Побудовано математичну модель фільтрації з урахуванням кольматаційно-суфозійних процесів в системі біоплато-фільтра. Числові розв'язки отриманої крайової задачі знайдено методом скінченних елементів з програмною реалізацією відповідних алгоритмів в середовищі FreeFem++ Проведено ряд числових експериментів та здійснено аналіз впливу концентрації суспензії та кольматуючих частинок на процеси фільтрації в біоплато-фільтрі

Ключові слова: біоплато, проблема фільтрації, кольматація, суфозія, метод скінченних елементів, FreeFem++

Построена математическая модель фильтрации с учетом кольматационно-суффозионных процессов в системе биоплато-фильтра в двумерном случае. Числовые решения полученной краевой задачи найдены методом конечных элементов с программной реализацией соответствующих алгоритмов в среде FreeFem++. Проведен ряд численных экспериментов и осуществлен анализ влияния концентрации суспензии и кольматирующих частиц на процессы фильтрации в биоплато-фильтре на разных временных пластах

Ключевые слова: биоплато, проблема фильтрации, кольматация, суффозия, метод конечных элементов, FreeFem++

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COMPUTER MODELING OF WATER CLEANING IN WETLAND TAKING INTO ACCOUNT OF SUFFOSION ANG COLMATATION

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1. Introduction

Bioplato that are facilities for the purification of household and industrial wastewater, as well as contaminated surface runoff, have been gaining popularity in recent years in different countries, specifically the United Kingdom, China, the Netherlands, Japan, Norway, Australia, etc. [1, 2]. The advantage of bioplato over a number of other water-treatment structures is the fact that they almost do not require electricity and chemical reagents, nor intensive operational maintenance [3, 4]. They also ensure the required quality of water purification from a wide range of pollutants of organic and mineral character [5].

The most common are the bioplato with an open water mirror (or similar structures, such as lagoons, ponds, channels, etc.) for water purification in countries with warm and moderate climate [6, 7]. The primary mechanism of water purification at a bioplato is the complex and interconnected life activities of heterotrophic and autotrophic organisms. These organisms develop in the thickness of filtration backfill, submerged in water, and on the surface of the root organs of plants in the form of immobilized bacterial medium. However, the open bioplato do not provide for the effective regulation of processes of mass exchange, gas saturation and aeration of water; the silt and sediment are not removed. This leads to the secondary water pollution and significantly reduces the effectiveness of purification from various, and particularly toxic, contaminants. In addition, in areas with moderate climate the efficiency of open bioplato performance reduces in autumn-winter period by 30–40 % on average.

More effective are the closed bioplato of hydroponic type [8]. In them, water level is below the top level of the backfill, which has higher aquatic plants planted in it whose root system is constantly washed by water that moves vertically from top down or from bottom up. A special feature of such bioplato is the regulation of water quality through artificially created hydrobiocenosis, the characteristics of components of which form under the direct influence of plants or by using biopreparations.

However, known structures of bioplato undergo gradual colmatation of porous space in the filtering backfill and the bottom drainage with a biofilm and mineralized sediment, the accumulation of sludge in the ground part of the structure. The result is a decrease in the supply of oxygen to the root system of plants, which may reduce effectiveness of the work of structures, lead to sediment peptization and secondary pollution of water. Since the sediment in these bioplato is not removed, its accumulation gives rise to anaerobic biological processes occurring in the backfill, resulting in reduced sorption and detoxification of toxic impurities. Especially negative is feeding these bioplato with water with an elevated content of suspended solids particles, which greatly enhances negative processes that proceed in the thickness of a filtering backfill. Gradual colmatation of porous space in the filtering backfill leads to the process of suffusion, that is extracting captured particles with purified water, which reduces efficiency of bioplato operation. To restore the work of bioplato, there should be a periodic pause in its operation to carry out complex and lengthy repair and restoration work related to washing and regeneration of the filtering backfill and drainage.

Therefore, it is an important task to explore suffusion-colmatation processes that occur in the thickness of a filtering backfill in a bioplato when filtering contaminated water, in terms of efficiency of its operation. Mathematical and computer modelling of such processes are associated with non-linear interdependence between parameters of the porous medium and parameters of the processes themselves. Specifically, suffusion and colmatation affect porosity of the backfill, which in turn is reflected on the magnitude of filtration coefficient. This impacts motion rate of the porous fluid, filtration-suffusion processes, and hence the performance of the bioplato. Therefore, ensuring the adequacy of research into these interconnected processes necessitates taking into consideration such non-linear mutual influences when constructing mathematical models of filtering in the bioplato.

2. Literature review and problem statement

In terms of the physics of a phenomenon, study of the processes of migration of insoluble particles in saturated porous media can be considered from two sides. The first is the problem of suffusion [9] (in the simplest case – carrying away movable particles from the skeleton of a porous medium [10]), related to problems of safety for hydro-technical, civil and industrial facilities [11]. Along with suffusion, the problems of colmatation are considered [12]. Processes of colmatation represent another side of the study [13]. These processes are physically opposite to the suffusion processes [14]. However, in terms of tools for mathematical and computer modeling, the specified processes are described by the same form of differential equations. The relations between parameters of these equations, assignment of the initial and boundary conditions for unknown functions, define mathematically the essence of the physical process. Specifically, when polluted water with a high concentration of suspended solid particles is fed to the soil massif, we observe predominance of colmatation processes over suffusion processes. If clean water is fed, suffusion processes will prevail. The importance of the process of migration of solid particles in porous media is emphasized in paper [15]. The observed processes are part of the comprehensive task on water purification from impurities by means of bioplato [7].

Mathematical model of suspension transport in porous media was constructed and applied to the processes of suffusion in paper [16]. Authors of work [17] applied for the specified processes a model of transfer (a system of first order differential equations), and a diffusion model when a degenerated equation of the parabolic type is obtained. Article [18] investigated iron nanoparticles transport in porous media and their application to clean up contaminated soil and groundwater. Results of laboratory study into colmatation and transfer of particles in a porous medium are given in paper [19].

Mathematical models of filtration-colmatation processes were constructed in some of the aforementioned scientific papers. Main attention is given to the processes of nanoparticles transport and the kinetics of colmatation processes. However, the known studies failed to consider a dynamic change in the porosity of a porous medium as a result of its colmatation with particles and the non-linear impact of this process on the coefficient of filtration.

3. The aim and objectives of the study

The aim of present research is to quantify the influence of colmatation processes in filtering polluted water on the performance efficiency of the filter-bioplato by means of mathematical and computer modeling. This would make it possible to draw conclusions about the effectiveness or ineffectiveness of the work of bioplato of the applied design and to make a decision about the need (or lack of it) to introduce modifications to the engineering elements of the filter.

To accomplish the aim, the following tasks have been set:

– to account for the effect of concentration of colmatating particles on a change in the porosity of a filtering backfill, which in turn would affect the modification of filtration equation;

– to take into consideration that the modified equation of filtration would affect via a convective component a change in the form of equation of mass transfer of suspension in the pores of the filter-bioplato;

– to build a mathematical model of filtering in the filter-bioplato with respect to the nonlinearity of effect of suffusion-colmatation processes on the coefficient of filtration and porosity of the filtering backfill;

– find numerical solutions to the corresponding nonlinear boundary value problem, which describes a mathematical model to be constructed, applying the finite element method, and to implement software realization of the proposed algorithms using the software package FreeFem++.

4. Description of a model problem on the process of filtration in the filter-bioplato with respect to influence of suffusion and colmatation

Procedure of present research implies the construction of a mathematical model of the process of filtration in the filter-bioplato with respect to influence of the suffusion-colmatation processes. The effect of colmatating particles on filtration processes manifests itself in the nonlinear dependence of porosity coefficient on concentration. Specifically, for taking this dependence into consideration, one can apply the Kozeny-Karman's formulae [20]. Non-linearity of the appropriate boundary value problem, which describes the mathematical model constructed, requires the application of numerical methods, such as the method of finite elements. In order to automate the finite-element computation of model problems, we employed free specialized programming environment FreeFem++. The model problem for computer simulation was considered to be a bioplato with a length of 50 meters and a height of 2 meters with a gravel filling with fractions the size of 20 mm. Polluted water is fed through the upper drainage system made from perforated pipes and is discharged at the bottom of the filling through the perforated drainage deployed at the bottom of the bioplato. The bioplato was considered to be sufficiently wide to be able to apply the profile circuit of filtration and to reduce a spatial problem to the two-dimensional problem. Software implementation using the FreeFem++ makes it possible to alter dimensions of the bioplato for model problems, to consider particularities of the backfill and porosity via the value of a filtration coefficient. We accepted the magnitude of 200 kg/m^3 to be the maximum concentration of pollutants arriving at the bioplato.

5. Construction of mathematical model of filtration with respect to colmatation-suffusion processes

Let $\sigma(X,t)$ be the porosity of soil, which is variable over time due to change in the concentration of colmatating particles; $\sigma_0(X)$ is the porosity of the “skeleton” of the soil (at full absence of colmatating particles); $s(X,t)$ is the mass concentration of colmatating particles (the mass of particles, which are associated with the skeleton of the soil and related to a unit volume of the porous environment); c is the concentration of suspension, which is filtered (the mass of suspended particles per a unit volume of a porous fluid); ρ_s is density of a material of colmatating particles.

Let V_n be the volume of pores in separated volume V of the porous medium.

Then by definition we obtain

$$\sigma(X,t)=\frac{V_n}{V}=\frac{V^0{}_n-V_s}{V}=\frac{V_n^0}{V}-\frac{V_s}{V}=$$

$$=\sigma_0(X)-\frac{\left(\dfrac{s(X,t)\cdot V}{\rho_s}\right)}{V}.$$

Therefore

$$\sigma(X,t)=\sigma_0(X)-\frac{s(X,t)}{\rho_s}. \tag{1}$$

From [21], we obtain filtration equation

$$\nabla\cdot\left(\rho_p(c)k_h(c,s,\sigma)\nabla h\right)=\sigma\frac{\partial\rho_p}{\partial c}\cdot\frac{\partial c}{\partial t}-\frac{\rho_p}{\rho_s}\frac{\partial s}{\partial t}. \tag{2}$$

Here V_s is the volume of colmatating particles in separated volume V; $\rho_p=\rho_p(c)$ is the density of porous fluid (suspension), which depends on the concentration of suspended solids particles c; $k_h=k_h(c,s,\sigma)$ is a filtration coefficient, which depends on the concentration of suspension and porosity; h is the head in a porous fluid.

Equation (2) is quasi-stationary relative to function $h=h(X,t)$ and contains two unknown functions – $c=c(X,t)$ and $s=s(X,t)$, and, therefore, must be complemented with two more equations for the specified functions. To change the concentration of suspension $c=c(X,t)$, we shall use a diffusion model. Specifically, according to [21], the modified equation of mass transfer takes the form

$$\sigma\left(1-\frac{c}{\rho_p}\frac{\partial\rho_p}{\partial c}\right)\frac{\partial c}{\partial t}=$$

$$=\nabla\cdot(D_c\nabla c)-\left(u\left(1-\frac{c}{\rho_p}\frac{\partial\rho_p}{\partial c}\right)-w\right)\nabla c-\frac{\partial s}{\partial t}, \tag{3}$$

where D_c is the coefficient of dispersion of particles in the porous suspension; $u=-k_h(c,s,\sigma)\operatorname{div}h$ is the filtration rate of the porous suspension; w is the sedimentation rate of solids in suspension.

As regards the equation for change $s=s(X,t)$ – the concentration of colmatating (glued to the soil skeleton) particles, there are two fundamental approaches – linear and non-linear. According to [12], it is possible to use a linear equation of colmatation and suffusion

$$\frac{\partial s}{\partial t}=\alpha\cdot c-\beta\cdot s, \tag{4}$$

or a non-linear equation of colmatation and suffusion

$$\frac{\partial s}{\partial t}=\alpha^*\cdot\left(s_{\max}-s\right)\cdot c-\beta\cdot s, \tag{5}$$

where α, α^* are the coefficients of speed at which particles stick; β is a factor of speed of particle separation; $s_{\max}$ is the maximum concentration of colmatating particles.

It was substantiated in [13] that it is more appropriate, rather than (5), to use a slightly modified equation. Specifically

$$\frac{\partial s}{\partial t}=-\frac{1}{\delta}\left(\sigma-\sigma_{\min}\right)\cdot c\cdot\left|\vec{v}\right|, \tag{6}$$

where $\delta=l_0(\sigma_0-\sigma_{\min})$, $\sigma_{\min}$ is the minimum porosity value (all passages are filled with colmatating particles); l_0 is the average distance that a particle travels before being captured by a porous channel.

Paper [22] proposed, based on the study of filters, using the following equation for a change in the concentration of particles in the solid component:

$$\frac{\partial s}{\partial t}=\alpha\cdot c-\varepsilon\cdot\beta(t)\cdot s,$$

where ε is a small parameter.

Let $\sigma_{\min}$ be the minimum porosity value. Then

$$\sigma_{\min}=\sigma_0\cdot\sigma_s, \tag{7}$$

where σ_s is the porosity of porous medium, which is composed of colmatating particles only. Then, from (7) and (1), we obtain

$$\sigma_{\min}=\sigma_0-\frac{s_{\max}}{\rho_s},$$

$$s_{\max}=\rho_s\left(1-\sigma_s\right)\cdot\sigma_0. \tag{8}$$

Thus, the mathematical model of filtration with respect to the colmatation-suffusion processes is described by the following boundary value problem:

$$\nabla\cdot\left(\rho_p(c)k_h(c,s,\sigma)\nabla h\right)=\sigma\frac{\partial\rho_p}{\partial c}\cdot\frac{\partial c}{\partial t}-\frac{\rho_p}{\rho_s}\frac{\partial s}{\partial t},\quad X\in\Omega,$$

$$\sigma\left(1-\frac{c}{\rho_p}\frac{\partial\rho_p}{\partial c}\right)\frac{\partial c}{\partial t}=$$

$$=\nabla\cdot(D_c\nabla c)-\left(u\left(1-\frac{c}{\rho_p}\frac{\partial\rho_p}{\partial c}\right)-w\right)\nabla c-\frac{\partial s}{\partial t},\quad X\in\Omega,$$

$$\frac{\partial s}{\partial t}=\alpha\cdot c-\beta\cdot s,\ X\in\Omega,$$

$$u=-k_h(c,s,\sigma)\nabla h,\ X\in\Omega,$$

$$c(X,0)=C_0(X),\ \ s(X,0)=s_0(X),\ \ X\in\overline{\Omega}=\Omega\cup\Gamma,$$

$$h\big|_{\gamma_1}=h_1(X,t),\ X\in\gamma_1,\ \ (u,n)\big|_{\gamma_2}=0,$$

$$c\big|_{\gamma_1}=C_1(X,t),\ X\in\gamma_1,\ \ (q_c,n)\big|_{\gamma_2}=0.$$

Here, q_c is the flow of suspended particles in the suspension; $\gamma_1 U\gamma_2=\Gamma$ is the bound of region Ω, in which we examine the process; $h_1(X,\ t)$, $C_1(X,\ t)$ are the assigned functions.

6. Algorithm for finding an approximate solution to the obtained boundary value problem

In order to find an approximate solution to the stated boundary value problem, we employed the method of finite elements (FEM).

Weak statement of a boundary value problem implies the following. We shall multiply equation (2) by the test function

$$v1(\mathbf{X})\in H_0=\left\{v1(\mathbf{X}):v1(\mathbf{X})\in W_2^1(\Omega),v1(\mathbf{X})\big|_{\gamma_1}=0\right\},$$

integrate over region **Ω**, next we apply the Ostrogradsky-Gauss formula and obtain

$$\iint_\Omega (k_h\rho_p\nabla h\nabla v1)\mathrm{d}\Omega+$$
$$+\iint_\Omega\left(\sigma\frac{\partial\rho_p}{\partial c}\cdot\frac{\partial c}{\partial t}\cdot v1\right)\mathrm{d}\Omega-\iint_\Omega\left(\frac{\rho_p}{\rho_s}\cdot\frac{\partial s}{\partial t}\cdot v1\right)\mathrm{d}\Omega=0.$$

Similarly, we shall multiply equation (3) and the initial condition for the concentration of suspension by the the test function

$$v2(\mathbf{X})\in H_0=\left\{v2(\mathbf{X}):v2(\mathbf{X})\in W_2^1(\Omega),v2(\mathbf{X})\big|_{\gamma_1}=0\right\},$$

integrate over region **Ω**, next we apply the Ostrogradsky-Gauss formula and obtain

$$\iint_\Omega D_c\nabla c\nabla v2\mathrm{d}\Omega-\iint_\Omega\left(u\left(1-\frac{c}{\rho_p}\frac{\partial\rho_p}{\partial c}\right)-w\right)\cdot\nabla c\cdot v2\mathrm{d}\Omega+\iint_\Omega\frac{\partial s}{\partial t}\cdot v2d\Omega=$$
$$=\iint_\Omega\left(\sigma\left(1-\frac{c}{\rho_p}\frac{\partial\rho_p}{\partial c}\right)\cdot\frac{\partial c}{\partial t}\cdot v2\right)\mathrm{d}\Omega,$$

$$\iint_\Omega c(x,y,0)\cdot v2(\mathbf{X})\mathrm{d}\Omega=\iint_\Omega c_0\cdot v2(\mathbf{X})\mathrm{d}\Omega.$$

For the concentration of particles in the solid component, we obtain

$$s^i=\left(\alpha\cdot c^{i-1}-\beta\cdot s^{i-1}\right)\cdot\tau+s^{i-1},$$

where τ is the sampling time step, $t_i=i\cdot\tau$, $s^i=s(X,\ t_i)$.

In order to find an approximated generalized solution to the obtained non-linear Cauchy problem, it is necessary to apply sampling over time. It is possible to use, for example, a predictor-corrector scheme [23], or fully implicit linearized difference scheme [24].

7. Results of the numerical experiment using the developed mathematical model of filtration with respect to the colmatation-suffusion processes

To perform a computer experiment using the developed mathematical model, we examined the filter-bioplato, which is described in the research procedure. Fig. 1 shows schematic of the region where the problem is being solved. At bound Γ_1, there is a perforated pipe, which is used to feed polluted water to the surface of the bioplato. Although water is fed into the pipe under a certain pressure, when it is discharged out of the pipe it is freely filtered into the porous environment. Thus, we consider the pressure at which polluted water is fed to bound Γ_1 equal to the atmospheric pressure. Since $p_a=0$, the boundary condition for heads on Γ_1: $h=2$ m. At bound Γ_2, there is a perforated pipe, out of which purified water is pumped out. The flows are accepted, respectively, at $x=0$ m, $q_{\min}=0.13$ m/day, and at $x=50$ m, $q_{\max}=0.17$ m/day. This enables performance efficiency of the bioplato at a volume of 160–200 m^3 of water per day. Bounds Γ_3, Γ_4 are the impermeable boundaries.

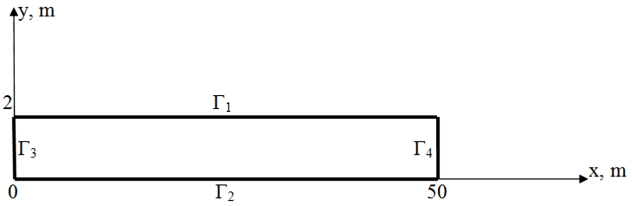

Fig. 1. Schematic of the region where the problem is solved

At bound Γ_2, the flow depends on the distance to the right edge:

$$q\big|_{\mathbf{X}\in\Gamma_2}=\frac{q_{\min}\left(x-x_2\right)}{x_1-x_2}+\frac{q_{\max}\left(x-x_1\right)}{x_2-x_1},$$

where q is the flow of fluid per unit length; $x_1=0$ m; $x_2=50$ m; at bound Γ_1, $c(X,\ t)=200$ kg/m^3. Other initial parameters are as follows:

$$\sigma_0=0.7,\ \ e_0=2.3,\ \ \rho_s=2200\ \left(\mathrm{kg/m^3}\right),$$

$$D_c=9.51\cdot10^{-3}\ \left(\mathrm{m^2/day}\right),\ \alpha=0.1\ \left(\mathrm{day^{-1}}\right),$$

$$\beta=0.01\ \ \left(\mathrm{day^{-1}}\right),\ \ w_1=0\ \left(\mathrm{m/day}\right),$$

$$w_2=3\ \left(\mathrm{m/day,}\right)\ \ C_0=8\ \left(\mathrm{kg/m^3}\right),$$

$$s_0=0\ \left(\mathrm{kg/m^3}\right).$$

Sampling time step $\tau=30$ days.

Fig. 2 shows difference in heads taking into account effect of the suspension concentration and the concentration of colmatating particles (filtration coefficient $k=k_0\cdot(1+e_0)/(1+e)\times\times((e)/(e_0))^3$ [20]) and excluding it (filtration coefficient $k=k_0=100$ m/day [25]), respectively.

Numerical experiments show that the maximum difference in heads considering and excluding effect of the suspension concentration and the concentration of colmatating particles amounts to 0.39 m in six months after launching the operation of a bioplato.

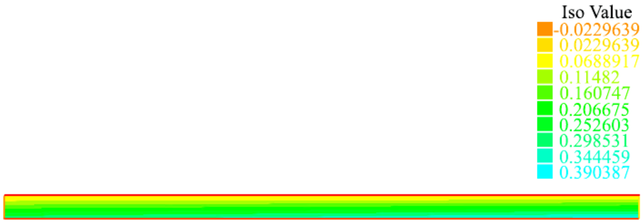

Fig. 2. Difference in heads in the bioplato backfill in 180 days

Fig. 3. Distribution diagram $u_2=-k(e)\cdot\partial h/\partial y$ with respect to effect of the suspension concentration and the concentration of colmatating particles in 180 days

Fig. 4. Distribution diagram $u_2=-k\cdot\partial h/\partial y$ excluding effect of the suspension concentration and the concentration of colmatating particles in 180 days

8. Discussion of results of computer numerical experiments of filtration in the filter-bioplato

The research performed, although using a model problem as an example, showed that at the stage of designing it is important to investigate suffusion-colmatation processes that occur in the thickness of a filtering backfill in the bioplato during filtration of polluted water. These processes have a significant influence on the effectiveness of the filter-bioplato. The tools of mathematical modeling and computer simulation, which were used, allow us to take into consideration non-linear mutual influences between parameters of a porous medium and parameters of the processes themselves. They make it possible to save significant resources and time required to carry out field experiments.

ith respect to that the maximum value of heads in the backfill of a bioplato is 2 m, one can see in Fig. 2 that the maximum relative difference reaches 19.5 %. Velocity diagrams of filtration along the 0y axis (component u_2) demonstrate that over 180 days (Fig. 3, 4) maximum relative difference in the values of filtration velocity is about 25 %. In other words, the predicted performance efficiency of the bioplato will drop in six months by at least a quarter. Such an effect is explained by considering the nonlinear dependence of filtration coefficient on the concentration of colmatating particles. The increasing volume of particles that are captured by a backfill in the filter-bioplato leads to a decrease in the backfill porosity. This in turn results in the decreased filtration coefficient, hence a reduction in the rate and volume of fluid that is filtered in the bioplato. The built mathematical model accounts for the physical effects of dynamic change in porosity and the dependence of filtration coefficient on the concentration of pollutants, in contrast to known analogs. Taking these effects into consideration allows us to argue about improving the adequacy of the mathematical model to the examined physical processes. The negative impact of increasing concentration of colmatating particles on the performance efficiency of the filter could be quantified even excluding the mathematical model proposed. However, it is impossible to obtain specific forecast data without numerical study into constructed mathematical model and without conducting numerical experiments. Nonlinearity of the model built does not make it possible to argue about analytical solutions to the appropriate boundary value problem. Even more so for the would-be consideration of a three-dimensional problem. Mathematical modelling makes it possible to estimate the effect of impact of the examined factors, but it does not provide for the reduction of such a negative impact. Therefore, in order to maintain the operational performance of the bioplato, it is required to design engineering solutions that would reduce the impact of colmatation-suffusion processes on the effectiveness of the filter-bioplato.

9. Conclusions

1. We have constructed an improved mathematical model for the process of suspension filtration in the filter-bioplato, which, in contrast to known analogues, accounts for a non-linear dependence of filtration coefficient on the concentration of colmatating particles, and a dynamic change in porosity in the process of filtration.

2. Numerical solutions to the corresponding nonlinear boundary value problem were derived applying the method of finite elements in the free software package FreeFem++. The use of FreeFem++ allowed us to partially automate programming implementation of algorithms for solving nonlinear boundary value problems for the systems of equations in partial derivatives. Specifically, one of the advantages of the employed programming environment is the automated coverage of regions with a grid of triangular finite elements, as well as the automatic reduction of the problem in weak statement to the system of linear algebraic equations.

3. Computer simulation revealed that, when taking into account the nonlinearity, the predicted performance efficiency of a bioplato reduces by 25 % in six months. This effect cannot be traced if the nonlinearity is neglected. Mathematical model allowed us to improve the adequacy of results in the examined physical processes; however, it does not make it possible to reduce the negative impact of colmatation. Therefore, such a task requires the development of engineering solutions to reduce the influence of colmatation-suffusion processes on the processes of filtration. This would require, in turn, accounting for these engineering solutions in the mathematical model, as well as further exploration of the efficiency of such solutions.

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