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DETERMINING THE URATION OF PREPARATION FOR THE DEVELOPMENT OF TECHNOGENIC COAL DEPOSITS WHEN USING BIOREMEDIATION METHODS FOR THEIR DEWATERING ACTION

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Abstract. The subject of the study is the patterns and parameters of the process of achieving a state of dynamic equilibrium between the liquid and solid phases of a technogenic coal deposit under the influence of climatic and production factors in the presence of biotechnogenic impact on the coast and on the free surface of storage facilities. The aim of the study is to establish the dependencies of the processes of dehydration of man-made coal deposits using bioremediation technology, which will ensure their environmentally safe and efficient extraction and utilization. A mathematical model describing the state and parameters of man-made coal deposits during their preparation for development using bioremediation methods has been modernized. It uses the fundamental laws of mass conservation for the liquid and solid phases of deposits, taking into account the inflow of liquid from atmospheric precipitation and coal enrichment waste, and its losses during evaporation under the influence of the sun and transpiration by green spaces, as well as possible mass transfer during the extraction of carbon-containing raw materials in the form of a high-concentration hydro mixture. Taking into account the influence of the absorption capacity of green spaces existing in the environment of a man-made coal deposit is based on the equations of a flat filtration process of an ideal heavy liquid, taking into account Darcy's law and a non-homogeneous continuity equation, considering the existence of liquid flows in the form of a biological crop transpiration coefficient. At the same time, the characteristics of the profile of the banks of the coal enrichment waste storage facility significantly affect only the time it takes to establish this state, but not the liquid level in the storage facility or the value of the plant transpiration coefficient that ensures this equilibrium. It has been shown that the time it takes for the coal enrichment waste layer to reach a state of dynamic equilibrium in a storage facility whose shores are planted with biological crops is directly proportional to the cube root of the product of the Darcy coefficient and the square of the storage facility radius, and inversely proportional to the cube root of the product of the specific fluid consumption per unit length of the coal enrichment waste storage perimeter and the magnitude of the biotechnogenic impact. The scientific novelty of this conclusion lies in the fact that, for the first time, the dependence of the thickness of the liquid layer above technogenic coal deposits, corresponding to the state of dynamic equilibrium, on the specific liquid flow rate, the Darcy coefficient, and the magnitude of biotechnogenic impact has been scientifically substantiated.

Keywords: bioremediation, biological culture, transpiration, dewatering, man-made deposits, coal enrichment waste, waste storage facilities.

1. Introduction

The history of the coal industry in Ukraine spans more than 120 years. Coal was mined at 276 mines and enriched at 61 coal enrichment plants (CEPs) during the most successful period of coal mining. All these industrial enterprises had a technogenic impact on the environment, which will not disappear even after their inevitable closure [1–4]. The most significant such impact is that of coal enrichment waste storage facilities (CEWF) and mine water ponds (MWP), without which the coal industry cannot operate. As global experience with the closure of coal enterprises shows, it is necessary to begin dealing with the negative consequences of this impact while the coal preparation waste storage facilities and mine water ponds are still in operation [5–7]. For example, the process of closing coal mines in the UK began in 1985 and ended in 2020 with the closure of the last coal mine in County Durham. Throughout these 35 years, the country's leadership has made great efforts to revive and develop former coal regions, but most of them are still considered depressed and have no prospects in the near future. In addition, the disposal of man-made coal deposits (MCD) is complicated by their location under a lay-

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er of liquid containing certain chemical and organic contaminants, which makes it impossible to remove and use them for agro-industrial needs. Given this, a number of experts consider the use of bioremediation technology (BT) to be the most effective and environmentally safe method of dewatering MCDs when preparing them for extraction and disposal [8–14]. Due to the ability of biological culture (BC) to ensure transpiration processes, it becomes possible to increase the flow rate of liquids for production needs, accelerate the dewatering of man-made reservoirs to depths that will allow the extraction of MCD by hydromechanization in the form of a high-concentration hydro mixture. This ability of BC is known to energy wood growers [15–17], but these studies do not examine the process of dewatering reservoirs on the coast where BC are planted. At the same time, in order to apply this approach in domestic conditions, it is necessary to study the peculiarities of bioremediation processes during the dewatering of MCD, justify the methods of their implementation, and establish the characteristics of the processes that affect the parameters of technological schemes for preparing these deposits for development.

Thus, the aim of the work is to establish the patterns of change in the heights of the liquid and solid phases of man-made coal deposits and the duration of this process, taking into account climatic and production factors when applying bioremediation technologies on the coast, to improve the efficiency and environmental safety of the development of man-made coal deposits, which is a relevant scientific task that is of great importance for the mining industry.

2. Methods

To determine the fluid flow through the side surface of the CEWF, we use fluid filtration equations that take into account fluid loss during transpiration by green spaces that exist in the CEWF environment. We consider the filtration process in two zones into which the soil mass is divided (Figure 1) [17–19]. The first zone is located below the bottom of the CEWF, where there are no drains simulating the influence of plants, and the second zone is located above the bottom of the CEWF in the volume of the soil mass and is characterized by evenly distributed drains of equal intensity that remove liquid. Taking into account the conditions of creation and operation of the CEWF when developing a mathematical model of the process of liquid filtration from the reservoir in the presence of biotechnogenic load around the perimeter, we make the following assumptions: the liquid filtered from the reservoir is ideal and incompressible [18–20]; the filtration process obeys Darcy's law [18–25]; the reservoir has a circular shape in plan; the banks of the reservoir are vertical in depth; the bottom of the reservoir is impermeable; liquid filtration occurs only through the side surface of the banks; the impermeable horizon is located in the soil mass below the bottom; the radius of the pond is significantly greater than its depth; the surface of the banks around the pond is horizontal; the biotechnogenic load around the perimeter of the pond is evenly distributed over the volume of the soil mass to a depth not exceeding the depth of the pond; we neglect the influence of the process of evaporation of liquid from the surface; the soil mass around the pond is not deformed; filtration characteristics and pore parameters do not change over time and are the same for the entire soil mass [17 – 19].

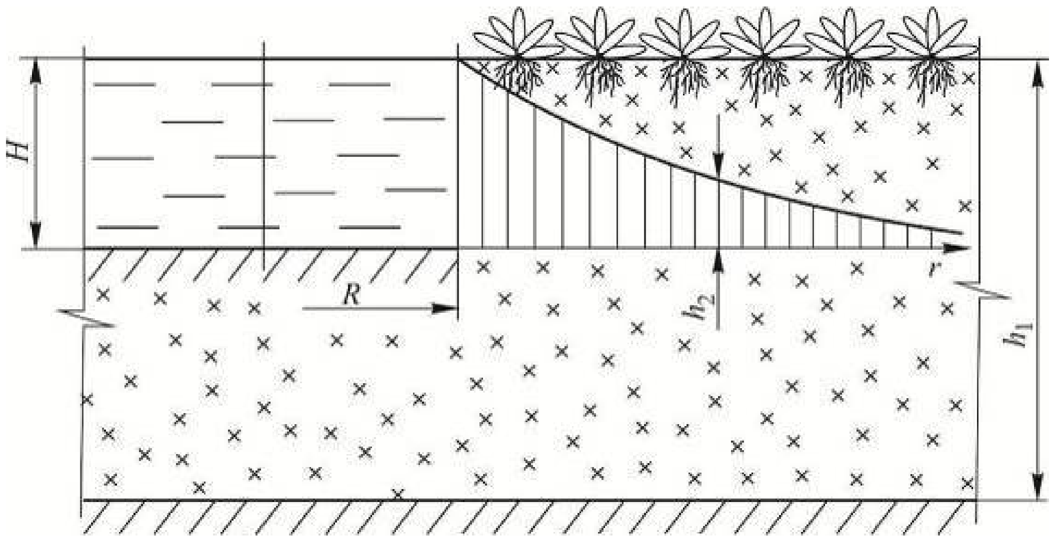

Figure 1 – Formalization of the process of filtering liquid from a storage facility in the presence of bio-technogenic load around the perimeter

3. Theoretical part

Usually, calculations of the liquid level in the CEWF are performed taking into account the inflow of liquid from atmospheric precipitation, the inflow of liquid from coal enrichment waste (CEW) and mine water, and liquid losses due to evaporation under the influence of the sun, using the following equation [5 – 7, 26 – 29]:

$$\frac{dH_W}{dt} = q_A - a\left(H_W + h_p\right)^{3/2}, \quad (1)$$

$$q_A = \frac{231 q_{OS}}{1000000} + \frac{\left(1 - C_0'\right)Q_{OF} + K_{SW} Q_{SW}^{min}}{\pi R^2} - \frac{7\Sigma_+}{1000}, \; a = \frac{2}{R}\left(\frac{\delta g}{k}\right)^{1/2}, \; h_p = \frac{2\sigma}{\rho g r_P}, \quad (2)$$

where H_W – CEWF filling level; q_A – specific fluid consumption per unit area of the CEWF free surface; k – Darcy coefficient; δ – transpiration coefficient characterizing the volumetric consumption of fluid by plants within the limits of their root systems; σ – surface tension coefficient of the liquid; ρ – liquid density; g – acceleration of free fall; r_P – effective pore radius of the soil mass; h_P – height of liquid rise in the pores of the soil mass; C'_0 – volume concentration of the hydro mixture coming from the CEP; Q_{OF} – flow rate of water entering the reservoir; t – time; R – radius of the water intake; q_{OS} – precipitation rate for this region; Σ_+ – sum of air temperature norms for the months of the warm period of the year (Table 1); K_{SW} – water inflow coefficient (Table 2); $Q_{SW}^{\min}$ – minimum monthly mine water discharge during the year.

Thus, we consider a visesymmetric problem of filtering an ideal incompressible fluid in a porous homogeneous array that does not deform through the side surface of a cylinder, whose upper base coincides with the surface of the soil array, and the lower base is located in the soil mass above the water-impermeable horizon (Figure 1) [17–19]. The soil mass is divided into two zones-above and below the bottom of the cylinder. Above the bottom of the cylinder, drains of equal intensity are evenly distributed throughout the soil mass, removing liquid. Below the bottom of the cylinder, there are no such drains. It is assumed that at the boundary between the two areas, the velocity and pressure in both areas are equal, and at the outer boundary of the second area, the pressure is equal to atmospheric pressure.

Table 1 – Climatic characteristics of the Dnipro region [17–21]

Month of the year	Average temperature, °C	Precipitation, mm
January	-4.5	43
February	-3.8	35
March	+0.6	33
April	+9.2	37
May	+16.2	44
June	+20.3	59
July	+22.3	53
August	+21.5	38
September	+15.8	37
October	+9.3	33
November	+2.9	42
December	-1.4	46

Table 2 – Dependence of K_{SW} on periods of the year for the Dnipro region [17–21]

Period of the year	Coefficient value K_{SW}
September – February	1.0
June – August	1.5
March – May	4.5

In [17–19], we obtain a dependence for determining the fluid flow through the side surface of the CEWF:

$$Q=\frac{2g^2}{k^2R\delta}\left[\frac{k\delta}{g}\left(H_W+h_p\right)\right]^{\frac{3}{2}}\sqrt{1-\frac{k\delta}{g}\left(H_W+h_p\right)}. \qquad (3)$$

When using formula (3), provided that [17–19]

$$\delta\le\frac{0.1g}{k\left(H_W+h_p\right)}, \qquad (4)$$

and taking into account the latter dependence from (2), it follows that the fluid flow through the side surface of the CEWF can be represented as:

$$Q = \sqrt{q \frac{g\delta}{k} H_W^3} \frac{2}{R}; \qquad q = 1 + \frac{2\sigma}{\rho g r_p H_W}, \tag{5}$$

where q – coefficient that takes into account the surface properties of the liquid and the characteristics of the pore space of the soil mass.

4. Results and discussion

Thus, from formula (5), it follows that the fluid flow through the side surface of the CEWF at the planted banks of the BC is directly proportional to the square root of the product of the biotechnogenic impact and the cube of the free surface level, and inversely proportional to the product of the CEWF radius and the square root of the Darcy coefficient. In this case, when the area of the reservoir does not depend on its depth, the solution of the differential equation (5) can be obtained in quadratures. Otherwise, as well as when requirement (4) is violated, the possibility of obtaining the solution of this differential equation in quadratures depends on the type of the reservoir bank profile. When the requirements for the geometric dimensions of the reservoir [17–19] are met, equation (1), taking into account (5), is a first-order differential equation with separated variables, the solution of which with inhomogeneous initial conditions [17 – 19]

$$H_W(t = 0) = H_{W0}, \tag{6}$$

where H_{W0} – initial value of the CEWF fill level.

The results of the analytical study of differential equation (1) indicate the existence of a dynamic equilibrium for this process, when BCs transpire excess fluid between the volumes entering and leaving the storage facility [17–19]:

$$H_{WA} = H'_{WA} - h_p, \qquad H'_{WA} = \left(\frac{q_A}{a}\right)^{\frac{2}{3}}, \tag{7}$$

where H_{WA} – thickness of the BB layer in the storage facility corresponding to the state of dynamic equilibrium; H'_{WA} – thickness of the CEW layer in the storage facility corresponding to the state of dynamic equilibrium without taking into account the influence of the surface properties of the liquid.

Taking into account formulas (1) and (5), dependence (7) can be rewritten as follows:

$$H_{WA} = \sqrt[3]{\frac{k}{\delta g} q_A} (1 - q), \qquad q'_A = q_A \frac{2}{R}, \tag{8}$$

where q'_A – specific fluid consumption per unit length of the CEWF perimeter.

In a state of dynamic equilibrium, the fluid level in the CEWF remains unchanged. Solving equation (1) taking into account (5) after converting to dimensionless quantities, replacing variables, namely, transition to the radical with the relative thickness of the CEW layer, and decomposition of the subintegral expression into simple fractions, reduces to tabulated indefinite integrals, which, after satisfying the initial conditions and corresponding transformations, allow determining the time of reaching a state of dynamic equilibrium using the formulas [17 – 19]:

$$t_A = \frac{\tau_A}{12a\sqrt{H'_{WA}}}, \tag{9}$$

$$\tau_A = ln\left(\frac{1-p^3}{1-p}\right) - 3ln\left(\frac{1-p}{1-p'}\right) + \sqrt{12}arctg\left(\frac{p'-p}{\left(2+p'+\left(1+2p'\right)p\right)\sqrt{H'_{WA}}}\right), \tag{10}$$

$$p = \sqrt{\frac{H_W + h_p}{H'_{WA}}}, \qquad p' = \sqrt{\frac{H_{W0} + h_p}{H'_{WA}}}, \tag{11}$$

where t_A – process duration; p' – relative initial depth of filling of the CEWF.

Dependencies (9) – (11), taking into account formulas (2) and characteristic values of the quantities included in them, allow determining the time of reaching a state of dynamic equilibrium. For this purpose, assuming $p = 1$, we can write

$$T_A = \Theta \sqrt[3]{\frac{k}{\delta}} \sqrt[3]{\frac{2R^2}{gq_A}}; \quad \Theta = 2.8405 + \frac{1}{24} ln \frac{\left(1-p'\right)^3}{\left(1-p\right)} + \frac{1}{\sqrt{48}} arctg\left(\frac{1+2p'}{\sqrt{3}}\right), \tag{12}$$

where T_A – time to reach dynamic equilibrium; Θ– dimensionless duration of the liquid filtration process from the storage facility, taking into account the initial liquid level.

5. Conclusions

The conditions for the formation of MCD were analyzed and the factors influencing the water balance in the “reservoir - groundwater - atmosphere” system were identified. An equation of the water balance was formulated for a pond with a clay bottom and liquid filtering through its side surface, assuming evaporation from the free surface and uniform distribution of runoff over the surrounding area.

A mathematical model has been developed that describes the water level in the CEWF, taking into account the suction capacity of the BC existing in its environment, the possible consumption of liquid coming from atmospheric precipitation, from the CEW, as well as the loss of liquid in the process of evaporation under the action of the sun. It has been proven that in cases where the area of the CEWF does not depend on its depth, the model allows the dependence of the water level in the CEWF on the above factors to be obtained in analytical form.

A methodology has been developed for determining the parameters of MCD and the feasibility of applying BT methods and means of hydromechanization, which allow calculating the level of the liquid mirror in the CEWF and the thickness of the layer of highly concentrated solid waste formed at the bottom of the storage facility at the end of a certain period of operation. It has been established that when using BC for MCD dewatering, there is a state of dynamic equilibrium depending on the value of the transpiration coefficient. Due to the fact that BC transpire excess liquid between the volumes entering and leaving the storage facility, the liquid level in the CEWF remains unchanged. At the same time, the characteristics of the CEWF shore profile significantly affect only the time it takes to establish this state, but not the liquid level in the reservoir or the value of the plant transpiration coefficient that ensures this equilibrium.

Thus, it follows from formula (12) that the time it takes for the CEW layer to reach a state of dynamic equilibrium in a reservoir whose shores are planted with BC is directly proportional to the cube root of the product of the Darcy coefficient and the square of the reservoir radius, and inversely proportional to the cube root of the product of the specific fluid flow per unit length of the CEWF perimeter and the magnitude of the biotechnogenic impact.

Using formula (12), we can calculate the time it takes for the CEWF to reach a state of dynamic equilibrium and estimate the probability of it being achieved within a given time frame. The results of additional analytical studies indicate that the characteristics of the CEWF shore profile will significantly affect only the time required to establish such a state, but not the liquid level in the reservoir or the value of the plant transpiration coefficient that ensures this equilibrium.

It has been established that formula (8) allows us to assert that the thickness of the liquid layer above the man-made coal deposits, which corresponds to the state of dynamic equilibrium, is directly proportional to the cube root of the product of the square of the specific liquid flow rate and the ratio of the Darcy coefficient to the magnitude of the biotechnogenic impact. The scientific novelty of this conclusion lies in the fact that, for the first time, the dependence of the thickness of the liquid layer above man-made coal deposits, corresponding to the state of dynamic equilibrium, on the specific liquid flow rate, the Darcy coefficient, and the magnitude of biotechnogenic impact has been scientifically substantiated.

Conflict of interest

Authors state no conflict of interest.

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ВИЗНАЧЕННЯ ТРИВАЛОСТІ ПІДГОТОВКИ ДО РОЗРОБКИ ТЕХНОГЕННИХ ВУГІЛЬНИХ ПОКЛАДІВ ПРИ ЗАСТОСУВАННІ ДЛЯ ЇХ ЗНЕВОДНЕННЯ МЕТОДІВ БІОРЕМЕДІАЦІЇ

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Анотація. Предметом дослідження є закономірності та параметри процесу досягнення стану динамічної рівноваги шарів рідкої та твердої фаз техногенного вугільного покладу під дією кліматичних та виробничих чинників при наявності біотехногенного впливу на узбережжі та на вільній поверхні сховищ. Метою дослідження є встановлення залежностей процесів зневоднення техногенних вугільних покладів при застосуванні технології біоремедіації, що забезпечать екологічно безпечний та ефективний їх видобуток та утилізацію. Була модернізована математична модель, що описує стан й параметри техногенних вугільних покладів при підготовці їх до розробки з застосуванням методів біоремедіації, яка використовує фундаментальні закони збереження маси для рідкої та твердої фаз покладів з урахуванням надходження рідини з атмосферними осадами та відходами вуглезбагачення, та її втрат в процесі випаровування під дією сонця та при транспірації зеленими насадженнями, а також можливий масообмін при видобутку вуглецевмісної сировини у вигляді гідросуміші високої концентрації. Врахування впливу всмоктувальної потужності зелених насаджень, що існують в навколишньому середовищі техногенного вугільного покладу, базується на рівняннях плоского процесу фільтрації ідеальної важкої рідини з урахуванням закону Дарсі та неоднорідного рівняння нерозривності, яке враховує існування стоків рідини у вигляді коефіцієнту транспірації біологічної культури. При цьому особливості профілю берегів сховища відходів вуглезбагачення значною мірою впливають лише на час встановлення такого стану, але не на рівень рідини в сховищі, або на значення коефіцієнту транспірації рослин, яке забезпечує цю рівновагу. Показано, що час досягнення шаром відходів вуглезбагачення стану динамічної рівноваги у сховищі, узбережжя якої засаджено біологічними культурами, прямопропорційний кореню кубічному з добутку коефіцієнта Дарсі та квадрату радіусу сховища, й обернено пропорційний кореню кубічному з добутку питомої витрати рідини, що припадає на одиницю довжини периметру сховища відходів вуглезбагачення, та величини біотехногенного впливу. Наукова новизна цього висновку полягає в тому, що вперше науково обґрунтовано залежність товщини шару рідини над техногенними вугільними покладами, що відповідає стану динамічної рівноваги, від питомої витрати рідини, коефіцієнта Дарсі та величини біотехногенного впливу.

Ключові слова: біоремедіації, біологічної культури, транспірація, зневоднення, техногенні поклади, відходи вуглезбагачення, сховища відходів.