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Layer drainage of fibrous materials in the composition of the ground dams

E.I. Nizhegorodtcev*, V.M. Gerasimov, K.V. Svalova

Transbaikal State University, Chita, Russia

**E-mail: dj_world@mail.ru*

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Abstract. The article is devoted to the design substantiation of a new type of drainage structures based on fibrous materials for ground dams. To assess the effectiveness of the application, two-dimensional modeling of hydraulic processes using the software environment Plaxis 2D AE 2013 finite-element method of a ground dam was carried out. Experimental research has become the basis study the effect of the rock mass on the filtration flow of water passing through the drainage from fibrous polymeric materials. Method of valuation suggested in article of the height of the layer and the slope of drainage from fibrous materials take into account the experimental data obtained for ground dams.

1. Introduction

Embankments and dams from local natural materials made from local natural materials serve as water reserve generators, settling basins for gravitational clarification of process water and liquid waste storage. Most often, such structures (up to 10 m in height) are arranged at mining enterprises that carry out gold surface mining from placer deposits. [1]. The construction of embankments and dams in taiga conditions is made from local natural materials: rocks and semi-rocks, sedimentary materials, and loose rocks(gravel, sand, clay) [2]. As a rule, embankment and dam arrays have a mixed composition of these materials with the highest percentage of loose rocks that differ in compressibility. Sandy rocks are characterized by low compressibility and high-speed settlement, while clay rocks have high compressibility and slow settlement.

Embankments and dams are constantly in contact with water, which affects their stability; there are examples of emergency cases at rock embankments [3, 4]. The main reasons of these accidents and damage to structures are the following: water overflow through the crest of soil dams; concentrated filtration through the dam body or foundation; deformation and embankment of slopes; seismic and wave effects [5–10]. To reduce the deformation of the structure rock mass, filtration control devices in the body of the structure made of natural and artificial materials are used to minimize emergency cases due to violations of the filtration regime of the body and the foundation of the soil dam. Modern domestic industry offers a number of new polymeric materials with unique properties, the use of which allows you to create reliable and filtering efficient control-based devices [11, 12].

There are quite extensive scientific studies in the field of reinforcing various soil structures with fibrous polymer materials, a detailed description, and the scope of their application is presented in the works E.V. Sherbinoj, V.G. Ofrihtera, A.B. Ponomareva [13–16]. However, very few publications have been devoted to the issues of the arrangement of drainage structures based on fibrous polymeric materials in ground hydraulic structures.

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Using fiber polymeric materials in order to control the filtration of water in a rock mass is a rather strategic pathway, which allows achieving significant results at minimum cost. Nevertheless, we haven't done yet any industrial tests of reservoir drains based on fiber materials in soil dams [17].

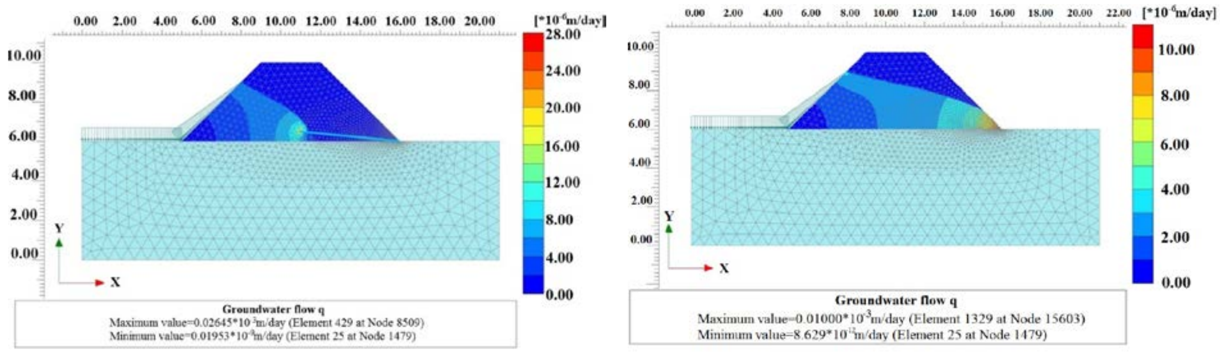
In order to assess the effectiveness of using fiber polymeric materials in controlling the water filtration in the body of the soil embankment, the filtration processes (finite element technique) that took place in the body of the structure were simulated using the Plaxis 2D AE 2013 program. The result of modeling the structure filtration fields with fiber polymer drain materials and without it, graphically presented in Fig. 1. It was found that the point of the maximum value of the field of water filtration in the absence of fiber material is located on the downstream surface, with the risk of erosion and suffusion slope. On the other hand, the maximum value of the filtration field for the case with a device made of fiber materials is in the body of the dam (the point of water entry into the material); water is filtered through the material, which excludes risk of erosion.

This survey was to investigate the effect of layer drainage from fibrous materials on the filtration process of ground dams, to analyze the effect of changes in the pressure of rocks of the structure on the filtration flow rate of water passing through the drainage.

The following tasks were set and then solved in order to achieve this goal:

1. To elaborate a numerical model of an embankment dam with layer drainage from fibrous materials based on the Plaxis 2D AE 2013 finite-element software package.
2. To elaborate experimental unit to investigate the effect of changes in the pressure of rocks of the structure on the filtration flow rate of water passing through the drainage
3. To elaborate methods for calculating the layer height and slope of the drain from fiber materials.

2. Methods



a b

Figure 1. Water filtration field in the rock mass of the structure:
a – fiber material devices, b – without using fiber material devices.

Based on the modeling results, it was found that filtration control devices based on fiber polymeric materials can reduce the possibility of emergency situations due to erosion and suffusion of the lower slope; it was also established that the main parameters of these filtration control devices are: bias towards the downstream and the layer height of fiber materials [18–20].

Horizontal drains based on fiber materials are characterized by the main parameters that determine their effectiveness: filtration water flow, position of the drawdown curve, layer height and bias of the fiber material towards the downstream.

The drain should be located in the lower part of the soil embankment with a slope towards the downstream, which ensures water removal (Fig. 2). Drain undergoes pressure from an overlying rock mass. The fiber polymer material is a porous medium, depending on the density of 70...130 kg/m^3, the average pore diameter is 13...82.4 microns. Previous research has established that the fiber material has a decrease in pore diameters of 3.67–4.57 times when compressed to 80 %. A drop in pore diameter leads to a decrease in the filtration water flow rate passing through the material; therefore, it affects the efficiency of the formation device made of fiber polymeric materials [21–23].

Changing the filtration water flow rate by drain (Kf) affects the main parameters: layer height (h_D) and slope towards the drain system (i_D) [20].

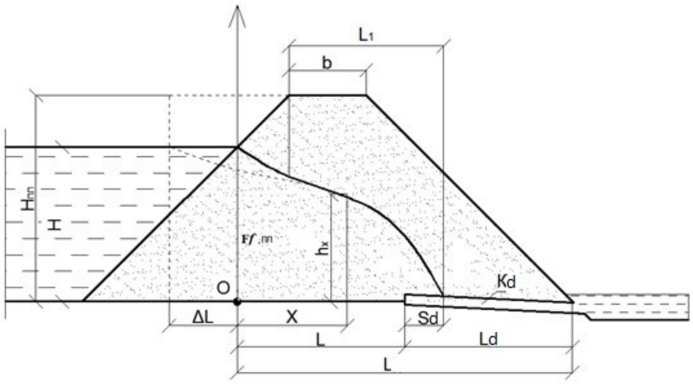


Figure 2. Location of the filtering control device in the body of the embankment.

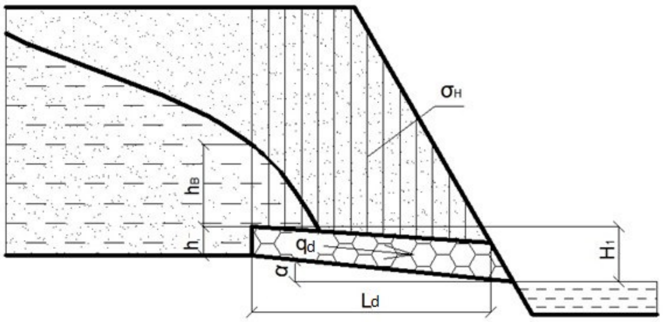


Figure 3. Calculation of the layer height of the reservoir device.

The filtration process follows the law of A. Darcy for liquids and gases in a porous medium. Previously, there was a formula proposed for determining the layer height of the reservoir device (Fig. 3) made of fiber materials [25, 26]:

$$h_D = \frac{q_D \cdot L_D}{Ff\left(h_B + H_1\right)}. \quad (1)$$

A filtering control device for fiber material is located at a certain angle in the body of the soil embankment. To calculate the slope angle, a formula was proposed based on the use of V.S. Kozlov [21], in relation to devices made of fiber polymeric materials:

$$i_D = \frac{2 \cdot q_D - \dfrac{F_f \cdot H_1^2}{L_D}}{F_f \cdot H_1}, \quad (2)$$

where q_D is filtration flow rate of the device, m²/s; L_D is width of the reservoir device, m; F_f is material filtration coefficient, m/s; h_B is pressure at front of the device, determined by the lines of equal pressure, m; H_1 is height of the drain towards the water level in the downstream, m

Formulas 1 and 2 include the width of the device and the filtration coefficient of the fiber material, but do not consider the change in the filtration water flow rate under the influence of external rock pressure.

An experiment was conducted in order to assess the change in the filtration water flow rate with a change in the pressure of the rock mass [23–26]. During the experimental studies, we selected Russian-made Dornite fiber type of the following grades by surface density: M250, M300, and M400. This type of fiber polymeric material is widely used in the road and railway construction, strengthening of coastal slopes, land-improvement works, etc. It is made of needle-punched material; surface density is 250–400 g/cm²; filtration coefficient is 70–150 m/day. These characteristics allow the use of this type of fiber polymeric material to design reservoir drain. The experimental unit is shown in Fig. 4.

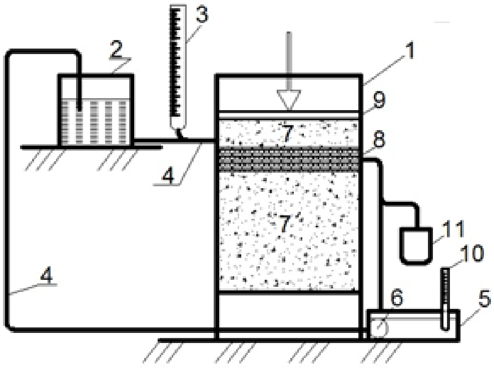


Figure 4. Scheme of the experimental unit for laboratory research:
1 – Prismatic body; 2 – water container; 3 – piezometer; 4 – flexible supply line;
5 – drain tank; 6 – pump; 7 – rock; 8 – drain design; 9 – stamp for load transfer;
10 – thermometer; 11 – dimensional cylinder.

In the unit body 1, the solid 7 is loaded to the level of the slot in the body of the unit. Then the drain design is made of fiber material 8, under a certain slope, which is set by changing the angle of inclination of the underlying soil surface. The upper layer of the rock is laid, and on top of which the plate 9 is laid, which later serves to transfer the load. A water tank maintains a constant amount of water. By changing the height of the location of the tank 2 we achieve the necessary water pressure according to the piezometer 3. The water from the tank 2 through a flexible connection 4 enters the unit body 1, passes through the rock 7, reaches the drain 8, discharged through a slot in the body, and enters the drain tank 5, from which it is pumped 6 to the tank 2. This cycle ensures the stability of the water temperature measured in the drain tank 5 using a thermometer 10. The measurement of the volume of water is carried out by a measuring graduate 11 on the way to the drain tank for a certain time.

3. Results and Discussion

During the experiments, it was found that the dependence of the filtration water flow rate passing through the drain on external pressure has two characteristic sections: 0...8 kPa (the dependence is non-linear) and 8...200 kPa (the dependence is linear), Fig. 5 and 6.

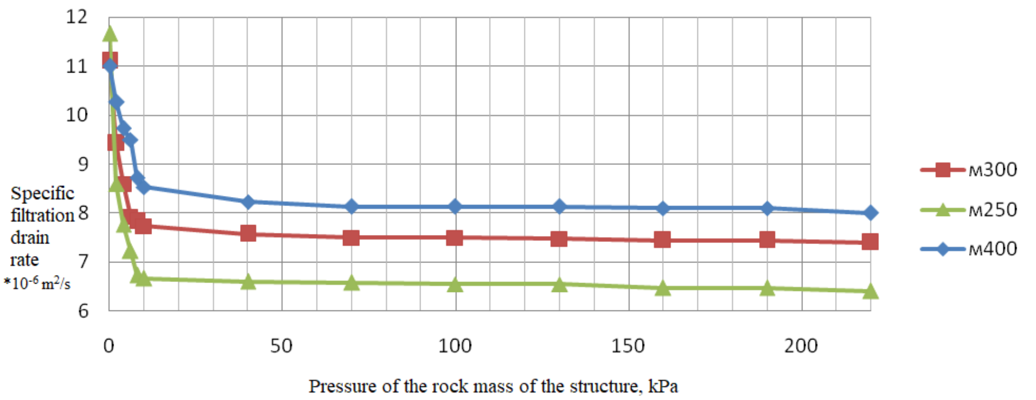


Figure 5. The dependence of the specific filtration water flow rate passing through the reservoir drain pressured by the rock mass.

Because the graphs are variable in the load range 0...200 kPa it is necessary to approximate the experimental results separately for two sections: 0...8 kPa and 8...200 kPa.

Let us consider the change in filtration flow in the load range 0...8 kPa (Fig. 6).

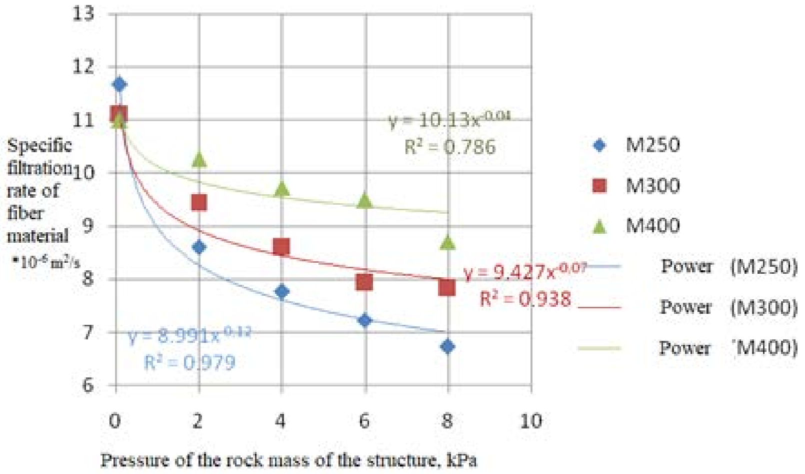


Figure 6. Approximation of the dependence of the specific filtration flow rate of reservoir drain pressured by the rock mass in the load range 0...8 kPa.

The math dependencies obtained in the course of approximation by means of Microsoft Excel have the nature of a power function of the form:

$$y = a_1 \cdot x^{-b_1}, \quad (3)$$

where a_1, b_1 are empirical coefficients of change in filtration flow obtained during approximation in the load range 0...8 kPa (Fig. 6).

Confidence level of the power approximation of experimental data, depending on the grade of material has the following meanings:

– for the fiber material M400, the accuracy of the approximation is $R^2 = 0.79$;

– for the fiber material M300, the accuracy of the approximation is $R^2 = 0.94$;

– for the fiber material M250, the accuracy of the approximation is $R^2 = 0.98$.

The change in filtration water flow in the load range of 0...8 kPa is:

– for the fiber material M400 – 42.3 %;
– for the fiber material M300 – 29.5 %;
– for the fiber material M250 – 20.8 %.

Let's consider the change in filtration water flow in the load range of 10...200 kPa (Fig. 7).

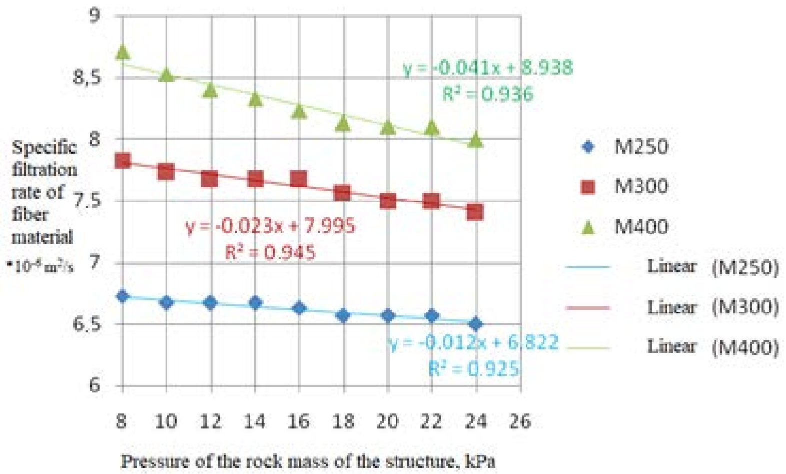


Figure 7. Approximation of the dependence of the specific filtration flow rate of reservoir drain pressured by the rock mass in the load range of 10...200 kPa.

The dependence obtained during the approximation is expressed in general terms by the formula (linear dependence):

$$y = a_2 \cdot x + b_2, \tag{4}$$

where a_2, b_2 are empirical coefficients of change in the filtration flow obtained during the approximation in the load range of 10...200 kPa (Fig. 7).

The confidence level of the power approximation of experimental data, depending on the grade of material has the following meanings:

- for the fiber material M400, the accuracy of the approximation is $R^2 = 0.67$;
- for the fiber material M300, the accuracy of the approximation is $R^2 = 0.76$;
- for the fiber material M250, the accuracy of the approximation is $R^2 = 0.93$.

The change in filtration water flow in the load range of 10…200 kPa is:

- for the fiber material M400 – 8.2 %;
- for the fiber material M300 – 5.5 %;
- for the fiber material M250 – 4.8 %.

A decrease in the filtration water flow rate of a fiber device under pressure is determined by the gradient of the filtration flow rate according to Formula 5, depending on the surface density of the material.

$$\Delta q_D = \left(q_{D,0} - q_{D,P}\right) = \frac{\partial q_D}{\partial \sigma_n} \cdot \sigma_n, \tag{5}$$

where $q_{D,0}$ is filtration flow rate without load, m²/s; $q_{D,P}$ is filtration flow rate at a given load, m²/s; σ_n is pressure of the rock mass of the structure on the polymeric material, kPa.

The height value of the gradient of the filtration water flow rate is obtained by the experiment and is presented in Table 1.

Table 1. The gradient of the filtration water flow rate passing through the drain.

Material grade	Gradient of filtration water flow $\frac{\partial q_D}{\partial \sigma_n}$ for pressure range:	
	0…8 kPa	8…200 kPa
M250	0.618	$0.146*10^{-2}$
M300	0.409	$0.208*10^{-2}$
M400	0.286	$0.333*10^{-2}$

Therefore, to determine the parameters of the filtration control device (layer height and slope), taking into account the change in the gradient of the filtration flow rate of the fiber polymer material is carried out according to Formulas 6 and 7 (A. Darcy's formula for calculating the layer height, V.S. Kozlov's formula for determining the slope of the unit [21, 24, 25]).

$$h_D = \frac{\left(q_D + \frac{\partial q_D}{\partial \sigma_n} \cdot \sigma\right) \cdot L_D}{F_f \left(h_B + H_1\right)}, \tag{6}$$

$$i_D = \frac{2 \cdot \left(q_D + \frac{\partial q_D}{\partial \sigma_n} \cdot \sigma\right) - \frac{K_f \cdot H_1^2}{L_D}}{F_f \cdot H_1}. \tag{7}$$

Formulas 6 and 7 allow to determine the main parameters of filtration control devices based on fiber polymeric materials of artificial hydraulic rock structures, taking into account the decrease in longitudinal filtration flow caused by the presence of external pressure created by the overlying rock mass of embankments and dams [27].

Calculation of and embankments made from rocks is performed by the equivalent profile method [17]. It determines the filtration coefficient of the rocks composing the body of the structure and the base (in this case there is a permeable base under the structure), and generates the drawdown curve. Next, it determines the filtration water flow rate passing through the fiber material, the drain width L_D, and material load. The layer height and slope is determined according to Formulas 6 and 7.

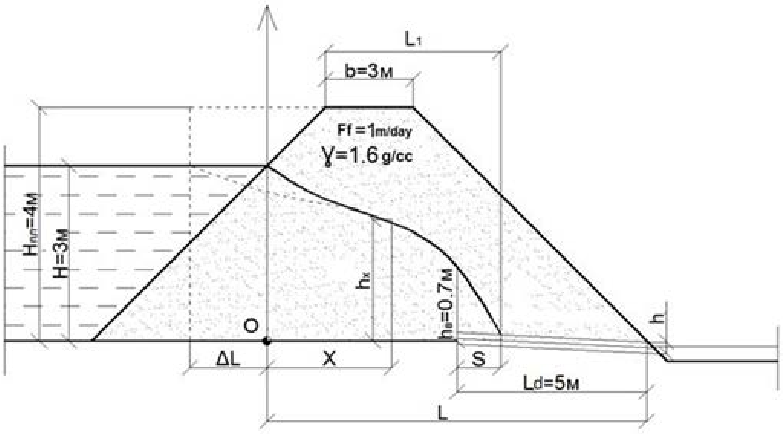


Figure 8. Water filtration through the body of the dam with drain of fiber materials on a waterproof base.

It is done with the following parameters of the structure: the height of the structure is 4m, the filtration coefficient of rocks is 1 m/day, the slope is 1:2, and the fiber material is M300 with a filtration coefficient of 100 m/day. The calculation showed: the pressure at the front of the device is 0.7 m, the drain width is 5 m, the drain load is 0.04 MPa, the filtration water flow rate passing through the structure is 0.6 m^2/day, and the filtration water flow rate through the drain is 0.69 m^2/day.

$$h_D = \frac{\left(q_D + \frac{\partial q_D}{\partial \sigma_n} \cdot \sigma\right) \cdot L_D}{K_D\left(h_B + H_1\right)} = \frac{\left(0.69 + 0.208 \cdot 10^{-2} \cdot 0.04\right) \cdot 5}{100\left(0.7 + 0.1\right)} = \frac{3.45}{80} = 0.04\ \text{m},$$

$$i_D = \frac{2 \cdot \left(q_D + \frac{\partial q_D}{\partial \sigma_n} \cdot \sigma\right) - \frac{K_D \cdot H_1^2}{L_D}}{K_D \cdot H_1} = \frac{2 \cdot \left(0.69 + 0.208 \cdot 10^{-2} \cdot 0.04\right) - \frac{100 \cdot 0.1^2}{5}}{100 \cdot 0.1} = 0.118\left(6.7^{\text{O}}\right).$$

4. Conclusions

1. There has been established the possibility of using reservoir drain structures based on fiber polymeric materials, including the weight of the rock mass of the structure.

2. Experimental research were conducted to investigate the effect of changes in the pressure of rocks of the structure on the filtration flow rate of water passing through the drainage.

3. Methods for calculating the layer height and slope of the drain from fiber materials was developed.

Professor Gerasimov V.M. a methodology for calculating reservoir drainages was proposed [21], but it does not take into account the influence of the pressure of the rock mass on specific filtration water flow rate passing through the reservoir drain. The proposed formulas for calculating the layer height and slope allow taking into account pressure of the rock mass.

The question of clogging of fibrous materials with fine particles remains open; in future works, this issue will be elucidated.

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Contacts:

Evgenii Nizhegorodtcev, dj_world@mail.ru

Viktor Gerasimov, kafsmim@zabgu.ru

Kristina Svalova, kristi24091990s@yandex.ru

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