Determination of the permeability coefficient of unsaturated zone by the method of pouring water into open test pits

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For solving of groundwater contamination issues it is very important to know the geofiltration parameters of unconsolidated rocks of an unsaturated zone which largely predetermine the possibilities and rate of groundwater and confined groundwater contamination. These parameters are not easily determined because of the heterogeneous character of unsaturated zone, which is not fully saturated with water, thus making test pumpings impossible. Along with the not very accurate laboratory method, the method of pouring water into open test pits with the aid of N. S. Nesterov's infiltrometer is used to determine the geofiltration parameters of the mentioned zone.

Experimental field tests revealed that pouring into low-permeability rocks (the permeability coefficient <0.1 m/d) using an infiltrometer with the ratio of standard ring area (1:4) does not form a vertical flow under infiltrometer from the internal ring. The mentioned ratio should be 1:10.

The article also contains the values of permeability coefficients of rocks in unsaturated zones of exposures in the Klaipėda, Šiauliai, Šilutė, Kretinga towns and the Šventoji, Pelyša and Armona rivers, determined with the aid of an infiltrometer.

Keywords: permeability coefficient, Kamenski tube, infiltrometer, unsaturated zone

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INTRODUCTION

Determination of the permeability coefficient of unconsolidated rocks of an unsaturated zone represents one of the more complicated tasks of hydrogeological field tests, because such a zone is not fully saturated with water, what makes test pumpings impossible. The only rather reliable way to determine the permeability coefficient of rocks in the mentioned zone is to employ the method of pourings into test pits with the aid of N. S. Nesterov's infiltrometer. The infiltrometer is composed of two (external and internal) rings with the diameters 0.452 m and 0.226 m and a frame fixing the Mariot's vessels measuring the amount of water permeating into the ground (Fig. 1). The external ring is necessary to prevent the side flows of water permeating from the internal ring, *i.e.* it ensures the vertical flow.

MODIFICATION OF N. S. NESTEROV'S INFILTROMETER

The staff members from the Departament of Hydrogeology and Engineering Geology of Vilnius University performed experimental pourings into differently sized rings of the N. S. Nesterov's infiltrometer (Table 1). It was observed that with increasing the area of the external ring the values of the

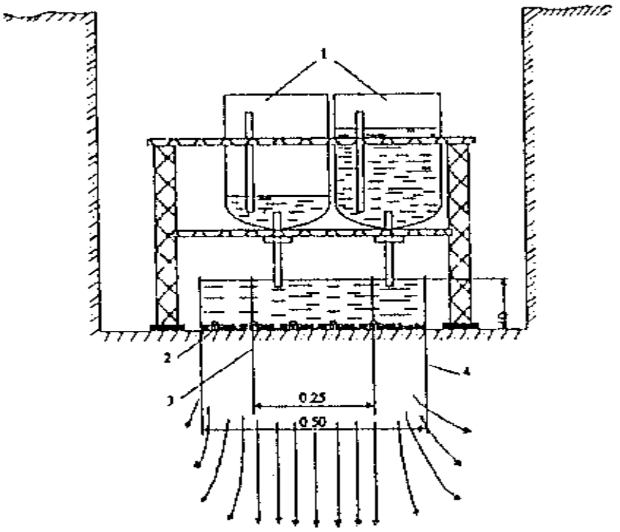

Fig. 1. Scheme of pouring into the test pit (after N. S. Nesterov): *1* – Hariot's vessels, *2* – shingle layer, *3, 4* – internal and external rings

1 pav. Įpylimo į šurfą schema (pagal N. S. Nesterovą): *1* – Marioto indai, *2* – žvirgždo sluoksnis, *3, 4* – vidinis ir išorinis žiedas

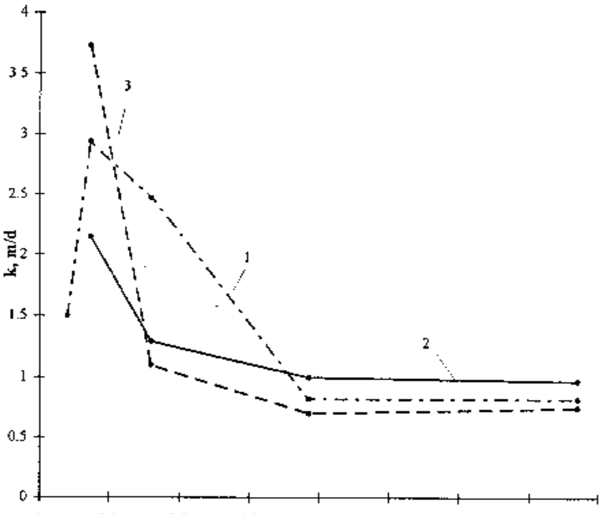

Fig. 2. Dependence of the permeability coefficient on the external ring. The area of internal ring in graph: *1* – 0.0075 m^2, *2, 3* – 0.04 m^2

2 pav. Filtracijos koeficiento priklausomybės nuo išorinio žiedo ploto grafikas. Vidinio žiedo plotas: *1* – 0,0075 m^2; *2, 3* – 0,04 m^2.

permeability coefficient tended to decrease to the stable values.

Figure 2 illustrates the dependence of the permeability coefficient (k) on the area of the external ring. These values were obtained by pouring into fine-grained dusty sands on the banks of the Pelyša river and into sandy loams in Šiauliai environs.

The results of experiment demonstrated that the standard external ring of N. S. Nesterov's infiltrometer (Table 1, № 4) did not contribute to the formation of absolutely vertical flow within the internal ring (№ 2). Part of the flow streams sideways, what accounts for 1.5–2 times higher values of the permeability coefficient.

The area of the external ring which would facilitate the formation of the vertical flow within the internal ring must be no less than 0.385 m^2. In other words, the ratio between the internal and external rings must be 1:10 instead of 1:4 (as in the standard infiltrometer). The test also demonstrated that the diameter of the internal ring should be no less than 0.04 m^2.

Table 1. **Ring size of upgraded N. S. Nesterov's infiltrometer**

1 lentelė. **Patobulinto N. S. Nesterovo infiltrometro žiedų matmenys**

Ring number	Ring radius	Ring area, m^2
1	0.041	0.0075
2	0.113	0.040
3	0.152	0.073
4	0.226	0.160
5	0.350	0.385
6	0.495	0.770

Otherwise the dependence values are not very representative (Fig. 2, graph 1). The standard rings of N. S. Nesterov's infiltrometer may be used only in deposits with the permeability coefficient higher than 0.2 m/d.

Permeability coefficient calculation method

The common methods include the unsettled and settled geofiltration test and filtration parameters schemes of calculating. Following the first scheme it is important that the poured water level in both rings would be stable. In the second case the Hariot's vessels are disconnected, and the water level sinking speed in the internal ring is measured.

The vertical water soakage (percolation) under the infiltrometer is described by the equation (Nilsen, Van Genuchten, Biggar, 1986):

$$\mu \frac{dl}{dt} = \frac{k\ (h_o + l + h_k)}{l}, \tag{1}$$

where l is the water soaking depth, h_o is the height of water column in the internal ring, h_k is the height of the capillary zone.

The methods of processing the data of pourings into the infiltrometer, based on this equation were suggested by N. N. Bindeman and N. N. Verigin (Кац, Шестаков, 1992). The shortcoming of these methods is the necessity to know the depth of the percolated water column. It may be determined in a test pit, yet this way of identification is not always accurate. V. V. Bedov and V. M. Shestakov have suggested to express the percolation depth through the volume of percolated water W = μωl (μ is the coefficient of water output, ω is the surface area of the infiltrometer) and *dl/dt* of equation (1) is replaced by v_s/μ (v_s is the water percolation rate). After rearrangement of equation (1) (Бедов, 1971) we have:

$$v_s = k + \frac{k\ (h_o + h_k) l \mu \varpi + W}{W}. \qquad (2)$$

This equation implies that in the graphic expression of pouring data under stable pressure (the height of the water column in the infiltrometer is $h_o = const$) $v_s \cdot W = A + kW$ (Fig. 3), where test data are plotted on a straight line, the numerical value of the straight line direction coefficient C is equal to the permeability coefficient k. Taking the values of the two points on the straight line we get:

$$k = C + \frac{k\ (v \cdot W_2) - (v \cdot W)_1}{W_2 - W_1}. \qquad (3)$$

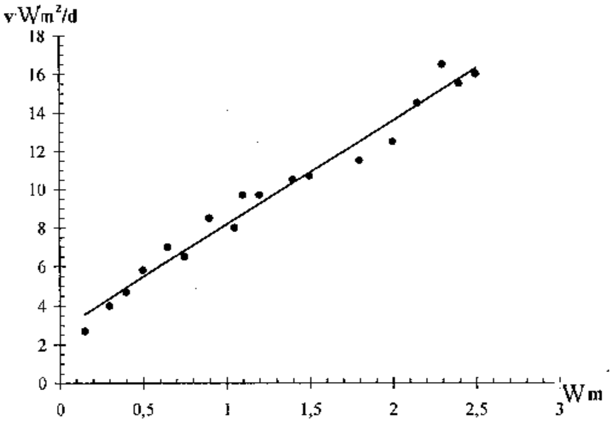

Fig. 3. Graph of dependence of vw on w
3 pav. vW nuo W prikausomybės grafikas

RESULTS

It should be pointed out that geofiltration properties of formations in an unsaturated zone have been very little investigated. The author has performed more than 300 pourings into test pits at various depths in Lithuanian and Latvian territories (in the environs of the Klaipėda, Šiauliai, Kretinga and Šilutė towns and in the valley exposures of the Šventoji, Pelyša, Armona, Gauja and Atmata Rivers. The obtained results imply that the unsaturated zone of the mentioned regions in terms of lithology is very heterogeneous, resulting in the diversity of filtration capacity values (Table 2). There are cases when in a segment of 20 cm the permeability coefficient changes even 3 times, *e.g.*, in Klaipėda environs in an hour water percolated to the depth of 0.2 m in loam, whereas the permeability coefficient changed three times (k_1 = 1.37 m/d, k_2 = 0.78 m/d, k_3 = = 0.44 m/d) (Dobkevičius, Klizas, 1994).

In the Armona River exposure, pourings were performed in five planes at different depths. The planes were spaced at 40–50 cm (Fig. 4). The values of the permeability coefficient at different depths were from 1.1 m/d to 8.4 m/d. A wide range of variations in small intervals of a section implies that water pourings into test pits should be performed at a different depth. This is the only way to find out the geofiltration properties of rocks in unsaturated zone and on the basis of the actual rate of water flow and straight lines of functional dependence $v_k \cdot W = f(W)$ graphs to determine the thickness of interlayers with different permeability.

When a section of the unsaturated zone is composed of heterogeneous thin layers, one water pouring helps to determine the permeability coefficient of only one layer with the lowest permeability. This is illustrated in Fig. 5 (for example, in the case of water percolating into the rock at a considerably greater depth than in the underlying 3d plane). However, the water percolating from the 2d plane reached the 3d plane, and the permeability coefficient decreased, whereas in deeper layers it became stable.

We may draw a conclusion that the flow from the second plane leans upon the less permeable and well cemented sandstones and takes a sideway course with a stable discharge which, taken as a starting point, yields an incorrect value of the permeability coefficient. Moreover, judgements made on the rates of filtration lead to overestimation of percolation depth. This circumstance was tested in laboratory with different sand samples. In the first stage, on the basis of Kamenski's scheme of unsettled geofiltration (Kamenski tube), the values of the permeability coefficient of these samples were determined to be 24 and 168 m/d. The next step included water filtration through one layer composed of equal portions of sand samples. In the first case the sand with better permeability lay in the lower part and in the second in the upper part of the layer. The values of the permeability coefficient were 25 and 34 m/d, respectively. The ratios of the interlayers were set to 2:8 and 8:2. In the first case the value of the permeability coefficient was 26 m/d and in the secon 28 m/d. It is obvious that the inter-

Table 2. **Values of the permeability coefficient for lithological varieties of rocks of unsaturated zone at a water temperature of 15 °C**
2 lentelė. **Aeracijos zonos uolienų atmainų filtracijos koeficiento reikšmės esant 15°C vandens temperatūrai**

№	Lithological composition of rocks	Value of permeability coefficient																	
		Klaipėdos r.			Šiaulių r.			Šilutės r.			River Šventoji			River Armona			River Pelyša			average
		min	max	med.	min	max	med.	min	max	med.	min	max	med.	min	max	med.	min	max	med.	
1.	Coarse-grained sand										24.0	41.0	31.0							31.0
2.	Medium-grained sand				20.0	40.0	30.0	15.0	22.4	18.7	15.3	20.5	17.6							22.1
3.	Fine-grained sand	2.5	18	10	2.5	10	4.5	0.6	14.7	7.6	1.5	7.0	5.5	1.4	7.6	4.0				6.3
4.	Dusty sand	2.0	5.0	3.3																3.3
5.	Mixed composition sand	0.2	3.0	1.5	0.03	2.0	0.5	3.9	9.0	6.4										2.8
6.	Sand with organics							0.05	3.9	2.0										2.0
7.	Sandstone													1.8	8.4	5.7				5.7
8.	Loam	0.5	2.0	1.0	0.3	1.5	0.7													0.85
9.	Aleurolite sandy							0.16	3.9	2.0							0.34	2.35	1.34	1.7
10.	Aleurolite				0.03	0.2	0.1										0.08	0.12	0.11	0.1
11.	Peat							0.08	1.25	0.7										0.07
12.	Clay							0.02	0.07	0.04										0.04

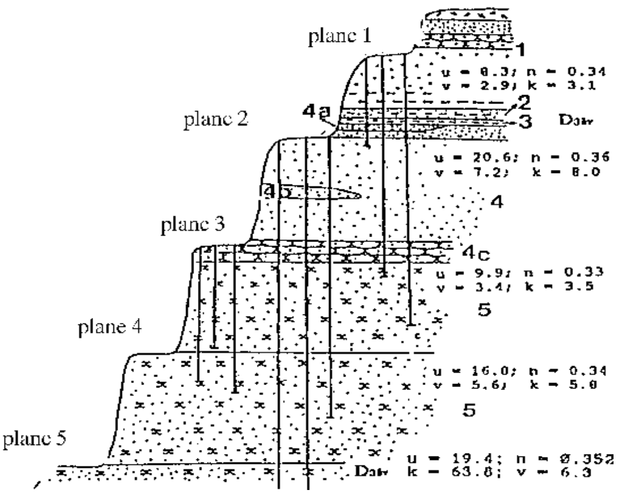

Fig. 4. Lithological composition, physical and hydrodynamic parameters obtained by pouring performed on different planes of the right slope of the Armona River valley. *1* – fine-grained sand, clayey and cemented in the lower part; *2* – fine-grained and thin-grained sand; *3* – clay; *4* – fine-grained sand; *4a* – grey; *4b* – limonitic; *4c* – cemented; *5* – weakly cemented sandstone. Vertical lines – maximal depths of infiltration; numbers above them – pouring points

4 pav. Uolienų litologinė sudėtis, fiziniai ir hidrogeodinaminiai parametrai nustatyti pagal įpylimų duomenis, atliktus skirtingose dešiniojo Armonos upės šlaito plokštumose: *1* – smulkiagrūdis smėlis, apatinėje dalyje molingas, sucementuotas; *2* – smulkiagrūdis ir itin smulkiagrūdis smėlis; *3* – molis; *4* – smulkiagrūdis smėlis (*a* – pilkas, *b* – limonitizuotas, *c* – sucementuotas); *5* – silpnai sucementuotas smiltainis. Vertikalios linijos – maksimalūs infiltracijos gyliai; skaičiai virš jų – įpylimo numeris

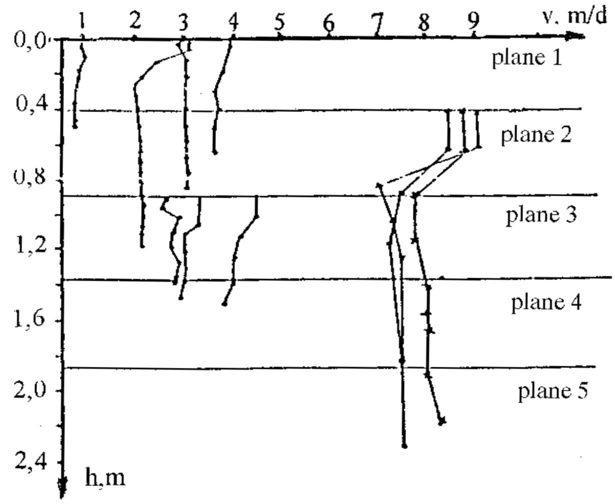

Fig. 5. Percolation rates of pourings at different depths of the slope of the Armona River valley

5 pav. Įpylimų sunkimosi greitis įvairiuose Armonos upės slėnio šlaito gyliuose

layer with the permeability coefficient 168 m/d produced no influence on the permeability of the whole layer in general.

CONCLUSIONS

1. To perform pourings into low-permeability rocks of unsaturated zone (with the permeability coefficient > 0.2 m/d), the ratio between the external and internal rings of N. S. Nesterov's infiltrometer should be 1:10 instead of 1:4. Otherwise the permeability coefficient is overstimated from 1.5 to 2 times.

2. Rocks of the unsaturated zone of NW Lithuania are very heterogeneous. The values of the permeability coefficient vary from 0.04 to 31 m/d.

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AERACIJOS ZONOS UOLIENŲ FILTRACIJOS KOEFICIENTO NUSTATYMAS VANDENS ĮPYLIMŲ Į ŠURFUS METODU

Santrauka

Vienas pagrindinių hidrogeologinių uždavinių yra uolienų geofiltracinių savybių teisingas nustatymas. Geofiltraciniai parametrai yra būtini sprendžiant įvairius ūkinius klausimus: požeminio vandens panaudojimą, apsaugą nuo užteršimo, jų eksploatacijos įtaką gamtos aplinkai bei įvairiems inžineriniams statiniams ir t. t. Reikia pažymėti, kad ypač sunku nustatyti aeracijos zonos uolienų optimalius geofiltracinius parametrus, kadangi jų negalima gauti pagal tiriamųjų išpumpavimų duomenis. Tam tikslui naudojami laboratoriniai metodai, skaičiavimai pagal empirines formules ir vandens įpylimai į šurfus. Tačiau daugelį šių metodų teorinio pagrindimo ir panaudojimo klausimų dar reikia papildomai analizuoti ir tobulinti.

Eksperimentiniais tyrimais nustatyta, kad atliekant vandens įpylimus į silpnai laidžias uolienas, kurių filtracijos koeficientai yra mažesni negu 0,2 m/d, N. S. Nesterovo infiltrometro vidinio ir išorinio žiedo plotų santykis 1:4 nesuformuoja vertikalaus srauto iš vidinio žiedo, todėl gaunamos 1,5–2 kartus didesnės filtracijos koeficiento reikšmės. Norint gauti realias reikšmes, reikia atlikti įpylimus, kai žiedų ploto santykis yra 1:10.

Litologiniu atžvilgiu šiaurės vakarų ir rytų Lietuvos (Šiaulių, Klaipėdos, Kretingos, Šilutės, Ukmergės, Anykščių rajonai) aeracijos zonos uolienos yra labai nevienalytės. Tai nulemia ir filtracinių savybių kaitą tiek plane, tiek profilyje. Vandens įpylimų į šurfus rezultatai rodo, kad filtracijos koeficiento vertės svyruoja nuo 0,04 iki 31 m/d.

Миколас Добкевичюс

ОПРЕДЕЛЕНИЕ КОЭФФИЦИЕНТА ФИЛЬТРАЦИИ ПОРОД ЗОНЫ АЭРАЦИИ МЕТОДОМ НАЛИВОВ ВОДЫ В ШУРФЫ

Резюме

Одной из основных задач гидрогеологии является правильное определение фильтрационных свойств пород. Геофильтрационные параметры необходимы при решении самых разнообразных хозяйственных задач, таких как региональное использование подземных вод, их охрана от загрязнения, влияние эксплуатации инженерных сооружений и т. д. При этом особенно сложно определить фильтрационные параметры пород зоны аэрации, так как они не могут быть определены опытными откачками. Для этих целей применяются лабораторные методы, расчеты по эмпирическим формулам и наливы воды в шурфы. В то же время многие вопросы теоретического обоснования и практического применения этих методов нуждались в дополнительных разработках и анализе.

Экспериментальными наблюдениями установлено, что при наливах воды в слабопроницаемые породы, коэффициенты фильтрации которых ниже 0,2 m/d, соотношение площадей внутреннего и внешнего колец (1:4) инфильтрометра Н. Ц. Нестерова не обеспечивает вертикальности потока из внутреннего кольца, в результате чего получаемые значения коэффициентов фильтрации в 1,5–2 раза выше реальных. Реальные значения можно получить, если указанное соотношение колец будет 1:10.

В литологическом отношении породы зоны аэрации северо-западной и восточной частей Литвы (Шяуляйский, Клайпедский, Кретингский, Шилутский, Укмергский, Аникщяйский районы) очень неоднородны. Это определяет высокую изменчивость фильтрационных свойств пород как в плане, так и в разрезе. Результаты наливов воды показывают, что значения коэффициентов фильтрации пород в этой зоне изменяются от 0,04 до 31 м/сут.