can though be considered relevant.

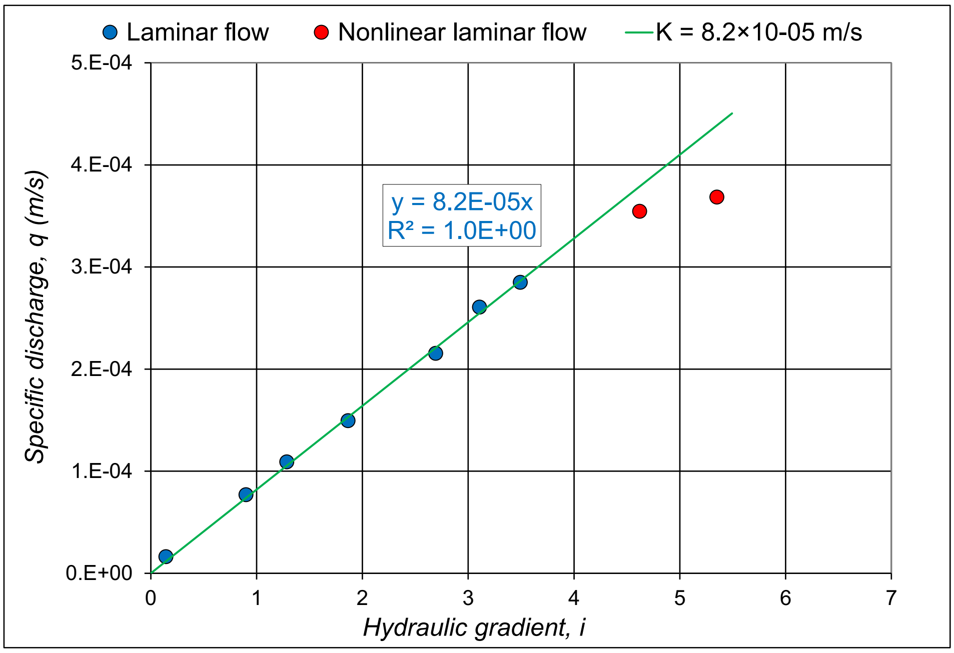

Figure 3.1: Permeameter constant head test data for sample taken from Zagreb aquifer plotted as q versus i

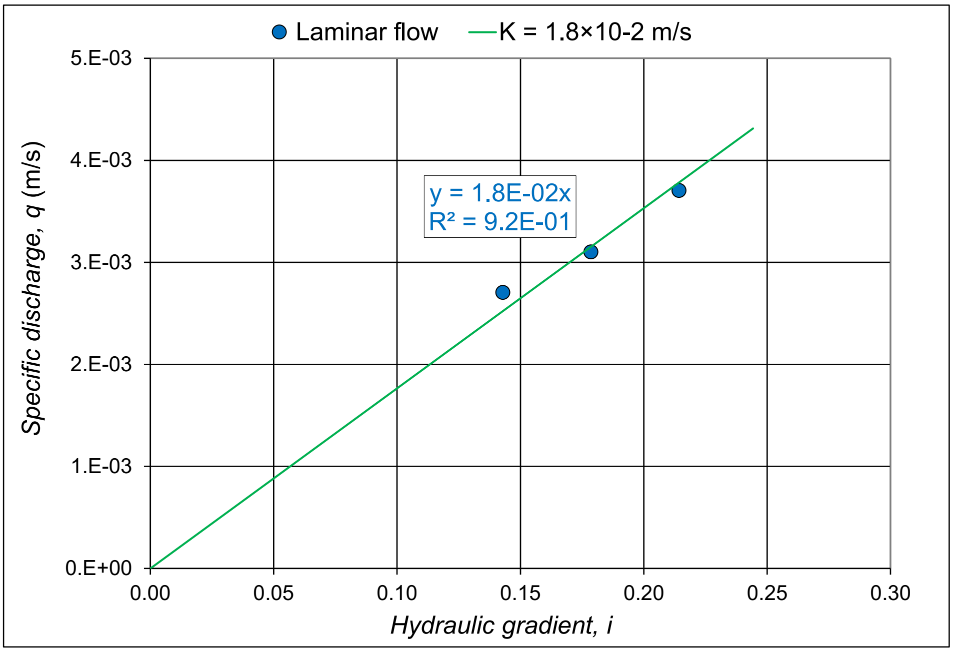

Figure 3.2: Permeameter constant head test data for sample taken from Virovitica aquifer plotted as *q* versus *i*

3.2. Discussion on terminology used in groundwater literature and practice

Terminology used in groundwater literature and practice for characterization of the capacity of a medium to transmit water often cause misunderstandings. One of the most often one is replacing the terms *hydraulic conductivity*, *K* [L/T] or *coefficient of permeability, k* [L/T] with the term *permeability, k* (L^2).

The term *hydraulic conductivity*, *K* [L/T] and to a lesser extent term *coefficient of permeability, k* [L/T] are most frequently used in groundwater literature for denotation of the capacity of a medium to transmit water while the term *permeability*, usually symbolized by the small letter *k* [L^2] is used in the petroleum industry where the fluids of interest are oil, gas and water (**Domenico and Schwartz, 1990**). While hydraulic conductivity characterizes the capacity of a medium to transmit water, permeability characterizes the capacity of a medium to transmit any fluid. Permeability is a property of the porous media only, not the fluid. Therefore using the terms *hydraulic conductivity*, *K* [L/T] or *coefficient of permeability,* [L/T] unambiguously with the term *permeability, k* (L^2) is erroneous and can cause confusion.

Terms *hydraulic conductivity* or *coefficient of permeability* are used specifically for the flow of water through a porous media when dealing with the single water phase. The former is commonly symbolized with the capital letter *K* while the latter is symbolized with the small letter *k*, both in units of L/T (m/s in SI system). Although the majority of the groundwater literature uses the term *hydraulic conductivity*, *K* [L/T] to denote the capacity of a medium to transmit water, the term *coefficient of permeability, k* [L/T] and erroneously *permeability, k* [L^2] are also used. Namely, standards for permeameter tests like the ASTM or ISO standard both have terms *permeability* in their titles. ISO standard CEN ISO/TS 17892-11:2004/AC is titled "Geotechnical investigation and testing - Laboratory testing of soil - Part 11: Determination of permeability by constant and falling head (ISO/TS 17892-11:2004) although within the text the term *coefficient of permeability, k* [L/T] is used. ASTM standard D 2434 – 68 also bears the term permeability in its title "Standard Test Method for Permeability of Granular Soils (Constant Head)" but also uses the term *coefficient of permeability, k* [L/T] within the text. Furthermore, term *permeability* can often be heard in groundwater, civil engineering, geotechnical and agricultural community while having in mind units [L/T], not [L^2].

Another often seen misunderstanding is related to the terms *intrinsic* or *absolute* or *specific permeability, k* [L^2] (m^2 in SI system), which are used in groundwater literature to characterize the property of the porous media only, not the fluid, when porous medium is 100% saturated with a single-phase fluid, which is the case when dealing with groundwater. Although the term *intrinsic permeability, k* [L^2] is often correctly used in groundwater literature, there are cases when notation *permeability, k* [L^2] is used instead or even cases when literature suggests that the term *intrinsic permeability, k* [L^2] could be shortened to the term *permeability, k* [L^2], as usually done in practice.

Groundwater literature and practice in Croatia offers different notations. **Miletić and Miletić (1981)** use the term *coefficient of hydraulic conductivity, K* [L/T] to denote the capacity of a medium to transmit water while they use the term *coefficient of filtration, k* [L^2] to characterize the property of the porous media only, not the fluid. **Mayer, D (1993)** uses term similar to **Miletić and Miletić (1981)** to denote the capacity of a medium to transmit water, i.e. *coefficient of hydraulic conductivity, K* [L/T] and the term *actual permeability, k* [L^2] to characterize the property of the porous media only. **Urumović, K. (2003)** denotes the capacity of a medium to transmit water as *hydraulic conductivity, K* [L/T] and the property of the porous media only, not the fluid, as *intrinsic or specific permeability, k* [L^2] although states that terms *intrinsic or specific permeability* are shorter called *permeability*. **Bačani, A. (2006)** uses similar terms, i.e. *hydraulic conductivity, K* [L/T] to denote the capacity of a medium to transmit water and *intrinsic permeability or permeability, k* [L^2] to denote the property of the porous media only, not the fluid.

In order to avoid confusion and misunderstandings with the petroleum industry it would be of interest for groundwater, civil engineering, geotechnical, and agricultural scientists, engineers and practitioners to use unique terms for the capacity of a medium to transmit water when the fluid of interest is single water phase, i.e. groundwater, and for the property of the porous media only, not the fluid, when porous medium is 100% saturated with a single-phase fluid, i.e. groundwater.

Therefore is suggested, when dealing with the porous medium 100% saturated with a single water phase, i.e. groundwater, to use the term *hydraulic conductivity*, *K* [L/T] to denote the capacity of a medium to transmit water and the term *intrinsic permeability, k* [L^2] to denote the property of the porous media only, not the fluid, since those are correct and most often used terms in groundwater literature.

4. Conclusions

Constant head permeameter tests for hydraulic conductivity of unconsolidated sediments conducted on gravel and sand samples taken from Zagreb alluvial aquifer (Sava basin, Croatia) and Virovitica alluvial aquifer (Drava basin, Croatia) showed substantial differences in values of obtained hydraulic conductivities. Sample taken from the shallow zone of the central part of the Zagreb aquifer near wellfield Velika Gorica contained more fine grained material, about 60% of gravel and some 40% of sand size grains versus more than 90% of gravel and less than 10% of sand size grains contained in the sample taken from the Virovitica alluvial aquifer. Therefore sample taken from the shallow part of the Virovitica alluvial aquifer showed higher value of hydraulic conductivity, in the range of 10^{-2} m/s, while sample taken from the Zagreb aquifer showed a value of hydraulic conductivity in the range of 10^{-5} m/s. Based on previous research it can though be concluded that obtained results are site specific, i.e. strongly dependent on the sampling location. Namely, eastern parts of the Zagreb aquifer tend to have hydraulic conductivities in the range from 10^{-3} to 10^{-5} m/s while western parts have somewhat higher values of *K*, ranging up to 10^{-2} m/s.

Tests were conducted in the laboratory using the ASTM standard D 2434 – 68 and an apparatus which is basically a modification of Darcy's apparatus used in his work on the public fountains of the city of Dijon conducted in 1856. Within this work Darcy conducted the first documented experiment to determine the laws of the water flow through sands. The year 1856 was the year of the birth of groundwater hydrology as a quantitative science and the law he obtained bears his name. Darcy's law is empirical, like Ohm's and Fourier's law. It is also linear, as one of the many that describe physical and chemical processes on earth. The key parameter in groundwater science and Darcy's law, the hydraulic conductivity, *K* is actually the slope of the line which passes through the *q* versus *i* dataset and the origin of a coordinate system. And as long as the plotted data of *q* versus *i* stay on the straight line, the flow is considered to be laminar, and Darcy's law valid. When deviation from the straight line occurs, the flow is considered to be nonlinear and Darcy's law no longer valid. Although the validity of Darcy's law can also be tested by Reynolds number, the *q* versus *i* plot is the only reliable measure to determine whether the flow is linear or nonlinear in a permeameter constant head test.

Although Darcy's law is more than 160 years old, terminology related to parameters describing the flow of water through porous medium still differs in groundwater literature. Terms hydraulic conductivity, *K* [L/T] (m/s in SI system), coefficient of permeability, *k* [L/T] (m/s in SI system), permeability, *k* (L^2) (m^2 in SI system) and intrinsic or absolute or specific permeability, *k* [L^2] (m^2 in SI system) are often unambiguously used, causing misunderstandings both in groundwater literature and practice. One of the most often used unambiguity's are the terms *hydraulic conductivity*, *K* [L/T] or *coefficient of permeability, k* [L/T] and the term *permeability, k* (L^2). The term *hydraulic conductivity*, *K* [L/T] and to a lesser extent term *coefficient of permeability, k* [L/T] are most frequently used in groundwater literature for denotation of the capacity of a medium to transmit a single water phase while the term *permeability*, usually symbolized with the small letter *k* [L^2] is used in the petroleum industry where the fluids of interest are oil, gas and water. Furthermore, permeability is a property of the porous media only, not the fluid. Therefore using these terms unambiguously is erroneous and can cause confusion. Another often misunderstanding comes from the terms *intrinsic* or *absolute* or *specific permeability, k* [L^2] (m^2 in SI system), which are also used to characterize the property of the porous media only, not the fluid, when porous medium is 100% saturated with a single-phase fluid, as for example groundwater. Those terms are, probably due to simplicity, often erroneously shortened to the term *permeability* in groundwater literature and practice.

Therefore is suggested to groundwater, civil engineering, geotechnical, and agricultural scientists, engineers and practitioners to use the term *hydraulic conductivity*, *K* [L/T] to denote the capacity of a medium to transmit water and the term *intrinsic permeability, k* [L^2] to denote the property of the porous media only, not the fluid, when dealing with the porous medium 100% saturated with a single water phase, i.e. groundwater in order to avoid confusion and misunderstandings with the petroleum industry.

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Extended abstract in Croatian

Testovi hidrauličke vodljivosti nekonsolidiranih sedimenata u permeametru sa stalnom razinom i pridružena terminologija

U radu su prikazani laboratorijski testovi hidrauličke vodljivosti nekonsolidiranih sedimenata te je dana rasprava o pridruženim terminima koji se koriste u literaturi i praksi. Uzorci nekonsolidiranih materijala, šljunaka i pijesaka koji su taloženi na dvije istraživane lokacije, zagrebačkom aluvijalnom vodonosniku (Savski bazen, Hrvatska) i virovitičkom aluvijalnom vodonosniku (Dravski bazen, Hrvatska), testirani su u laboratoriju primjenom permeametra sa stalnom razinom. Prikazane su glavne karakteristike eksperimenata i usporedba rezultata s dva istraživana područja. Dana je i rasprava vezana za terminologiju koja se koristi u hidrogeološkoj literaturi za označavanje kapaciteta porozne sredine da provodi vodu, s osvrtom na dvosmislenost najčešće korištenih termina. Termini koji se danas najčešće koriste u hidrogeološkoj literaturi i praksi su hidraulička vodljivost, *K* [L/T] (m/s u SI sustavu) ili koeficijent propusnosti, *k* [L/T] (m/s u SI sustavu), a koriste se specifično za označavanje jednofaznog tečenja vode kroz porozni medij. U dodatku, rasprava je proširena na termine propusnost, *k* [L^2] (m^2 u SI sustavu) odnosno unutarnju, apsolutnu ili specifičnu propusnost, također označavanu kao *k* [L^2] (m^2 u SI sustavu) za porozni medij koji je 100% saturiran s jednofaznim fluidom tj. vodom u razmatranom slučaju, a koji predstavljaju karakteristike isključivo porozne sredine, ne i fluida.

Terminologija koja se koristi u hidrogeološkoj literaturi i praksi za označavanje kapaciteta porozne sredine da provodi vodu često dovodi do nesporazuma. Jedan od najčešćih nesporazuma je zamjena termina *hidraulička vodljivost*, K [L/T] ili *koeficijent propusnosti*, k [L/T] s terminom *propusnost*, k (L^2).

Termin *hidraulička vodljivost*, K [L/T] i u manjoj mjeri termin *koeficijent propusnosti*, k [L/T] najčešće su korišteni termini u hidrogeološkoj literaturi za označavanje kapaciteta porozne sredine da provodi vodu dok se termin *propusnost*, uobičajeno označavan s malim slovom k (L^2) koristi u naftnoj industriji gdje su fluidi od interesa nafta, plin i voda (**Domenico i Schwartz, 1990**). Dok hidraulička vodljivost označava kapacitet porozne sredine da provodi vodu, propusnost označava kapacitet porozne sredine da provodi bilo koji fluid. Propusnost je karakteristika isključivo porozne sredine, ne i fluida. Stoga je korištenje termina *hidraulička vodljivost*, K [L/T] ili *koeficijent propusnosti*, k [L/T] jednoznačno s terminom *propusnost*, k (L^2) pogrešno i može dovesti do nesporazuma.

Termini *hidraulička vodljivost* ili *koeficijent propusnosti* koriste se specifično za označavanje tečenja vode kroz poroznu sredinu u slučaju kada se radi o jednofaznom tečenju. *Hidraulička vodljivost* se obično označava s velikim slovom *K* dok se *koeficijent propusnosti* obično označava s malim slovom *k*, a izražavaju se u jedinicama L/T (m/s u SI sustavu). Iako velika većina hidrogeološke literature koristi termin *hidraulička vodljivost*, K [L/T] za označavanje kapaciteta porozne sredine da provodi vodu, termin *koeficijent propusnosti*, k [L/T] i pogrešno termin *propusnost*, k (L^2) također su u upotrebi. Naime, norme za permeametarske testove kao što je to ASTM norma ili ISO norma koriste termin *propusnost* u svojim naslovima. ISO norma CEN ISO/TS 17892-11:2004/AC nosi naslov "Geotehnička ispitivanja i testiranja – laboratorijska testiranja tla – Dio 11: Određivanje propusnosti primjenom testa sa stalnom i promjenjivom razinom (ISO/TS 17892-11:2004)", iako se unutar samog teksta norme koristi termin *koeficijent propusnosti*, k [L/T]. ASTM norma D 2434 – 68 također nosi termin *propusnost* u svom naslovu „Standardna metoda za testiranje propusnosti zrnastih tala (stalna razina)", ali također koristi termin *koeficijent propusnosti*, k [L/T] unutar samog teksta norme. Nadalje, vrlo često se u hidrogeološkoj, građevinarskoj, geotehničkoj i agronomskoj zajednici može čuti termin *propusnost*, dok se zapravo imaju na umu jedinice [L/T], a ne [L^2].

Sljedeći najčešći nesporazum vezan je uz termine *unutarnja* ili *apsolutna* ili *specifična propusnost*, k [L^2] (m^2 u SI sustavu), koji se u hidrogeološkoj literaturi koriste za označavanje karakteristika isključivo porozne sredine, ne i fluida, kada je porozna sredina 100% saturirana jednofaznim fluidom, kao što je to slučaj kad se radi o podzemnoj vodi. Iako se termin *unutarnja propusnost*, k [L^2] često ispravno koristi u hidrogeološkoj literaturi, ima slučajeva kada se umjesto njega koristi termin *propusnost*, k [L^2], a i slučajeva kada literatura sugerira da se termin *unutarnja propusnost*, k [L^2] skraćeno može zvati *propusnost*, k [L^2], kao što se to često i koristi u praksi.

Hidrogeološka literatura i praksa u Hrvatskoj koriste različite termine. **Miletić i Miletić (1981)** koriste termin *koeficijent hidrauličke provodljivosti*, K [L/T] za označavanje kapaciteta porozne sredine da provodi vodu dok koriste termin *koeficijent filtracije*, k [L^2], za označavanje karakteristika isključivo porozne sredine, ne i fluida. **Mayer, D (1993)** koristi slične termine kao i **Miletić i Miletić (1981)** za označavanje kapaciteta porozne sredine da provodi vodu, tj. *koeficijent hidrauličke provodljivosti*, K [L/T] te termin *stvarna propusnost,* k [L^2] za označavanje karakteristika isključivo porozne sredine, ne i fluida. **Urumović, K. (2003)** označava kapacitet porozne sredine da provodi vodu kao *hidraulička vodljivost*, K [L/T], a karakteristike isključivo porozne sredine, ne i fluida, kao *unutarnja* ili *specifična propusnost*, k [L^2] iako navodi da se termini *unutarnja* ili *specifična propusnost*, k [L^2] kraće zovu *propusnost*. **Bačani, A. (2006)** također koristi slične termine, tj. *hidraulička vodljivost*, K [L/T] za označavanje kapaciteta porozne sredine da provodi vodu i *unutarnja propusnost* ili *propusnost*, k [L^2] za označavanje karakteristike isključivo porozne sredine, ne i fluida.

Kako bi se izbjegli nesporazumi unutar hidrogeološke, građevinarske, geotehničke i agronomske znanstvene i inženjerske zajednice, ali i nesporazumi s naftnom industrijom, bilo bi od interesa da se koriste jedinstveni termini za označavanje kapaciteta porozne sredine da provodi vodu kada je fluid od interesa jednofazni, tj. podzemna voda, i za označavanje karakteristika isključivo porozne sredine, ne i fluida, kada je porozna sredina 100% saturirana jednofaznim fluidom tj. podzemnom vodom.

Stoga se predlaže korištenje termina *hidraulička vodljivost*, K [L/T] za označavanje kapaciteta porozne sredine da provodi vodu i termina *unutarnja propusnost*, k [L^2] za označavanje karakteristike isključivo porozne sredine, ne i fluida, kada se radi o podzemnoj vodi tj. poroznoj sredini 100% saturiranoj jednofaznim fluidom tj. vodom s obzirom da su to ispravni i najčešće korišteni termini u hidrogeološkoj literaturi.

Ključne riječi: hidraulička vodljivost, propusnost, unutarnja propusnost, permeametar, terminologija

Authors contribution

Kristijan Posavec (PhD, Professor, Hydrogeology) provided a theoretical background and discussion on terms used in groundwater literature and practice. **Adriana Kukolja** (Student, Geological Engineering) provided examples of measurements from conducted permeameter test. **Valentina Kocijan** (Student, Geological Engineering) provided examples of measurements from conducted permeameter test.