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THE STUDY ON THE IRREGULARITY OF WATER COLLECTION AND DISTRIBUTION BY POROUS PIPES IN FREE-FLOW WATER MOVEMENT

[1]**Progulny V.,** D.Sc., Professor,
varkadia@ukr.net, ORCID: 0000-0001-8310-3823
[1]**Grachov I.,** Senior Lecturer,
giawork@ukr.net, ORCID: 0000-0002-4173-4452
[2]**Bulhakov R.,** PhD,
od_va_kaf_rao@ukr.net, ORCID: 0000-0002-8825-718X
[2]**Frolov A.,** Senior Instructor,
sanec418@ukr.net, ORCID: 0000-0002-0941-4299
[1]*Odessa State Academy of Civil Engineering and Architecture*
4, Didrikhson str., Odessa, 65029, Ukraine
[2]*Odesa Military Academy*
10, Fontanska doroga str., Odessa, 65009, Ukraine

Abstract. One of the main utilities used to obtain drinking water in households and drinking water supply in towns are filters with drainage distribution and diversion systems in their main structural elements. The filters are equipped with porous pipes for distributing and collecting water to increase efficiency and reliability. Therefore, obtaining reliable methods for their calculation is of scientific and practical interest.

The article notes that water in distribution and collection pipelines moves with a variable flow rate along the way. Moreover, the inflow or outflow of water depends on the pressure variable along the length of the pipe. If the movement is free-flowing, it depends on the variable water level. While for porous pipes, this movement is continuous.

The subject of fluid moving with a variable flow rate has been studied by many authors; however, the dependences obtained in those cases mainly concerned perforated pipelines and open trays.

The authors study the operation of a porous pipe under the conditions of free-flow movement, which is described by two equations, the movement of fluid inside the pipe and the movement of fluid through the pipe's walls. The article indicates the complexity of this problem. Namely, the fact that these equations are interconnected. That is, the fluid flow through the pipe walls depends on the depth of the water layer in the pipe, which is determined by the equation of motion inside the pipe. Similarly, the law of depth change is defined, particularly by the laws of the inflow.

A mathematical model was obtained during the investigation of the uneven distribution and collection of water by a porous pipe. Based on this model, an approximate calculation method was developed, which makes it possible to get the value of the average flow depth in the pipe from the critical depth of water installed at the end of the pipe. To simplify the calculations, the article gives the corresponding nomograms.

The validation of the model was carried out on an experimental setup. The analysis of the experimental data showed good correspondence to the calculation results performed according to the approximate method, i. e. the deviation of the flow depth in the middle section does not exceed 1.5%.

Keywords: porous pipe, free-flow movement, filters, collection (outflow) of water, hydraulic calculation.

Introduction. One of the priority tasks of the state is to provide settlements with high-quality drinking water, which is established by the Law of Ukraine "On Drinking Water and Drinking Water Supply". Ukraine wants to adjust its regulatory documents on drinking water supply with regulatory acts of the European countries [1]. It requires an increased efficiency of water treatment facilities and improvement of both the construction and hydraulic calculation methods [2].

Usually, to obtain water of the required quality, it is necessary to connect with the technological scheme of water purification in filtering facilities. At water treatment plants, filters are the most expensive and complex structures. The quality of the water supplied to the consumer, the practical productivity, and even the economic indicators of the entire station depend on them [3, 4]. In recent years, systems of porous pipes have been widely used in drainages and flushing water removal systems to intensify the work of fast filters [5, 6]. Therefore, improving the methods of hydraulic calculation and optimization is a vital task.

The analysis of recent research and publications. Water in porous distribution and collection pipelines (channels) moves with a variable flow rate, so it is impossible to describe the movement using the usual Bernoulli equation. Moreover, the inflow or outflow of water depends on the pressure variable along the length of the pipe. If the movement is free-flowing, it depends on the variable water level. The inflow or outflow of water can be continuous (if the pipe wall is porous) or discrete.

Many authors have studied fluid movement patterns with a variable flow rate. Numerous studies concern the movement of fluid with a variable flow path in perforated pipelines and open trays [7-12].

The research conducted by G.A. Petrov is devoted to the movement of fluid with a variable flow rate. From the equation of the amount of flow, he obtained the equation for a pressureless prismatic channel [13]:

$$\frac{2a_k Q}{gw^2}dQ = \frac{a_k Q^2}{gw^2}\frac{\partial w}{\partial h}dh + dh + dx\left(i_0 - i_f\right) = 0 \tag{1}$$

The closest to this question is studying fluid movement in channels covered by porous plates [14].

It appeared that the equations for the dynamics of variable mass differ from those for constant mass. It happens mainly because of the loss of energy due to the so-called "mixing" of masses or vortex resistance. During the flow of liquid these losses, in many cases, reach values that significantly exceed the usual losses due to internal friction. Vorticity is formed during outflow or inflow of water when the liquid is moving with a variable flow rate in perforated distribution pipes. This is caused by turbulent jets. It is these vortices that provide additional support to the main mass of the moving liquid. When collecting or draining water through porous pipes, vortices may also form at the boundary between the main flow and the porous layer. However, their size will be smaller compared with perforated pipes, since the pore sizes are much smaller than the diameter of the holes in the collection and distribution pipes. Accordingly, the speed of water entry (exit) is much lower than that of the transit flow.

The purpose and objectives of the research. The article is dedicated to the study of the porous pipes operating in pressureless movement. The task of these studies is to obtain an approximate method of calculation when collecting and draining water.

Research materials and methods. Let us consider a porous pipe (Fig. 1) with a constant radius R laid with a slope i_0 in the direction of the flow.

A decline curve is created in the pipe and the depth of this flow (h) will vary along its length, while the water level outside the pipe (H) is constant. Inflow of water to the pipe can occur in two zones, namely in the area below the water level in the pipe ($z \leq h$), where the specific inflow is q_1, and in the area above the water level in the pipe – inflow q_2. The mathematical model of the work of a porous pipe is defined by two main equations [15]:

1) movement of liquid inside the pipe;

2) fluid movement through the pipe walls.

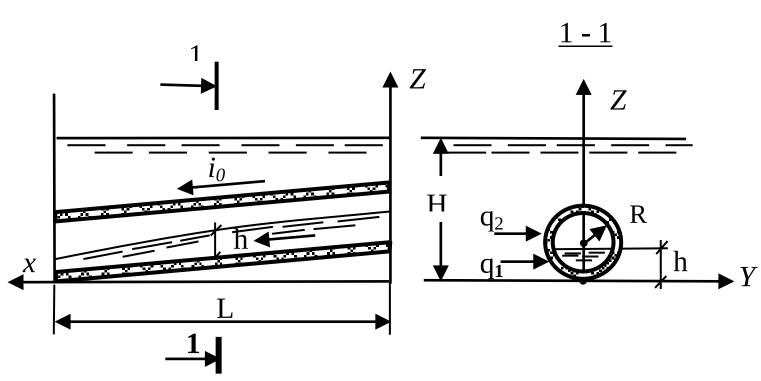

Fig. 1. Scheme of collecting water using a porous pipe

These equations are interconnected, i.e., the flow of liquid through the walls of the pipe depends on the movement of the liquid in the middle of the pipe with a layer (h), which is variable in length. Similarly, the law of change of depth h(x) is determined, in particular, by regularities of the water inflow.

Consider the equation defining the internal flow.

The liquid inside the pipe moves with a change in flow rate along its length, namely at the beginning of the flow (x = 0), flow rate Q = 0, and at the end (x = L) – Q = Q_k. Thus, movement with a variable flow rate in a prismatic channel is considered. To describe such a movement, the equation obtained by G. L. Petrov (1) was chosen, since it was obtained using a minimum of assumptions, and the results were verified experimentally.

If, for the sake of simplification, the losses of frictional pressure along the length are neglected, then the equation of motion in complete differentials is written in the following way:

$$\frac{\alpha}{g} d\left(\frac{Q^2}{\omega}\right) + \omega dh = \omega i_0 dx, \tag{2}$$

Q, ω is the flow rate and cross-sectional area of the flow at a distance *x* from its beginning;

h is the depth of the flow; i_0 is the slope of the pipe; α is the Coriolis coefficient; *g* is the acceleration of free fall.

The boundary conditions of equation (2) are the following:

$$\left.\begin{array}{c} x = 0,\ \ Q = 0,\ \ h = h_1 \\ \hline x = L,\ \ Q = Q_k,\ \ h = h_k \end{array}\right\}. \tag{3}$$

In the integral form the equation (2) looks the following way:

$$\frac{\alpha Q^2}{g\omega} + \int \omega dh + \tilde{C} = i_0 \int_0^x \omega dx, \tag{4}$$

$\tilde{C}$ – is the constant of the integration.

To integrate (4), it is necessary to have the dependence of the flow cross-sectional area on its depth *h*. To integrate (4), it is necessary to have the dependence of the flow cross-sectional area on its depth h. The volume of liquid in the pipe from the initial cross-section to the cross-section *X* is determined by the integral on the right-hand side of (4). This volume can be roughly calculated from the average cross-section of the stream, i.e.:

$$\int_0^x \omega dx \cong \omega_{cp} x. \tag{5}$$

The dependence *ω(h)* is also needed to calculate ω_{cep}.

As the analysis and performed calculations showed, the dependence *ω(h)* can be represented with sufficient accuracy by a power function:

$$\overline{\omega}(\overline{h}) = \beta \overline{h}^{\kappa}, \tag{6}$$

β and *κ* are empirical coefficients calculated by the method of least squares;

$\overline{w} = w/R^2,\ \overline{h} = h/R$ – is the dimensionless area of the stream and its depth.

Satisfactory approximation of formula (6) is achieved by using two curves: at $h \leq R$ – $\beta_1 = 1.68$, κ_1 = 1.47 (the maximum deviation of calculated data from formula (6) does not exceed Δ = 3.9%, and the relative root mean square deviation – σ = 0.026).

Substituting (6) into (4), we have the following result after the integration:

$$\frac{\alpha Q^2}{g\omega} + \frac{\beta}{\kappa+1}h^{\kappa+1} + \tilde{C} = i_0\beta\frac{h_1^{\kappa} + h^{\kappa}}{2}x\,. \tag{7}$$

To determine $\tilde{C}$ we use the first boundary condition from (3): $x=0,\ Q=0,\ h=h_1$. Then

$$\tilde{C} = -\frac{\beta}{\kappa+1}h_1^{\kappa+1}, \tag{8}$$

where:

$$\frac{\alpha Q^2}{g\omega} + \frac{\beta}{\kappa+1}(h^{\kappa+1} - h_1^{\kappa+1}) = i_0\beta\frac{h_1^{\kappa} + h^{\kappa}}{2}x\,. \tag{9}$$

Let's include the coefficient $\kappa_h = h_1/h_\kappa$, which determines the ratio of the depths of the stream at the beginning and at the end. Then, using the second boundary condition from (3) – $x = L,\ Q = Q_\kappa,\ h = h_\kappa$, we obtain:

$$\frac{\alpha Q^2}{g\omega_\kappa^2 h_\kappa} + \frac{1}{\kappa+1}(1 - \kappa_h^{\kappa+1}) = \frac{i_0 L}{2h_\kappa}(1 + \kappa_h^{\kappa})\,. \tag{10}$$

In equation (10), the coefficient κ_h is a function of two dimensionless parameters. The first of them determines the ratio of the doubled velocity pressure at the end of the stream to its depth:

$$A_1 = \frac{\alpha Q_\kappa^{\ 2}}{g\omega_\kappa^2 h_\kappa} = \frac{\alpha V_\kappa^{\ 2}}{g h_\kappa}, \tag{11}$$

and the second parameter determines the flow geometry:

$$A_2 = \frac{i_0 L}{2h_\kappa}\,. \tag{12}$$

Then equation (10) can be represented as follows:

$$A_1 + \frac{1}{\kappa+1}(1 - \kappa_h^{\kappa+1}) = A_2(1 + \kappa_h^{\kappa}) \tag{13}$$

or in a form convenient for iterative calculations:

$$\kappa_h = \left\{1 - \left[A_2(1 + \kappa_h^{\kappa}) - A_1\right](1+\kappa)\right\}^{\frac{1}{\kappa+1}}. \tag{14}$$

When $h>R$ $\kappa=1$, the equation for κ_h is simplified:

$$\kappa_h = \sqrt{(A_2 - 1)^2 + 2A_1} - A_2\,. \tag{15}$$

By determining the K_h coefficient, you can find the average flow depth in the pipe. Thus, an approximate method of calculating for porous pipes was obtained, which allows to determine the depth of the flow in the middle cross-section and to calculate the inflow along this cross-section. For this, it is not necessary to know the law of change of depth inside the pipe, but only the parameters of the flow at its end (parameter A_1) and the geometry of the channel (A_2). Then, by determining the ratio of the depths of the stream at the beginning and at the end, you can find the depth of the stream in the middle section.

In the case of free flow of water from the end section of the pipe, a depth equal to the critical depth is set in it [16]. This depth, which corresponds to the minimum specific flow energy for round pipes is calculated by the following formula [17]:

$$\frac{h_{кр}}{R} = 0{,}844\left(\sqrt{\frac{\alpha}{g}}\frac{Q}{R^{2,5}}\right)^{0{,}511}, \tag{16}$$

valid upon fulfillment of the following conditions:

$$0{,}0023 < \sqrt{\frac{\alpha}{g}}\frac{Q}{R^{2,5}} < 4{,}53\,. \tag{17}$$

Research results. To simplify the following calculations the Fig. 2 shows the *h (Q,R)* dependence graph. The Fig. 3 is a graph for calculating the A_1 parameter. The Fig. 4 shows the nomograms for calculating the ratio of flow depths in the pipe at the beginning and at the end of κ_h for the cases $h \le R$ and $h>R$.

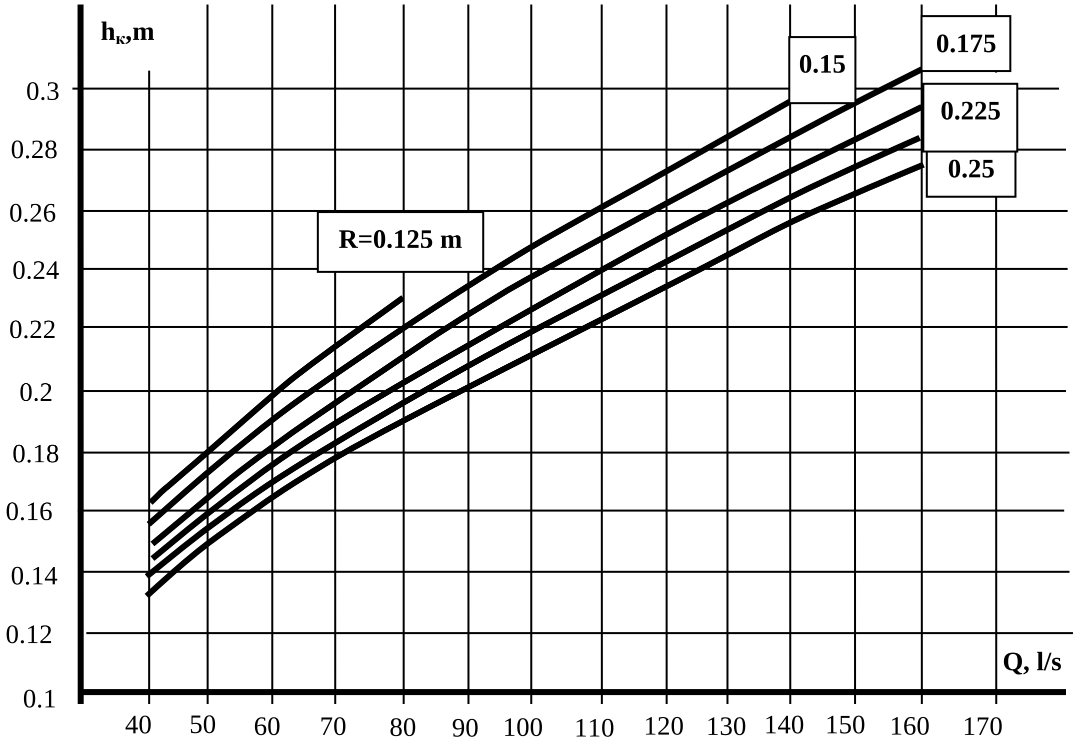

Fig. 2. Graph for determining the critical flow depth

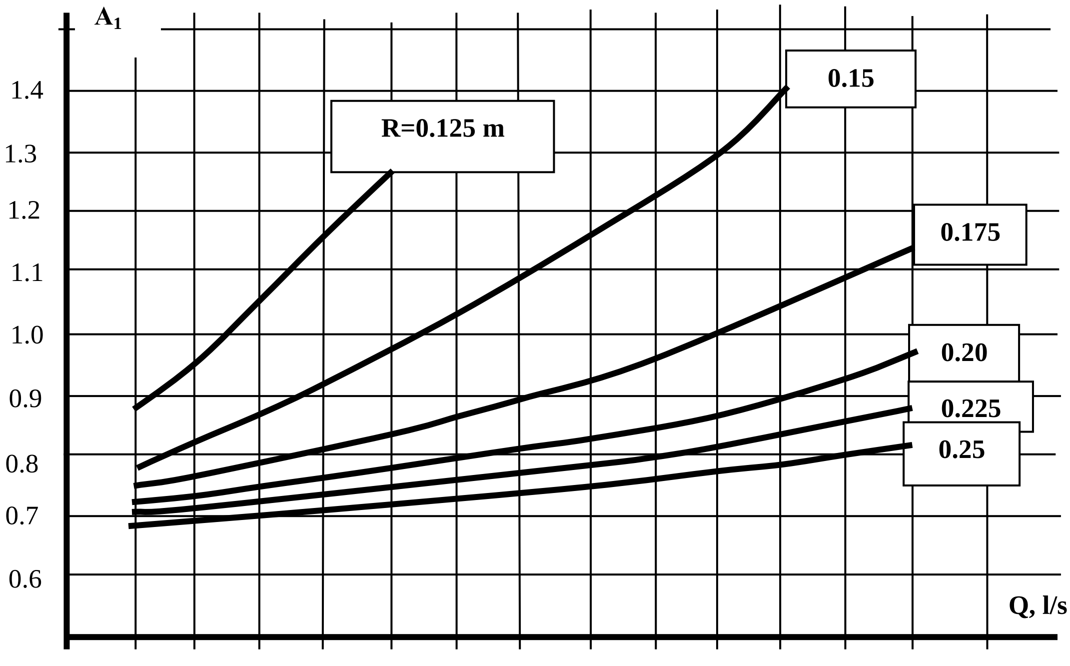

Fig. 3. Graph for calculating parameter A_1

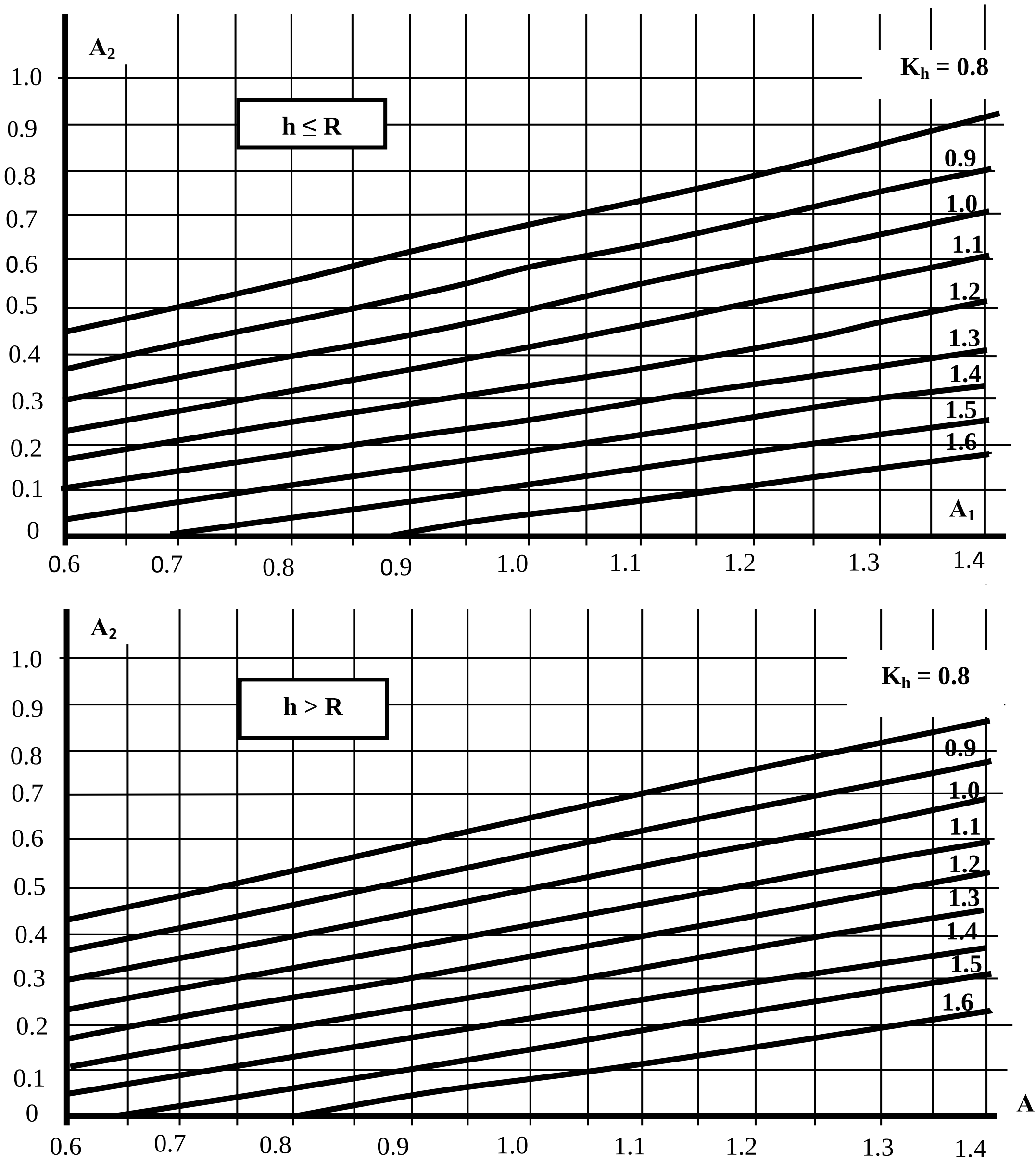

Fig. 4. Graph of determination of K_h for cases $h \le R$ & $h > R$

The order of calculations using Fig. 2 – 4 is the following:

1. According to the specified radius of the pipe and the calculated flow rate according to Fig. 2, one can determine the critical depth at the end of the pipe $h_{кр}$, and according to Fig. 3 parameter A_1 can be determined.

2. A_2 is calculated by formula (12), then using the nomogram in Fig. 4 κ_h is determined, after that the average depth of the flow is found.

The validation of the model was carried out on an experimental setup which includes a porous polymer concrete pipe with an outer diameter of 150 mm, a length of 1000 mm, a wall thickness of 20 mm, which was installed in a tank with a height of 2 m and a diameter of 1.2 m.

On one side, the porous pipe was connected by means of a flange with a 120 mm diameter outlet pipe, and on the other end, it was closed with a blank plug.

5 piezometers were installed in the pipe with a step of 200 mm to measure the depth of the flow along its length. Water was supplied to the installation using a pump.

Analysis of the graph (Fig. 5) shows a good correspondence between the experimental data and the results of the calculation performed according to the approximate method. That is, the deviation of the flow depth in the average cross-section obtained experimentally from the calculated data does not exceed 1.5%. This allows us to conclude that the developed approximate method of calculating porous pipes is reliable.

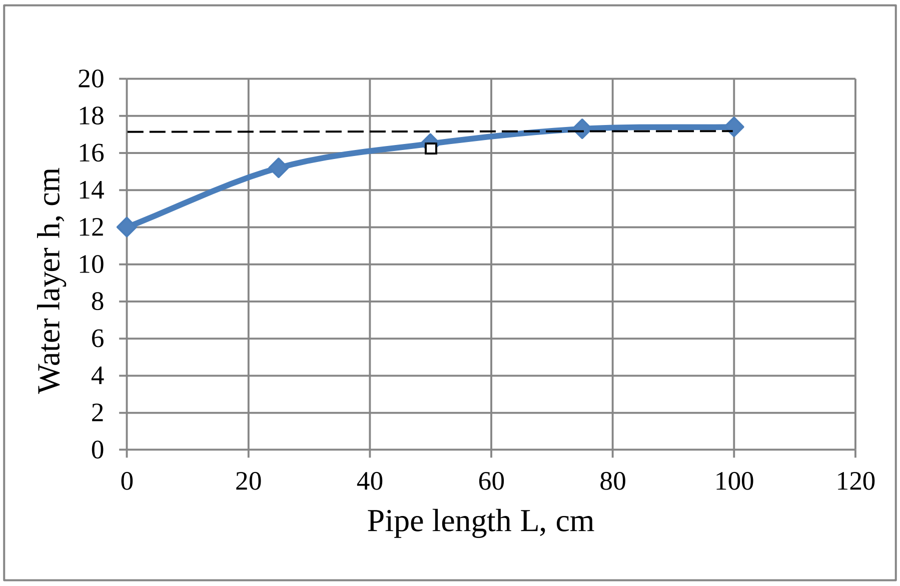

Fig. 5. Change in the flow depth in the pipe:
◆ – experimental data; □ – – calculation results;
---- – average flow depth obtained from
experimental data

Conclusions:

1. It is shown that to describe the operation of a porous collection pipe, it is necessary to use the equations of fluid movement in the pipe and fluid movement through the pipe walls at the same time, since these equations are interconnected.

2. To describe the movement of liquid in the pipe, the G. A. Petrov equation was used, the conclusion of which was made with a minimum number of assumptions, and which was verified experimentally. It is shown that when collecting water through a porous pipe, the projection of the speed of the connecting flow onto the direction of the main flow can be accepted $\theta=0$. In this case, the equation of motion is simplified, however, in this case, it will not be possible to integrate it. Therefore, in order to obtain the engineering method of calculations, it was necessary to neglect frictional pressure losses along the length of the flow for pressureless movement of water in the pipe.

3. To integrate the obtained equation (2), the dependence of the flow area in the pipe on the depth was approximated by the static formula (6), the coefficients of which were determined by the method of least squares. In addition, the ratio of depths at the beginning and at the end of the flow is introduced. The iterative formula (13) was obtained to calculate the ratio.

4. The procedure for calculating flow depths in the pipe has been developed. This makes it possible to determine the depth at the beginning and middle of the pipe with a known depth at the end (assumed equal critical depth).

5. The task of further research is to check the method of calculation of porous pipes in production conditions.

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ДОСЛІДЖЕННЯ НЕРІВНОМІРНОСТІ ЗБОРУ ТА РОЗДАЧІ ВОДИ ПОРИСТИМИ ТРУБАМИ В УМОВАХ БЕЗНАПІРНОГО РУХУ

[1]**Прогульний В.Й.,** д.т.н., професор,
varkadia@ukr.net, ORCID: 0000-0001-8310-3823
[1]**Грачов І.А.,** ст. викладач,
giawork@ukr.net, ORCID: 0000-0002-4173-4452
[2]**Булгаков Р.В.,** к.т.н.,
od_va_kaf_rao@ukr.net, ORCID: 0000-0002-8825-718X
[2]**Фролов О.С.,**ст. викладач,
sanec418@ukr.net, ORCID: 0000-0002-0941-4299
[1]*Одеська державна академія будівництва та архітектури*
вул. Дідрихсона, 4, м. Одеса, 65029, Україна
[2]*Військова академія*
вул. Фонтанська дорога, 10,м. Одеса, 65009, Україна

Анотація. Однією з основних споруд, що застосовуються для отримання води питної якості у схемах господарсько-питного водопостачання населених пунктів, є фільтри, головні конструктивні елементи яких включають дренажно-розподільні та відвідні системи. Для підвищення ефективності та надійності фільтри обладнуються пористими трубчастими системами для розподілу та збирання води. У зв'язку з цим отримання достовірних методик їх розрахунку представляє науковий та практичний інтерес.

У статті зазначається, що вода у розподільчих та збірних трубопроводах рухається зі змінною по шляху витратою. Причому приплив або відтік води залежить від змінного по довжині труби тиску, і якщо рух безнапірний – від змінного рівня води, а для пористих труб цей рух безперервний.

Задача руху рідини зі змінною по шляху витратою вивчалася багатьма авторами, проте залежності які при цьому були отримані в основному стосувалися перфорованих трубопроводів і відкритих лотків.

Авторами розглядається робота пористої труби за умовами безнапірного руху, що описується двома рівняннями – руху рідини всередині труби і руху рідини через стінки труби. Зазначається складність цієї задачі, яка обумовлена тим, що це рівняння взаємопов'язані. Тобто витрата рідини через стінки труби залежить від глибини шару води в трубі, яка визначається рівнянням руху всередині труби. Аналогічно закон зміни глибини визначається, зокрема, закономірностями припливу.

Досліджуючи нерівномірність розподілу та збору води пористою трубою отримано математичну модель, на підставі якої розроблено наближену методику розрахунку. Це дозволяє по критичній глибині води, яка встановлюється в кінці труби, отримати значення середньої глибини потоку в трубі. Для спрощення розрахунків в статті наведені відповідні номограми.

Перевірка достовірності моделі проводилася на експериментальній установці. Аналіз отриманих дослідних даних показав добру відповідність їх результатам розрахунку, виконаних за наближеною методикою – відхилення глибини потоку в середньому перерізі не перевищує 1,5%.

Ключові слова: пориста труба, безнапірний рух, фільтри, збирання (відтік) води, гідравлічний розрахунок.

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