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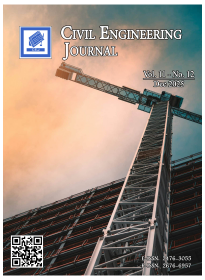

The Influence of the Fine Earth Composition of the Soil Mixture on the Parameters of Its Filtration, Moisture Content, and Density

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Abstract

The article presents the results of laboratory studies on the patterns of change in the filtration coefficient of the fine-grained component (fine earth) of the soil mixture from a number of influencing factors. The study was conducted to assess the impact of the fine earth fractional composition of a soil mixture on its filtration parameters and density-moisture state. The experiments were conducted using a compression device, the use of which is regulated by the standard of the Republic of Kazakhstan. One hundred and twenty-six fine earth samples were tested, containing 50 to 75% (by weight) of various fractions with particle sizes smaller than 5 mm. An analysis of the test results revealed that for large fractions (with particle sizes of 5 mm or less, but more than 1 mm), the filtration coefficient of fine earth increases as the weight content of fractions in it increases (from 50 to 75%), while for small fractions (with particle sizes of 1 mm or less), it decreases. It was determined that similar patterns are characteristic of the increase in moisture content and increase in the density of fine earth, which occur when water is filtered through it. The scientific novelty of the research lies in the fact that, based on the identified patterns, correlation dependencies were established between the filtration coefficient and the weight content of various fractions, as well as the increase in moisture content and the increase in the density of fine earth. Correlation dependencies of the filtration coefficient on the weight content of various fractions, as well as on the increase in moisture content and increase in the density of fine earth, were established. Based on the established relationships, formulas were developed for predicting the filtration coefficient, moisture content, and density of fine earth, which adds practical value to the research. These formulas are recommended for use in selecting optimal fine earth compositions for soil mixtures used in dam construction.

Keywords: Fine Earth; Soil Mixture; Fraction; Fraction Weight; Solid Particles; Filtration; Filtration Coefficient; Moisture; Density.

1. Introduction

The permeability of soils, i.e., their ability to filter water, is an important property that has a direct impact on the operational state of soil hydraulic structures. Soil filtration is characterized by the speed, duration, and coefficient of filtration, as well as the current and initial pressure gradients and other parameters.

Water filtration as a physical phenomenon in hydraulic structures is one of the frequent causes of their failures and destruction. This is especially typical for earth dams, the share of which is 80-90% of their total number [1]. It is known that approximately 40-45% of failures and destruction of earth dams occur due to the violation of their filtration regime and filtration deformations, which lead to water loss and the manifestation of suffusion and erosion [2-4]. Dam failures are also inherent in the water sector of the countries of Central Asia and Kazakhstan [5, 6]. In most cases, it is filtration that determines the need for the device of anti-filtration elements (screens, cores, blankets, etc.) in earth structures. For example, to ensure the necessary water-holding capacity of structures (flattened profile), erected from sand and on a sandy foundation, with filtration coefficient values more than 20-30 m/day, the device of anti-filtration elements is required [7]. At lower values of this coefficient, on the contrary, such elements are not required.

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Experience in the operation of hydraulic earth structures, as well as the results of scientific research in this area, indicate that water filtration through the body of an earth dam is a complex and dynamically changing process over time, depending on the properties of the soils, the design features of the dams, and the conditions of their operation [8-10].

The multifactorial dependence of the filtration process in soils on a number of circumstances, as well as its importance for the formation of the composition of earth dam structures, determines the relevance and value of studying and assessing the filtration properties of soils. Considering that one of the main parameters of soils characterizing their filtration capacity is the filtration coefficient, it is equally important to establish stable patterns of its change for the purpose of their subsequent use in the design and construction of earth structures. Numerous studies in the field of hydraulic engineering have examined this topic, and a concise synthesis of their key findings is presented below:

Kanarskii et al. [7] proposed to evaluate the water-holding capacity of a structure of a flattened profile, erected from sand-gravel-pebble soil, graphically based on the filtration coefficient. The values of the filtration coefficient for each soil layer are plotted on the cross-sectional diagram of the structure. In this case, the values of the filtration coefficient are preliminarily established by calculation depending on the following soil parameters:

- Viscosity coefficient;
- Specific gravity (density) of particles;
- Specific gravity of the skeleton (density in a dry state);
- Porosity in an extremely loose state, an extremely dense state, and an intermediate state;
- Average particle diameter.

Specialists have constructed corresponding schemes with filtration coefficient values for vulnerable sections of a number of structures, and based on them, a forecast of the filtration capabilities of the objects was made. The research results were used in the design and construction of water protection structures of the Tersko-Malkinsky hydroelectric complex.

The research of Semashkin & Shestakov [11] established that the filtration properties of clay soil when treated with a solution of NAOH (caustic soda) change significantly. Thus, the results of laboratory experiments made it possible to reveal that when treating light loam with a solution of NAOH, the filtration coefficient values are significantly reduced. It was determined that with a 2-3-fold increase in the concentration of this solution, the filtration coefficient of loam decreases by 2.2-4.0 times. This method of reducing the filtration capacity of clay soil is recommended for creating water-permeable screens in soil structures.

Kumar et al. [12] carried out work on improving the methods of filtration calculation of earth dams taking into account their anisotropic permeability. The relevance of the results of these studies is substantiated by the fact that one of the main causes of destruction and damage to earth dams with a height of 15 to 30 m is filtration deformations of the soils of the body and foundation of dams caused by their anisotropic permeability, i.e. unequal ability to filter water in different directions. This property of soils is due to their heterogeneity of composition, uneven placement and instability of the stress-strain state of dams during operation. In the studies, the filtration process in anisotropic-permeable soils was studied by the method of electrohydrodynamic analogies (EHA) on models made of homogeneously isotropic and anisotropic electrically conductive materials. In this case, the anisotropic medium was taken as a fictitious isotropic permeable medium with a filtration coefficient determined as the square root of the product of filtration coefficients related to two mutually perpendicular directions. The author developed recommendations for taking into account the anisotropic permeability of soils when performing filtration calculations for earth dams.

Amshokov [13] proposed methods for filtration calculations of dams with soil and non-soil anti-filtration devices. Based on the results of the studies, a correlation dependence was proposed for determining the filtration coefficient of the dam core soil based on the relative height of the impermeable (non-soil) anti-filtration diaphragm. Based on this dependence, filtration calculations of earth dams with anti-filtration diaphragms are recommended to be performed as for dams with rectangular cores. The results obtained from the experimentally established dependence are compared with the results of experiments performed using the electrohydrodynamic analogy method (EHA). It was revealed that the error in determining the filtration coefficient using the proposed dependence does not exceed 3-4%.

Sergeev et al. [14] recommended a method for calculating non-stationary filtration for homogeneous soil hydraulic cofferdams. The author notes that the process of establishing a depression curve in the cofferdam body from the moment of its commissioning covers a certain period of time. This period is characterized by non-stationary water filtration, which is caused by the heterogeneity of soil placement, their frost heaving and other factors. For such a case, the well-known Boussinesq equation is adopted as a theoretical basis for developing a method for calculating non-stationary filtration, which includes such parameters as the filtration coefficient, soil porosity, filtration flow depth, etc. The proposed method is distinguished by the fact that the non-linear Boussinesq equation is supplemented by integral relationships that allow one to establish instantaneous positions of depression curves through experimentally established values of the filtration coefficient of the cofferdam soils.

Malakhanov [15] introduced a quantitative relationship for determining the optimal stone diameter within the coarse -grained materials used in the filter spillway of earth dams. The required stone size ensuring adequate shear resistance under seepage flow is expressed as a function of key hydraulic and material parameters, including the specific gravity of water, the specific gravity of the stone particles, and the flow velocity along the downstream slope of the dam. The flow velocity itself is governed by the slope geometry and surface roughness. Based on the findings, the author concludes that the hydraulic stability and long-term performance of the dam's filter spillway are predominantly controlled by the diameter of the stones constituting the coarse-grained soil matrix.

Studies on alluvial gravel–pebble soils have shown that the filtration coefficient is strongly influenced by the size distribution of solid particles [16]. Experimental results indicate that an increase in the average particle diameter leads to higher filtration coefficients, although the rate of increase gradually diminishes as particle size becomes larger. It has also been observed that the variability of filtration coefficient values expands with increasing particle size, in some cases reaching ±150–200%. This behavior suggests that the presence and proportion of fine particles (smaller than 0.25 mm) play a significant role in controlling permeability. Recent research on gravel soils confirms that differences in fine-particle content are the primary cause of the observed spread in filtration coefficient values among soils with similar mean particle sizes.

Mikanovich & Lasuta [17] presented in their study the results of investigations into the filtration properties of the soils used in the hydraulic containment structures of sludge storage facilities. Their findings show that the sludge contains polyacrylamide, a surfactant that influences the rheological behavior of the sludge liquid. The authors identified a correlation between the filtration coefficient and the polyacrylamide content in the sludge for sandy soils, within a concentration range of 0.17 to 0.90 mg/dm^3. They also determined that the sludge filtration rate, measured at 0.045–0.047 cm/s, exceeds the filtration rate of water by a factor of 1.2–1.4. The results further demonstrate that the presence of polyacrylamide in the sludge is the primary factor causing filtration-related deformations in the soils of sludge storage facilities.

Muruzina [18] has found, based on experiments, that sandy soil in its natural state is characterized by constant heterogeneity in granulometric composition. Therefore, when determining the filtration coefficient of such soils, it is important to take into account the content of gravel particles with sizes from 2 mm to 10 mm. The author believes that the content of gravel particles leads to an increase in the values of the filtration coefficient of soils. However, despite such an affirmative conclusion, Muruzina [18] does not provide detailed data on the fractional composition of the gravel particles used in the experiments.

Noskov et al. [19] presented the results of experimental studies of the filtration properties of peat, carried out with the aim of using it as a material for anti-filtration screens in the soil foundations of structures. It is shown that as the duration of filtration increases, the values of the filtration coefficient of peat soil change significantly. Thus, experiments have established that the attenuation of the filtration rate for well and moderately decomposed peats occurs within 8-9 days. Then stabilization occurs. For poorly decomposed peats, on the contrary, the filtration rate increases over time. Experiments conducted at construction sites in the Novosibirsk Region have shown that complete stabilization of the filtration rate for moderately decomposed peat occurs after 10-15 days. The values of the filtration coefficient of peat decrease by 1.5-2 times. These changes are explained by the peculiarities of swelling of peat particles and the restructuring of its structure under the hydrodynamic effect of water.

Korolev & Fazylov [20] presented the results of a brief review of studies concerning the filtration properties of clay soils in aqueous salt solutions. It was revealed that the composition and concentration of aqueous solutions of various salts has a significant effect on the filtration parameters of soils. It is shown that the filtration coefficient of clay soils varies by 2-9 or more times depending on their mineralogical composition, degree of mineralization and composition of salt solutions. The established features of soil behavior are recommended to be taken into account when designing and constructing dams with a clay core, as well as when constructing sludge ponds and tailings storage facilities from salt-containing clay soils.

Baev et al. [21] presented the results of determining the filtration coefficient of cohesive soils of the foundation of the Yashkul channel in Kalmykia. The studies were conducted with the aim of developing and implementing measures to reduce water losses. By comparing the experimental and calculated values of the filtration coefficient, it was found that the Kruger calculation method used allows one to obtain underestimated data (by 7.1%). In this regard, the authors used only experimental values of the filtration coefficient when performing filtration calculations. The Kruger method is recommended for use only for an approximate estimate of the filtration coefficient of cohesive soils.

Research conducted by Kvashchuk [22] determined that the filtration properties of sandy soils are affected by the content of petroleum products formed during their pollution. It was found that the values of the filtration coefficient of coarse sand decrease as the content of petroleum products increases. This is explained by the fact that petroleum products, having viscous properties, promote the adhesion of sandy soil particles, and thus create micro-barriers to the path of water filtration. The author recommended that the established pattern be taken into account when performing a predictive assessment of the settlement and bearing capacity of sandy foundations contaminated with oil products.

Kharchenko et al. [23] presented the results of studies demonstrating the influence of the filtration coefficient of sandy soils on the spread of the injection mixture "Introcem" in them, created on the basis of slag microcement. It is shown that with an increase in the filtration coefficient from 0.5 to 4 m/day, the spreading radius of this mixture in soils increases from 20 to 180 cm. The established effect allows us to recommend the injection mixture "Introcem" for the compaction and strengthening of sandy soils, especially in their loose state. The authors consider the use of injection technologies as one of the promising methods for eliminating the karst-suffusion hazard of soil foundations.

Panov & Baranova [24] conducted experiments to determine the filtration coefficient of sandy soil with a variable pressure gradient and different fractional compositions. The experiments were conducted using a Kamensky tube. Homogeneous sand fractions with the following particle sizes were used in the experiments: 1.0; 0.5; 0.25 and 0.1 mm. Based on the processing of the research results, a correlation was obtained between the values of the filtration coefficient and the size of the sand particles. The nature of the dependence shows that an increase in the size of the sand particles is accompanied by an increase in its filtration coefficient. The research results qualitatively confirm the results of the experiments presented by Ma et al. [16].

Sainov & Boldin [25] reviewed the results of studies that showed that the filtration coefficient of Safedob sandy loam is significantly affected by the density of fine earth and its content. From the graph, constructed in semi-logarithmic coordinates and presented by the authors, it follows that the relationship between the values of the filtration coefficient of sandy loam and the density of fine earth is linear. Moreover, the higher the density and the lower the fine earth content, the lower the filtration coefficient of sandy loam. The established pattern is consistent with a change in the density of fine earth from 1.8 to 2.3 g/cm3 and a fine earth content from 40 to 80%.

In Kidder & Behaya [26], it is noted that the permeability of soils depends not only on their properties but also on the properties of the water passing through them. The author presents a relationship for determining the soil permeability coefficient, which allows for assessing the permeability of soil taking into account water parameters. This coefficient is determined based on water parameters such as dynamic viscosity and density, as well as the filtration coefficient of the soil itself.

The research results presented by Kozlowski & Ludynia [27] indicated that the filtration coefficient of soils depends on their porosity, and this relationship is described by a power function. Moreover, this pattern is characteristic of both parallel and perpendicular soil stratification. In non-layered soils, the filtration coefficient values in different directions differ only slightly, whereas in layered soils this difference is somewhat greater, amounting to 5-10%.

Marinin et al. [28] studied the filtration properties of pelletized sandy-clayey ores. It was found that the filtration coefficient of pelletized ores depends on their degree of water saturation. The research results indicate that increasing the degree of water saturation of the ores is accompanied by a decrease in their filtration coefficient. Thus, it was established that increasing the degree of water saturation from 0.55 to 0.95 leads to a decrease in the filtration coefficient from 20 to 1 m/day.

The presented analysis of the research results indicates that the filtration properties of soils depend on the following factors:

- Soil type, layering, anisotropic properties, density, porosity, and degree of water saturation;
- The size and quantity of large and small soil particles;
- The content of soda, salts, petroleum products, and polyacrylamide in the soils;
- The density and dynamic viscosity of water in the soils.

Of the factors influencing the seepage stability of earthen dams, those related to the particle size distribution of soils are poorly understood. This is because existing studies fail to reveal the specific influence of soil particle size and number on their seepage coefficient values, in relation to soil density and moisture content over a wide range of changes in their particle size distribution. This is evidenced by the lack of correlations between soil seepage coefficients and particle size distribution parameters, as well as between soil density and moisture content before and after the completion of the seepage process. The need to establish such relationships is driven by the fact that the density and moisture content of soils are directly related to their permeability, necessitating a comprehensive study of the variability of soil density, moisture content, and seepage coefficient as water passes through them.

The circumstances considered prevent specialists from differentially assigning soil particle size distributions based on required (minimum permissible) filtration coefficient values. A positive solution to this problematic issue would enable the selection of the optimal particle size distribution of the fine-grained component of soil mixtures used to construct impermeable elements of earth dams. Therefore, the objective of this research is to experimentally study the influence of various fine-grained component fractions in soil mixtures on their moisture content, density, and filtration coefficient. Furthermore, the objectives of the study include establishing possible correlations characterizing changes in the filtration coefficient of fine earth depending on the weight content of various fractions, as well as changes in its density and moisture content before and after filtration.

This research is part of the authors' ongoing research into the development of a methodology for selecting optimal soil mixture compositions for the efficient construction of earthen dams [29, 30].

Structurally, the article includes:

- A description of the research methodology, instruments, and soil data;
- A presentation of the experimental results, their analysis, and discussion;
- A statement of the main conclusions.

2. Materials and Methods

The studies were conducted using artificial compositions of soil mixtures obtained on the basis of heterogeneous gravel coarse-grained soil (weight of particles larger than 2 mm - 53.65%) with sandy loam filler (content of clay filler - 30.65%). By means of dosed selection and addition of soil particles, six groups of experimental samples of fine-grained component (hereinafter referred to as fine earth) with particle sizes of 5 mm and less were compiled (Table 1).

Table 1. Information on the fractional composition of experimental fine earth samples

Group number	Fraction designation	Particle size *d*, (mm)	Weight fraction content (%)
1	m_{5-2}	$5.0 \geq d > 2.0$	50-75
2	m_{2-1}	$2.0 \geq d > 1.0$	
3	$m_{1-0.5}$	$1.0 \geq d > 0.5$	
4	$m_{0.5-0.25}$	$0.5 \geq d > 0.25$	
5	$m_{0.25-0.1}$	$0.25 \geq d > 0.1$	
6	$m_{\leq 0.1}$	$0.1 \geq d$	

As can be seen from Table 1, each experimental fraction in the samples is characterized by a certain range of change in the size of solid particles and their specific weight amount in the fine earth composition. The range of change in the weight number of fractions in the samples is taken to be 5% of their total weight. The increase in the weight amount of each experimental fraction of fine earth was carried out by reducing the weight content of the coarse-grained component of the soil mixture.

The filtration properties of the experimental fine earth samples were studied in the scientific laboratory "Nanoengineering Research Methods" of the M.Kh. Dulaty Taraz University (Figure 1). The experiments were conducted using a compression device included in the PLL-9 field laboratory and designed to determine the filtration coefficient of dusty and clayey soils [31].

Filtration tests were performed in accordance with the requirements of regulatory documents [31, 32]. During the studies, the following characteristics of fine earth samples were established: duration of water filtration; level of water reduction during filtration; filtration coefficient; mass, moisture content and density before and after testing (Figure 1). The moisture content and density of fine earth were determined in accordance with the requirements of the standard [33]. A total of 126 fine earth samples were tested in the study. The tests were repeated three to four times with the same sample composition. Results (density, moisture content, and filtration coefficient) that differed by more than 5% were rejected.

Figure 1. Preparing Fragments of the process of studying the characteristics of fine-earth samples: the duration of water filtration, the level of water reduction during filtration, the filtration coefficient, mass, humidity, density before and after testing.

The laboratory testing procedure is presented in a simplified flowchart in Figure 2.

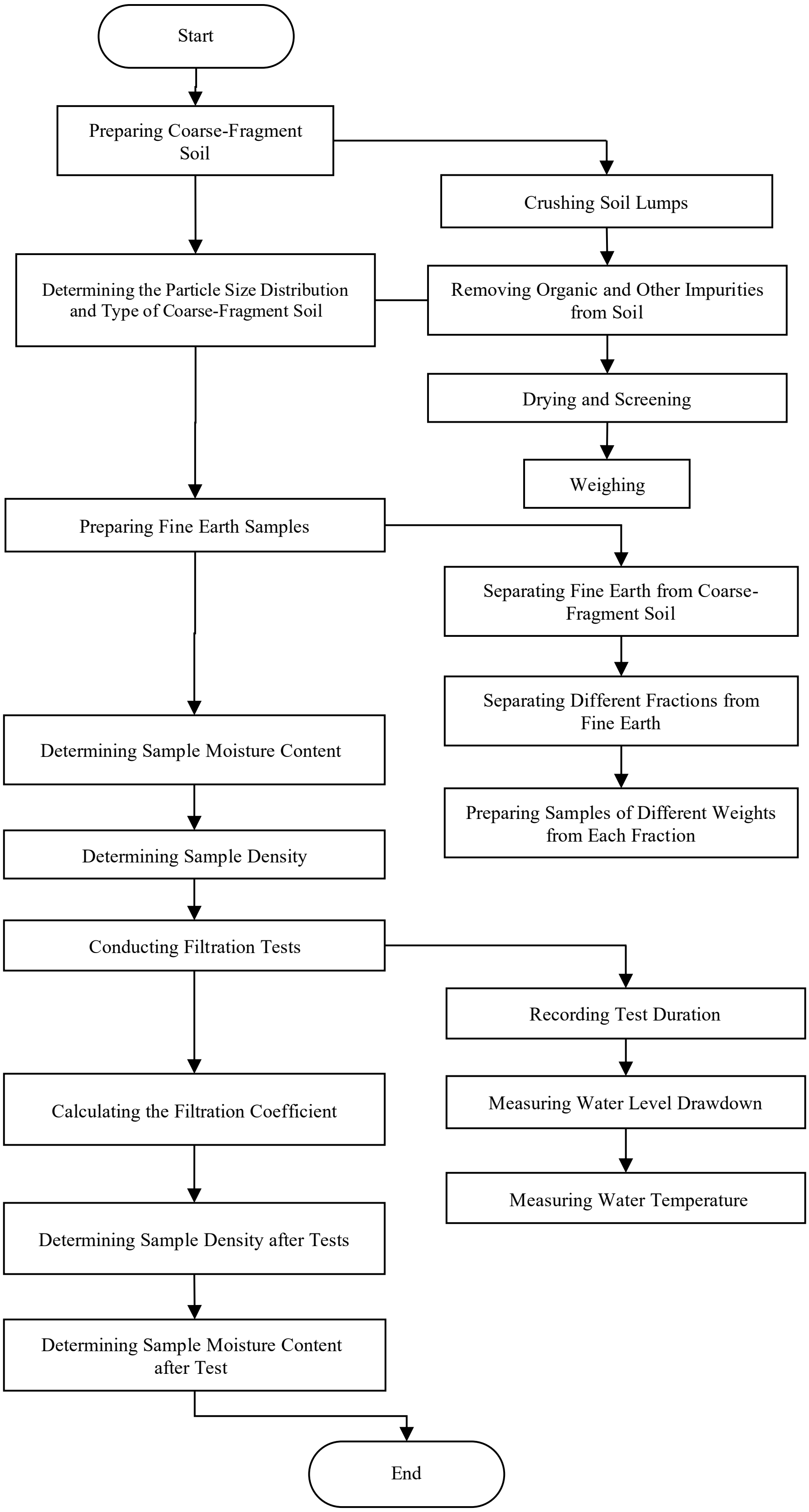

Figure 2. Research flow chart

3. Research Results

During the filtration process, the water level in the samples decreases. Figures 3 to 6 show, as an example, the graphs of the dependence of the water level decrease S on the filtration duration t_f, typical for samples containing fractions m_{5-2}, m_{2-1}, $m_{1-0.5}$ and $m_{\leq 0.1}$. It was found that as the filtration duration t_f increases, the water level decrease S increases, and the dependence $S = f(t_f)$ is a linear function.

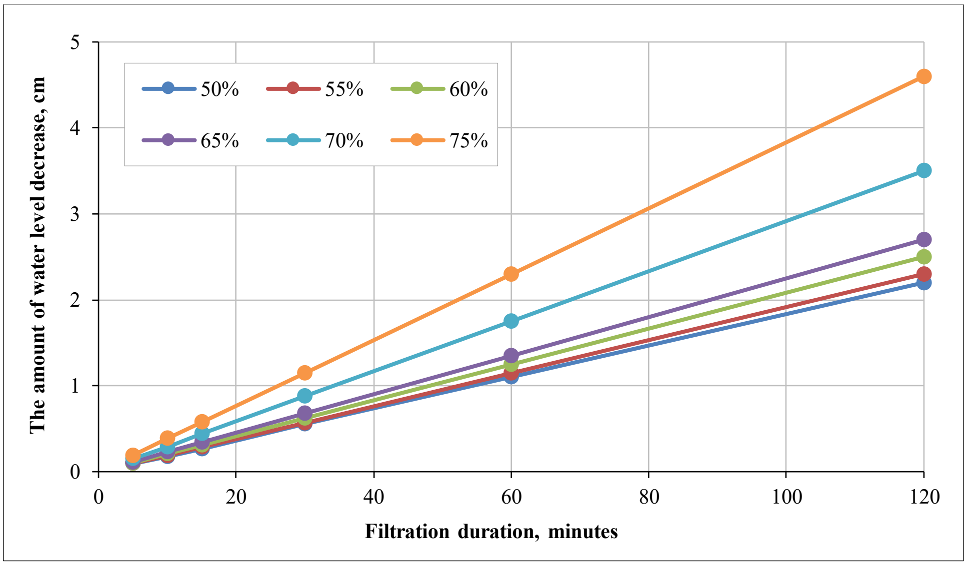

Figure 3. Dependence of the value of the decrease in the water level S on the duration of filtration t_f for samples containing fractions m_{5-2} (with a weight content from 50% to 75%)

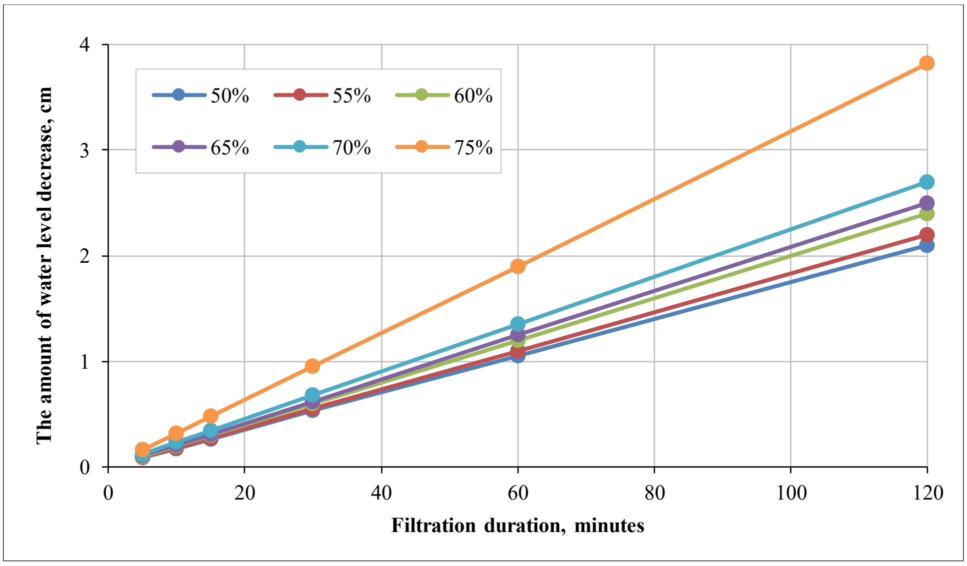

Figure 4. Dependence of the value of the decrease in the water level S on the duration of filtration t_f for samples containing fractions m_{2-1} (with a weight content from 50% to 75%)

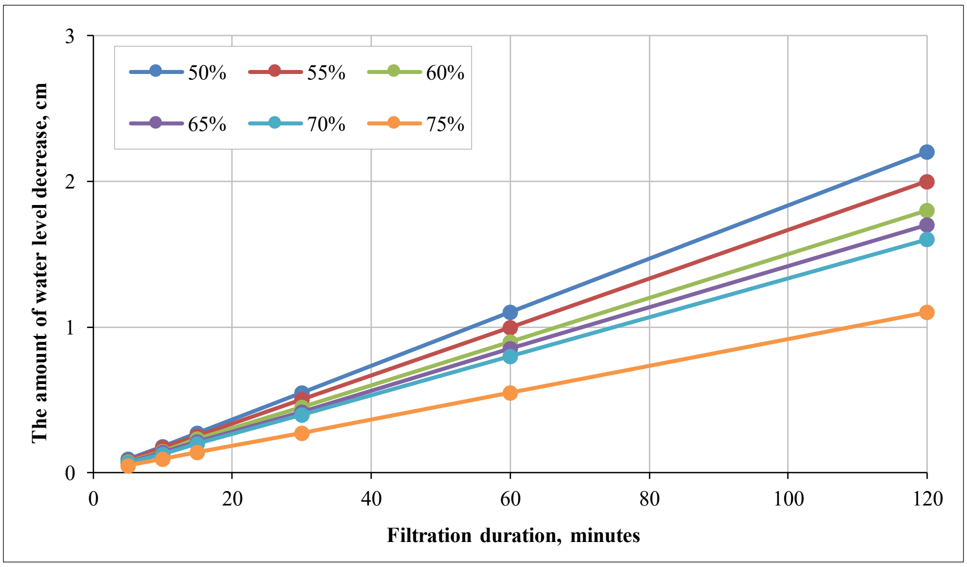

Figure 5. Dependence of the value of the decrease in the water level S on the duration of filtration t_f for samples containing fractions $m_{1-0.5}$ (with a weight content from 50% to 75%)

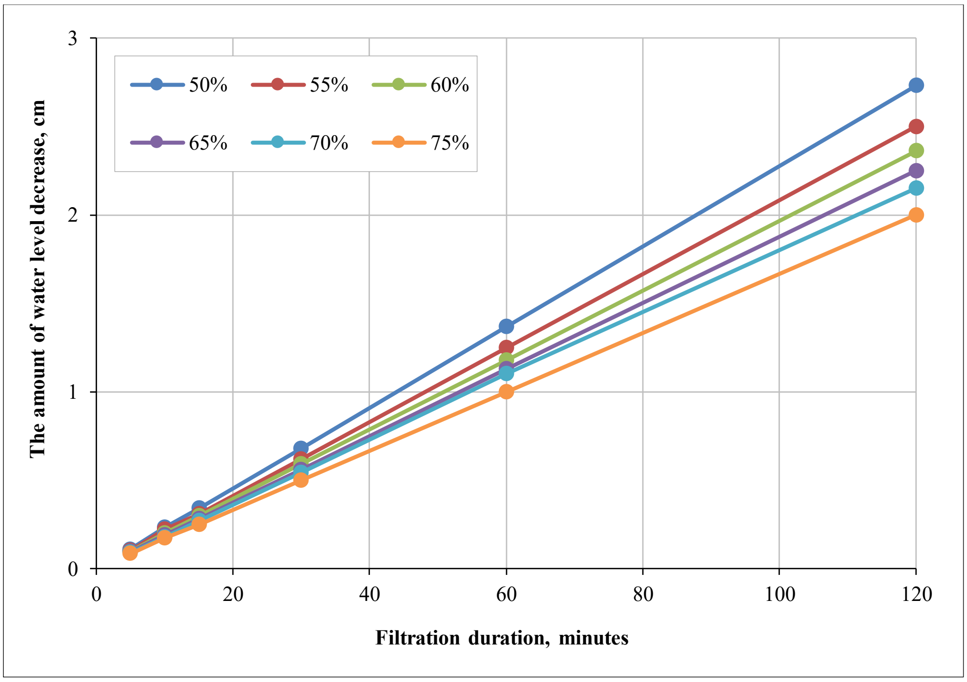

Figure 6. Dependence of the value of the decrease in the water level S on the duration of filtration t_f for samples containing fractions $m_{\leq 0.1}$ (with a weight content from 50% to 75%)

The magnitude of the water level decrease S also depends on the particle sizes and the weight number of fractions m_f. From the graphs shown in Figures 7 and 8, it follows that for the experimental samples containing fractions m_{5-2} and m_{2-1}, the magnitude of the water level decrease S in the filtration device is the greater, the larger the particle sizes and the weight number of fractions m_f in the fine earth. The dependence $S = f(m_f)$ for the samples containing fractions m_{5-2} and m_{2-1} increases intensively as the weight number of fractions m_f increases, and is curvilinear. This circumstance is due to the fact that with an increase in the particle sizes and the weight number of large fractions m_f in the samples, the pore volume in the fine earth increases, which ensures a greater decrease in the water level during filtration.

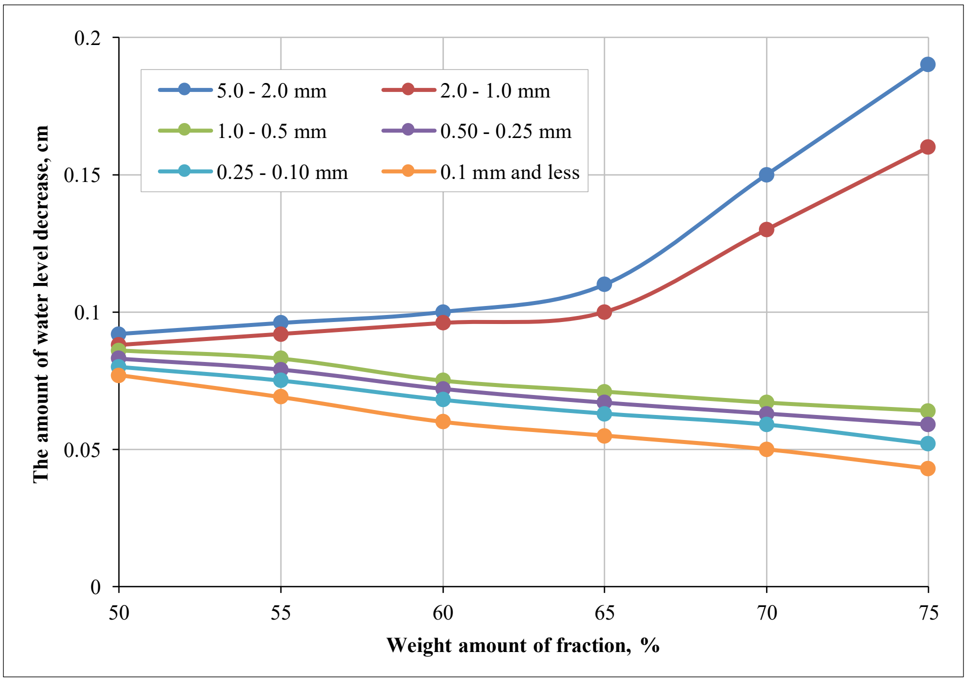

Figure 7. Dependence of the magnitude of the decrease in the water level S on the weight number of fractions m_f with a filtration duration of t_f = 5 min (for fractions m_{5-2}, m_{2-1}, $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$)

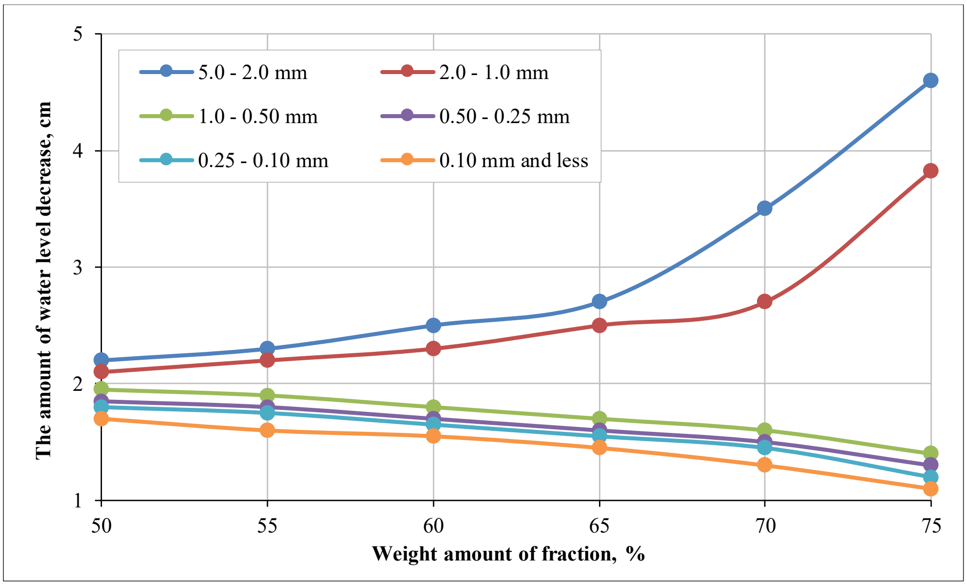

Figure 8. Dependence of the magnitude of the decrease in the water level S on the weight number of fractions m_f with a filtration duration of t_f = 120 min (for fractions m_{5-2} , m_{2-1} , $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$)

As can be seen from the graphs presented in Figures 7 and 8, a slightly different pattern is observed for samples containing fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$. For these samples, the dependence $S = f(m_f)$ decreases uniformly as the weight number of fractions m_f increases and is close to a linear function. Moreover, the smaller the particle sizes of the fractions, the smaller the value of the decrease in the water level S. The revealed features are explained by the fact that with a decrease in the particle sizes and an increase in the weight number of small fractions in the samples, the pore volume of the soil mixtures decreases, which ensures a small decrease in the water level during filtration.

The particle size and the weight percentage of fractions m_f in the samples also affect the rate of water level decrease v_b, which is determined as the ratio S/t_f). Within the test of one sample, the rate v_b remains virtually constant, but it varies for different samples and depends on the weight percentage of fractions m_f in them. Thus, the range of change in the rate v_b in the experiments was:

- 0.0184 – 0.0380 cm/min in samples containing fractions m_{5-2} from 50% to 75%;
- 0.0176 – 0.0320 cm/min in samples containing fractions m_{2-1} from 50% to 75%;
- 0.0183 – 0.0100 cm/min in samples containing fractions $m_{1-0.5}$ from 50% to 75%;
- 0.0204 – 0.0150 cm/min in samples containing fractions $m_{0.5-0.25}$ from 50% to 75%;
- 0.0216 – 0.0158 cm/min in samples containing fractions $m_{0.25-0.1}$ from 50% to 75%;
- 0.0228 – 0.0166 cm/min in samples containing fractions $m_{\leq 0.1}$ from 50% to 75%.

It follows from the data provided that for the samples containing fractions m_{5-2} and m_{2-1} , the lowest values of the velocity v_b apply to the samples with a low weight number of fractions, and the highest values apply to the samples with a high weight number of fractions. Thus, an increase in the weight number of fractions m_{5-2} by 1.1-1.5 times (from 50% to 75%) causes an increase in the velocity v_b by 1.04-2.07 times. For fractions m_{2-1}, such an increase in the velocity v_b is 1.1-1.83 times. In this case, the velocity v_b decreases with a decrease in the particle sizes of the fractions (with the same weight number of fractions). A decrease in the range of particle sizes of fractions from 5-2 mm to 2-1 mm corresponds to a decrease in the velocity v_b by 4.35-15.79%. From a comparison of the data related to samples containing fractions m_{5-2} and m_{2-1} , it follows that the rate of decrease in the water level v_b is more influenced by the weight of the fractions, and less by the particle sizes of the fractions.

For samples containing fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$, the lowest values of velocity v_b apply to samples with a large weight number of fractions, and the highest values apply to samples with a small weight number of fractions. An increase in the weight number of fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$ by 1.1-1.5 times leads to a decrease in velocity v_b by 3.92-45.35%, respectively. A decrease in the particle size range of fractions from 1-0.5 mm to 0.1 mm or less (with the same weight number of fractions) is accompanied by an increase in velocity v_b by 1.24-1.66 times. From a comparison of the data related to samples containing fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$, it follows that the rate of decrease in the water level v_b is less influenced by the weight of the fractions, and more influenced by the particle sizes of the fractions.

From the presented experimental results, it follows that for the two groups of samples considered, the patterns of change in the rate of decrease in the water level v_b differ significantly.

Analysis of the research results revealed that the filtration coefficient k_f during the testing of the samples varied in the range from 0.00102 cm/sec to 0.000053 cm/sec depending on the particle size and the weight number of fractions m_f contained in the samples (Table 2). For samples containing fractions m_{5-2} and m_{2-1}, with an increase in their weight amount by 1.1-1.5 times (from 50% to 75%), the filtration coefficient k_f increases by 1.05-2.43 and 1.02-2.09 times, respectively (Figure 9), and for samples containing fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$ – on the contrary, it decreases by 1.02-1.84, 1.03-2.15, 1.1-2.97 and 1.28-4.43 times, respectively (Figure 9). Reducing the range of particle sizes of fractions from 5-2 mm to 2-1 mm causes a decrease in the filtration coefficient k_f by 6.68-20%, and when reducing the range of particle sizes of fractions from 1-0.5 mm to 0.1 mm or less, the filtration coefficient k_f decreases by 34.54-72.82%. Comparison of the presented data shows that the values of the filtration coefficient k_f are more influenced by the weight number of fractions, and less by the sizes of the particle fractions.

Table 2. Values of the filtration coefficient k_f of fine earth

Weight quantity of fractions m_f, %	Values of the filtration coefficient k_f, cm/sec, for samples containing the following fractions					
	m_{5-2}	m_{2-1}	$m_{1-0.5}$	$m_{0.5-0.25}$	$m_{0.25-0.1}$	$m_{\leq 0.1}$
50	0.000419	0.000391	0.000359	0.000318	0.000282	0.000235
55	0.000438	0.0004	0.000353	0.000308	0.000256	0.000184
60	0.000488	0.000437	0.000332	0.000291	0.000237	0.000151
65	0.000531	0.000481	0.000311	0.000257	0.000214	0.00013
70	0.000728	0.000532	0.000288	0.000233	0.000179	0.000105
75	0.00102	0.000816	0.000195	0.000148	0.000095	0.000053

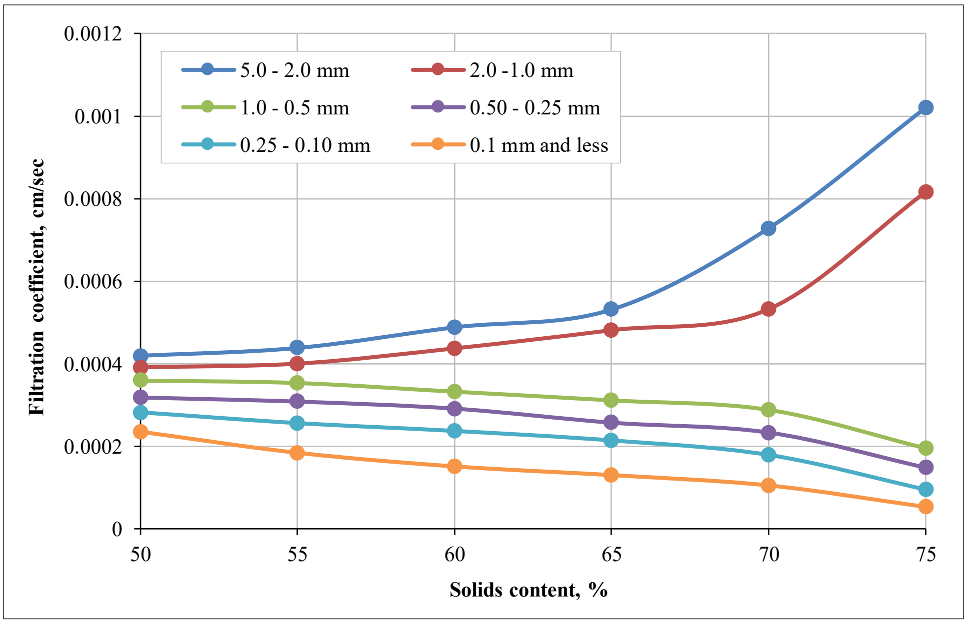

Figure 9. Dependence of the filtration coefficient k_f on the weight number of fractions m_f in the samples (for fractions m_{5-2}, m_{2-1}, $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$, and $m_{\leq 0.1}$)

The decrease in the filtration capacity of fine earth with decreasing particle size is explained as follows. The smaller the particle size, the greater their number in the fine earth, and consequently, the greater its pore volume. A small pore volume is accompanied by a lower water-permeability capacity of fine earth. Furthermore, some fine particles of fine earth are clay particles, which exhibit viscous-colloidal resistance to water movement. This type of resistance creates an initial pressure gradient in the fine earth, which in turn leads to a decrease in the primary pressure gradient. A decrease in the pressure gradient leads to a decrease in the permeability of fine earth, which corresponds to Darcy's law of laminar filtration.

By processing the experimental results, it was determined that the dependence $k_f = f(m_f)$ for samples containing fractions m_{5-2} and m_{2-1} is described by Equation 1, and for samples containing fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$, and $m_{\leq 0.1}$ by Equation 2. Figures 10 and 11 show the graphs of the dependence $k_f = f(m_f)$, which are described by these formulas:

$$k_f = am_f^2 - bm_f + d, \quad (1)$$

$$k_f = -cm_f^2 + pm_f - g, \quad (2)$$

where, a, b, and d are the coefficients taken from Table 3; c, p and g are the coefficients taken from Table 4.

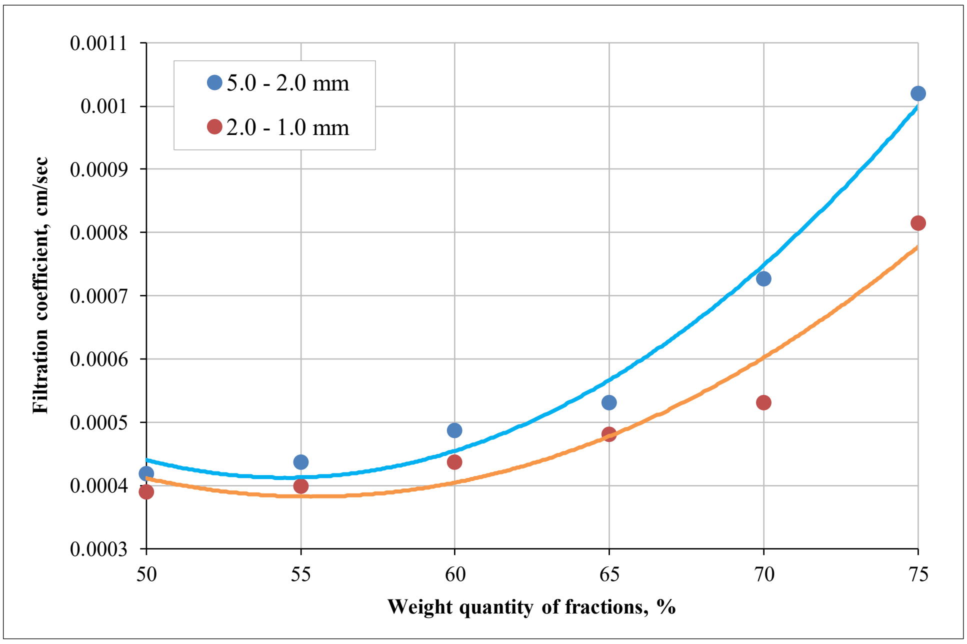

Figure 10. Dependence of the filtration coefficient k_f on the weight number of fractions m_{5-2} and m_{2-1} in the samples

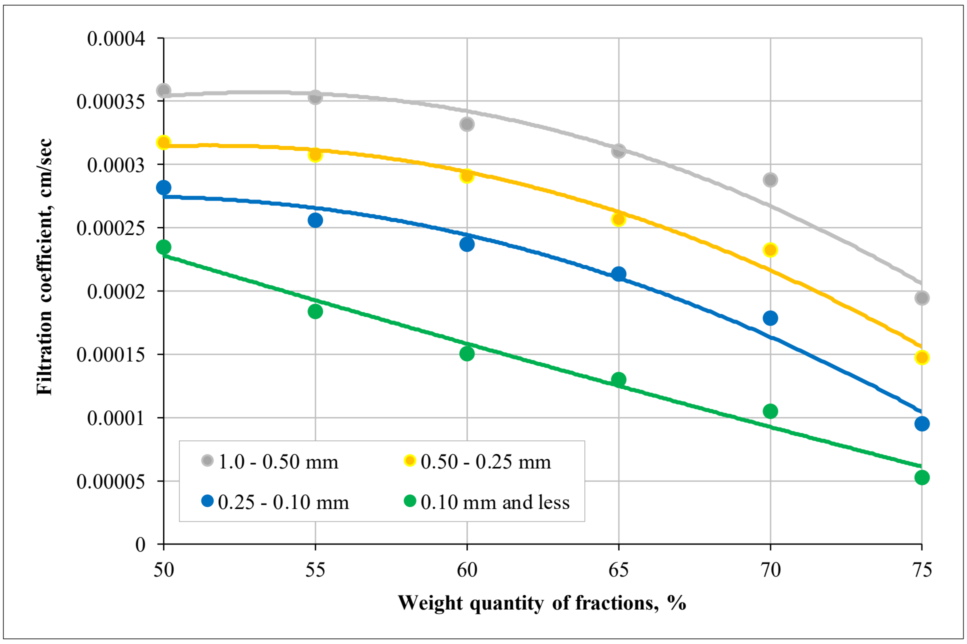

Figure 11. Dependence of the filtration coefficient k_f on the weight number of fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$ in the samples

Table 3. Coefficients a, b and d in equation 1

Fraction	Values of the coefficients			The magnitude of the approximation reliability R^2
	a	***b***	***d***	
m_{5-2}	1E-06	0.0002	0.0046	0.9840
m_{2-1}	1E-06	0.0001	0.0035	0.9353

Table 4. Coefficients c, p and g in Equation 2

Fraction	Values of the coefficients			The magnitude of the approximation reliability R^2
	c	p	g	
$m_{1-0.5}$	3E-07	3E-05	0.0005	0.9622
$m_{0,5-0,25}$	3E-07	3E-05	0.0004	0.9797
$m_{0,25-0,1}$	3E-07	2E-05	0.0003	0.9756
$m_{\leq 0,1}$	2E-08	9E-06	0.0006	0.9787

Based on the comparison of the moisture content of the samples before the W_{nf} tests and after the W_{kf} tests, it was found that due to water filtration in fine earth, there is an increase in moisture content Δ_w, which is 1.09-3.43% of the initial moisture content of the samples and varies depending on the weight of the fractions m_f and the particle sizes of the fractions in them (Table 5). The moisture content of fine earth in the samples before the start of filtration W_{nf} was 8.73-12.17%.

Table 5. Increase in moisture content Δ_w of fine earth

Weight quantity of fractions m_f, %	Increase in moisture content Δ_w, %, for samples containing the following fractions					
	m_{5-2}	m_{2-1}	$m_{1-0.5}$	$m_{0.5-0.25}$	$m_{0.25-0.1}$	$m_{\leq 0.1}$
50	2.23	2.21	2.11	1.97	1.87	1.78
55	2.46	2.36	2.02	1.86	1.72	1.6
60	2.58	2.45	1.98	1.79	1.6	1.51
65	2.72	2.55	1.87	1.65	1.49	1.32
70	2.98	2.71	1.78	1.57	1.34	1.2
75	3.43	3.08	1.67	1.42	1.21	1.09

From Table 5 and the graphs of the $\Delta_w = f(m_f)$ dependence presented in Figure 12, it follows that for samples containing fractions m_{5-2} and m_{2-1}, the increase in moisture content Δ_w with an increase in the weight content of fractions from 50% to 70% (by 1.1-1.5 times) increases, respectively, by 1.10-1.54 and 1.08-1.39 times. With a decrease in the size range of solid particles in fractions from 5-2 mm to 2-1 mm (with the same weight content of fractions), the increase in moisture content Δ_w decreases by 0.90-10.2%. Moreover, the minimum proportion of the decrease in the increase in moisture content Δ_w is observed at a weight content of the fraction of 50%, and the maximum - at a weight content of the fraction of 75%. These data indicate that after the completion of the filtration process, some of the water remains in the pores of the samples. Moreover, the larger the size and number of particles in the fractions, the greater the amount of water remains in the samples.

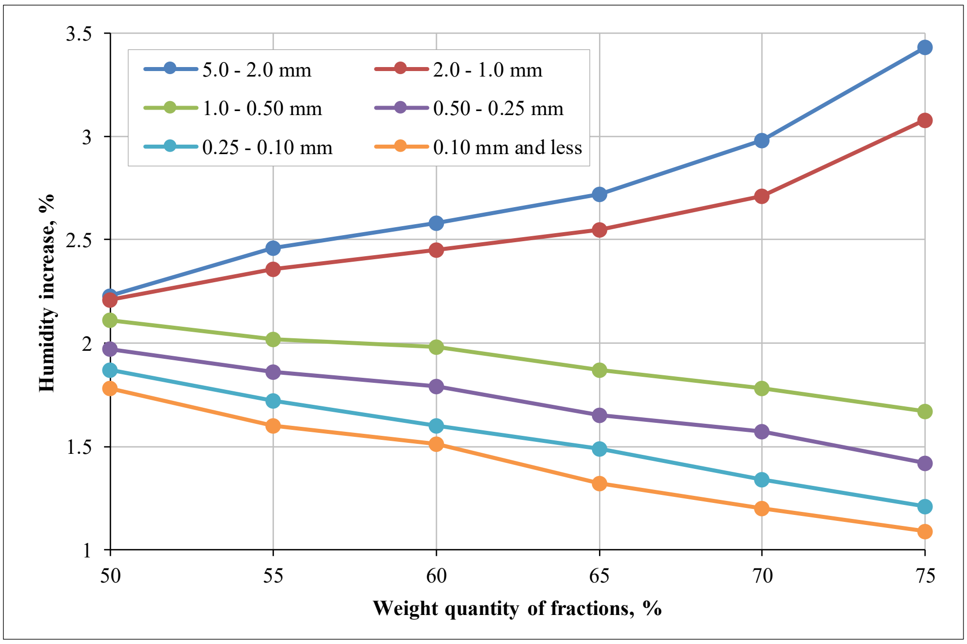

Figure 12. Dependence of the increase in humidity Δ_w on the weight number of fractions m_f in the samples (for fractions m_{5-2}, m_{2-1}, $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$)

For samples containing fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$, and $m_{\leq 0.1}$ an increase in the weight number of fractions from 50% to 75% (by 1.1-1.5 times) is accompanied by a decrease in the increase in moisture content Δ_w by 20.9%, 27.9%, 35.3%, and 38.8%, respectively (Table 6 and Figure 12). A decrease in the range of particle sizes of fractions from 1-0.5 mm to 0.1 mm and less causes a decrease in the increase in moisture content Δ_w by 6.63-34.73%. Consequently, in these samples, after the end of filtration process, the volume of water that accumulates in their pores decreases with an increase in the weight number of fractions and a decrease in the particle sizes of the fractions

A joint analysis of the test results presented in Tables 2 and 5 shows that there is a correlation between the increase in humidity Δ_w and the filtration coefficient k_f. Thus, for samples containing fractions m_{5-2} and m_{2-1}, the dependence $k_f = f(\Delta_w)$, has a curvilinearly increasing character (Figures 13 and 14), and for samples containing fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$, and $m_{\leq 0.1}$; a curvilinearly decreasing character (Figures 15 to 18). The presented graphs display the following quantitative patterns of the influence of the increase in moisture content Δ_w on the values of the filtration coefficient k_f of fine earth:

- For samples containing fractions m_{5-2}, an increase in moisture content from 2.23% to 3.43% is accompanied by an increase in the filtration coefficient by 1.04-2.86 times (see Figure 13);
- For samples containing fractions m_{2-1}, an increase in moisture content from 2.21% to 3.08% is accompanied by an increase in the filtration coefficient by 1.02-2.09 times (see Figure 14);
- For samples containing fractions $m_{1-0.5}$, an increase in moisture content from 1.67% to 2.11% is accompanied by an increase in the filtration coefficient by 1.48-1.84 times (see Figure 15);
- For samples containing fractions $m_{0.5-0.25}$, an increase in moisture content from 1.42% to 1.97% is accompanied by an increase in the filtration coefficient by 1.57-2.15 times (see Figure 16);
- For samples containing fractions $m_{0.25-0.1}$, an increase in moisture content from 1.21% to 1.87% is accompanied by an increase in the filtration coefficient by 1.88-2.97 times (see Figure 17);
- For samples containing fractions $m_{\leq 0.1}$, an increase in moisture content from 1.09% to 1.78% is accompanied by an increase in the filtration coefficient by 1.98-4.43 times (see Figure 18).

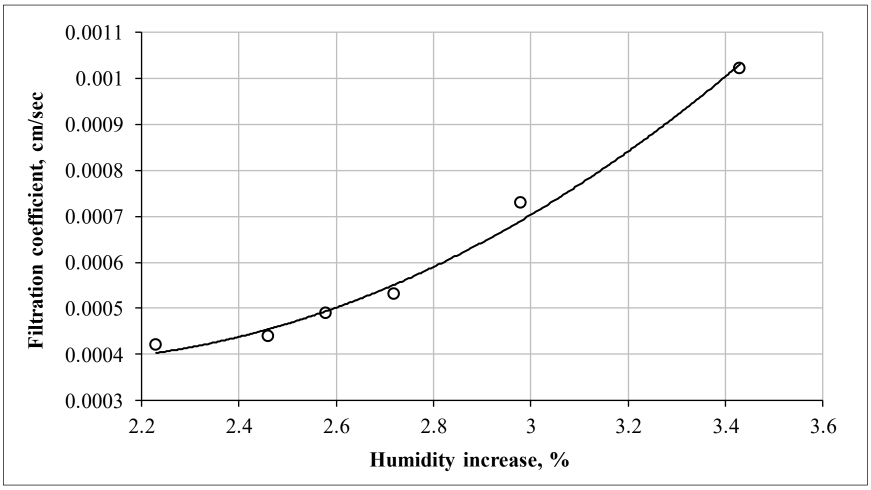

Figure 13. Dependence of the filtration coefficient k_f on the increase in humidity Δ_w in samples containing fractions m_{5-2}

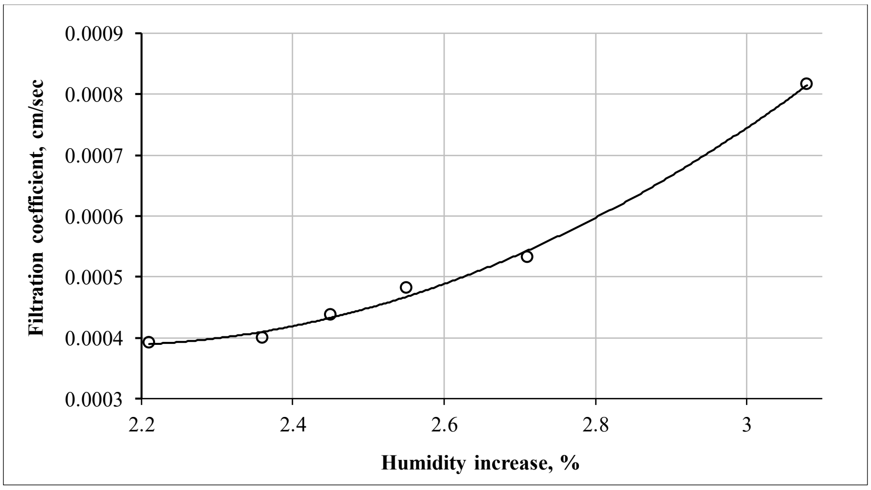

Figure 14. Dependence of the filtration coefficient k_f on the increase in humidity Δ_w in samples containing fractions m_{2-1}

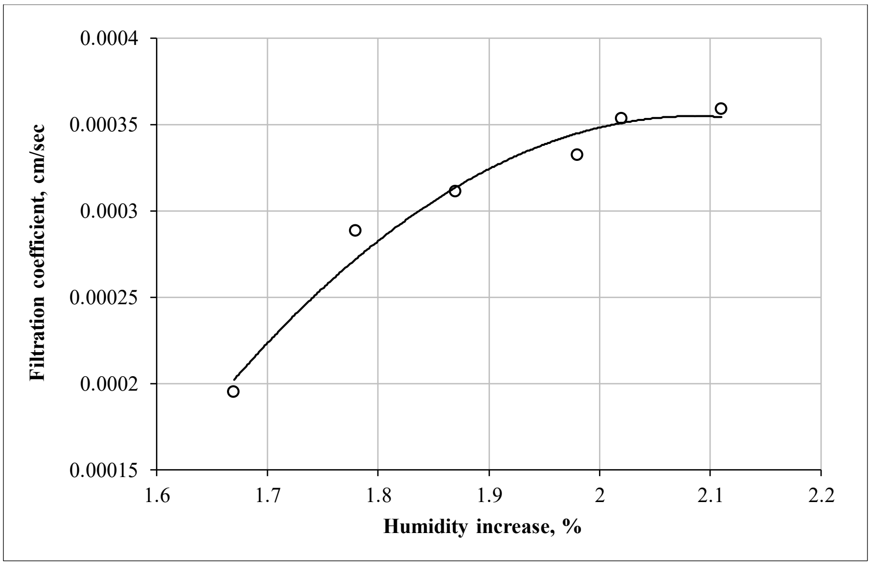

Figure 15. Dependence of the filtration coefficient k_f on the increase in humidity Δ_w in samples containing fractions $m_{1-0.5}$

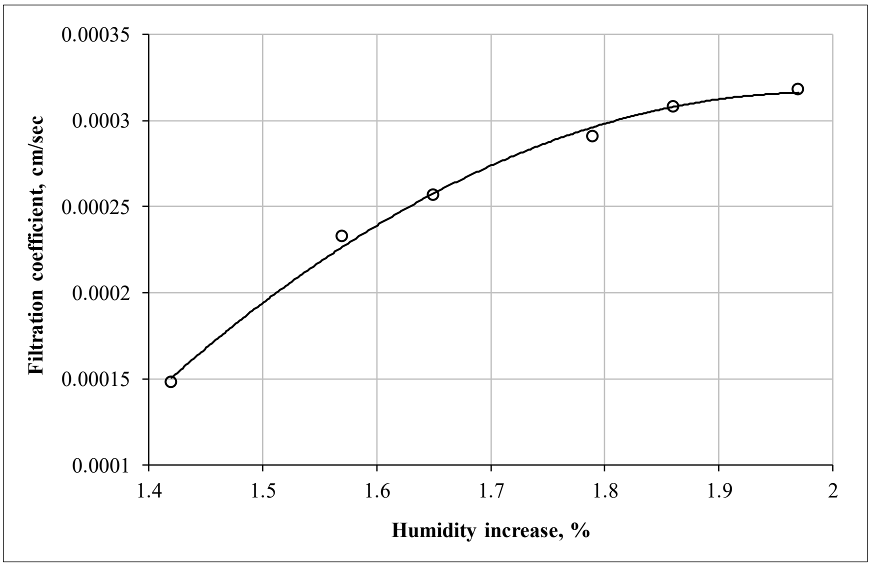

Figure 16. Dependence of the filtration coefficient k_f on the increase in humidity Δ_w in samples containing fractions $m_{0.5-0.25}$

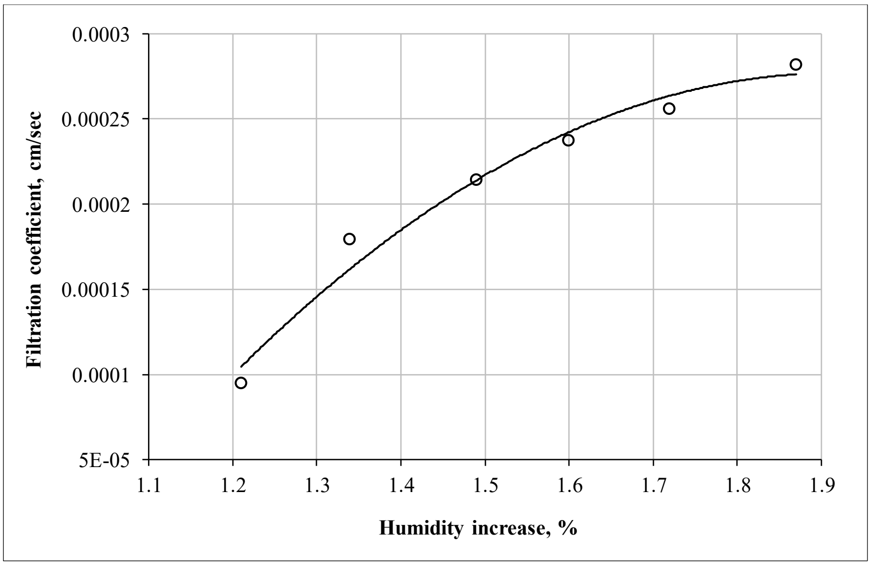

Figure 17. Dependence of the filtration coefficient k_f on the increase in humidity Δ_w in samples containing fractions $m_{0.25-0.1}$

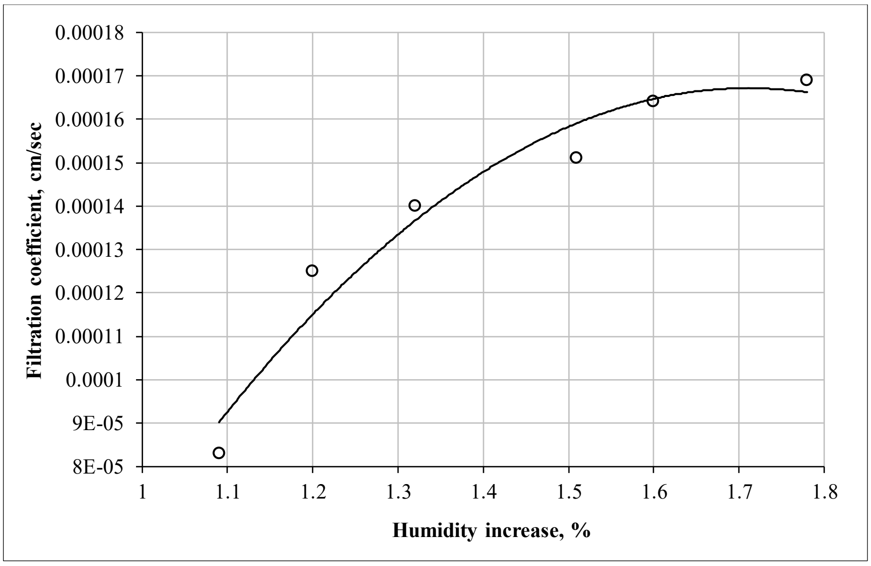

Figure 18. Dependence of the filtration coefficient k_f on the increase in humidity Δ_w in samples containing fractions $m_{\leq 0.1}$

The dependencies $k_f = f(\Delta_w)$, shown in Figures 13 and 14, are described by Equation 3, and in Figures 15 to 18 – by Equation 4.

$$k_f = y\Delta_w^2 - n\Delta_w + r, \tag{3}$$

$$k_f = x\Delta_w^2 - j\Delta_w + v, \tag{4}$$

where, y, n and r are coefficients taken from Table 6; x, j and v are coefficients taken from Table 7.

Table 6. Coefficients y, n and r in Equation 3

Fraction	Values of the coefficients			The magnitude of the approximation reliability R^2
	y	n	r	
m_{5-2}	0.0003	0.0012	0.0016	0.9908
m_{2-1}	0.0005	0.0021	0.0026	0.9966

Table 7. Coefficients x,j and v in Equation 4

Fraction	Values of the coefficients			The magnitude of the approximation reliability R^2
	x	j	v	
$m_{1-0,5}$	- 0.0009	0.0037	0.0035	0.9728
$m_{0.5-0.25}$	- 0.0005	0.0020	0.0017	0.9960
$m_{0.25-0.1}$	- 0.0008	0.0013	0.0010	0.9777
$m_{\leq 0.1}$	- 0.0002	0.0007	0.0004	0.9528

By comparing the values of sample density before testing ρ_{nf} and after testing ρ_{kf}, it was found that as a result of filtration in fine earth, there is an increase in density Δ_ρ, which is 0.009-0.126 g/cm^3 from the initial values of sample density and changes depending on the weight number of fractions m_f and the particle sizes of the fractions (Table 8). The values of fine earth density ρ_{nf} before filtration were 2.13-2.48 g/cm^3.

Table 8. Increase in density Δ_ρ of fine earth

Weight quantity of fractions m_f, %	Increase in density Δ_ρ, g/cm^3, for samples containing the following fractions					
	m_{5-2}	m_{2-1}	$m_{1-0.5}$	$m_{0.5-0.25}$	$m_{0.25-0.1}$	$m_{\leq 0.1}$
50	0.029	0.026	0.021	0.018	0.017	0.016
55	0.042	0.034	0.019	0.017	0.016	0.0151
60	0.058	0.045	0.017	0.016	0.015	0.0141
65	0.075	0.059	0.016	0.015	0.014	0.013
70	0.096	0.079	0.015	0.014	0.013	0.012
75	0.126	0.111	0.013	0.012	0.011	0.009

From Table 8 and the graphs of the $\varDelta_\rho = f(m_f)$, dependence presented in Figure 19, it follows that for samples containing fractions m_{5-2} and m_{2-1}, the increase in density $\varDelta_\rho$ with an increase in the weight content of fractions from 50% to 70% (by 1.1-1.5 times) increases by 1.45-4.34 and 1.31-4.27 times, respectively. With a decrease in the range of particle sizes in fractions from 5-2 mm to 2-1 mm (with the same weight content of fractions), the increase in density $\varDelta_\rho$ decreases by 10.34-11.90%. Moreover, the minimum share of the decrease in the increase in density $\varDelta_\rho$ is observed at a fraction weight content of 50%, and the maximum - at a fraction weight content of 75%.

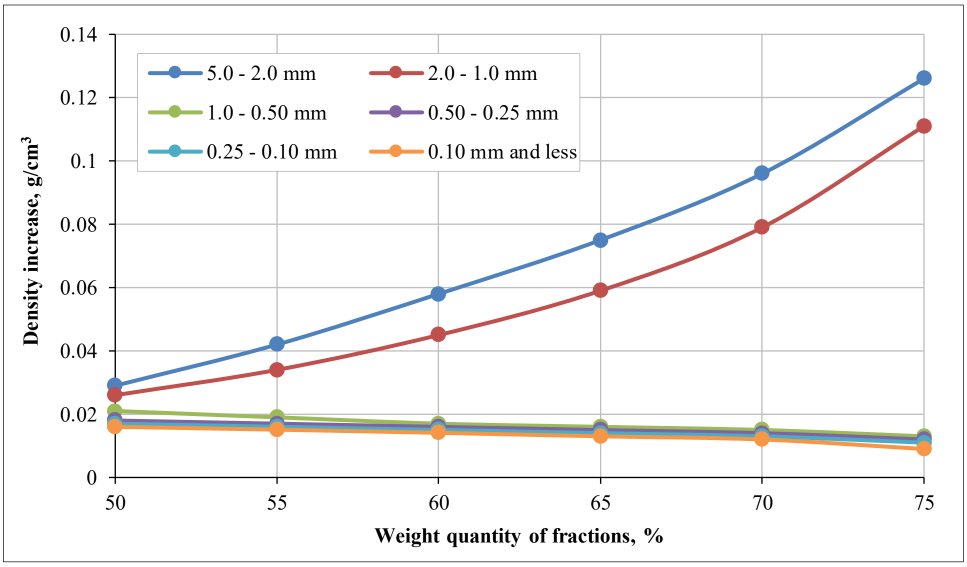

Figure 19. Dependence of the increase in density Δ_ρ on the weight number of fractions m_f in the samples (for fractions m_{5-2}, m_{2-1}, $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$)

For samples containing fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$, an increase in the weight number of fractions from 50% to 75% (by 1.1-1.5 times) causes a decrease in the increase in density $\varDelta_\rho$ by 38.1%, 33.3%, 35.3% and 43.8%, respectively (Table 9, Figure 19). A decrease in the range of particle sizes of fractions from 1-0.5 mm to 0.1 mm and less is accompanied by a decrease in the increase in density $\varDelta_\rho$ by 23.81-30.77%.

In general, the identified patterns of change in the increase in density $\varDelta_\rho$ of fine earth are similar to the patterns of change in the increase in its moisture content $\varDelta_w$, which is quite logically explainable, since an increase in the mass of water in the samples after filtration leads to an increase in the mass of the samples, and consequently to an increase in their density.

The analysis of the test results presented in Table 8 in conjunction with the data given in Table 2 shows that there is a correlation between the increase in density $\varDelta_\rho$ and the filtration coefficient k_f. Thus, for samples containing fractions m_{5-2} and m_{2-1}, the dependence $k_f = f(\varDelta_\rho)$ has a curvilinearly increasing character (Figures 20 and 21), and for samples containing fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$, and $m_{\leq 0.1}$; a curvilinearly decreasing character (Figures 22 to 25).

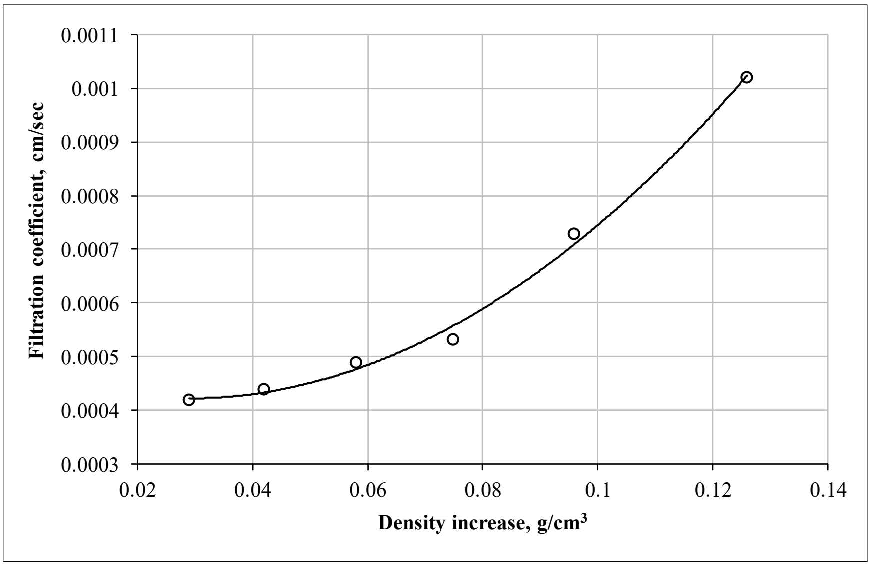

Figure 20. Dependence of the filtration coefficient k_f on the density increase $\varDelta_\rho$ in samples containing fractions m_{5-2}

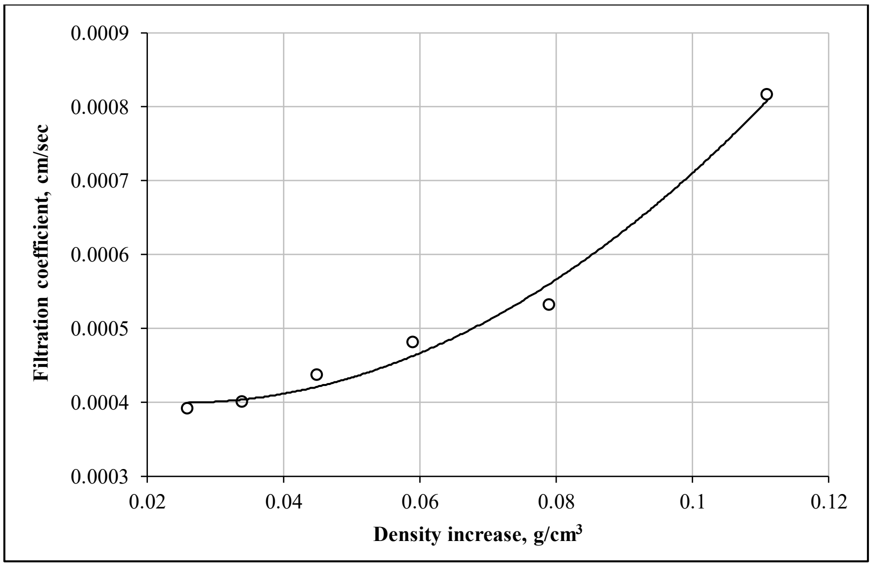

Figure 21. Dependence of the filtration coefficient k_f on the density increase Δ_ρ in samples containing fractions m_{2-1}

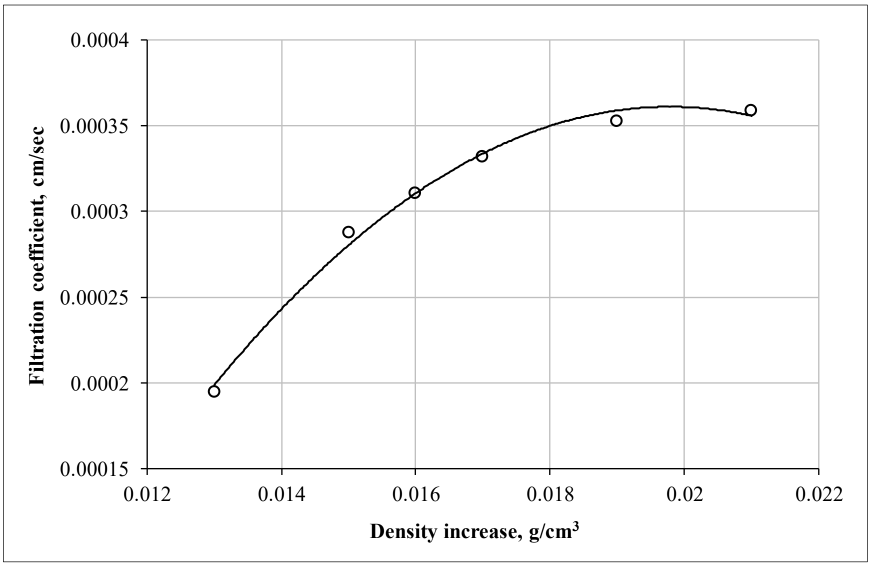

Figure 22. Dependence of the filtration coefficient k_f on the density increase Δ_ρ in samples containing fractions $m_{1-0.5}$

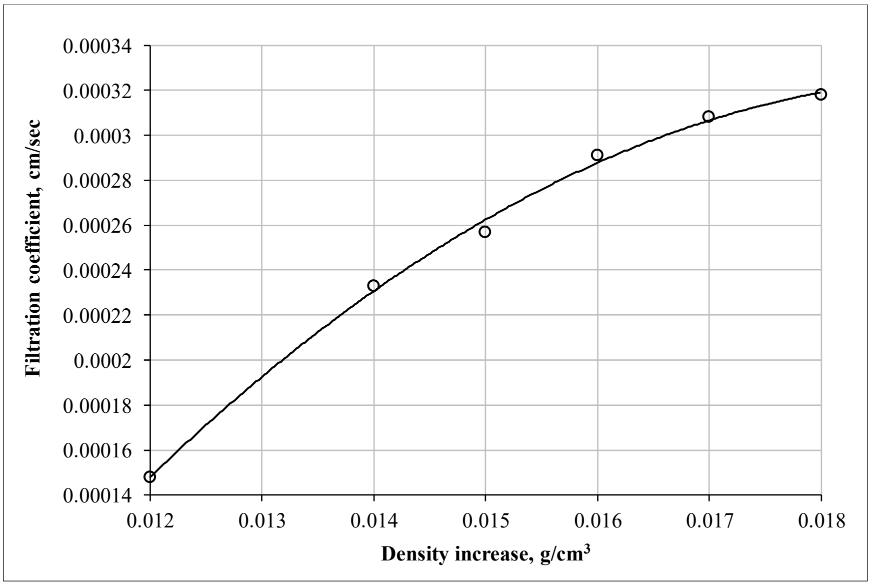

Figure 23. Dependence of the filtration coefficient k_f on the density increase Δ_ρ in samples containing fractions $m_{0.5-0.25}$

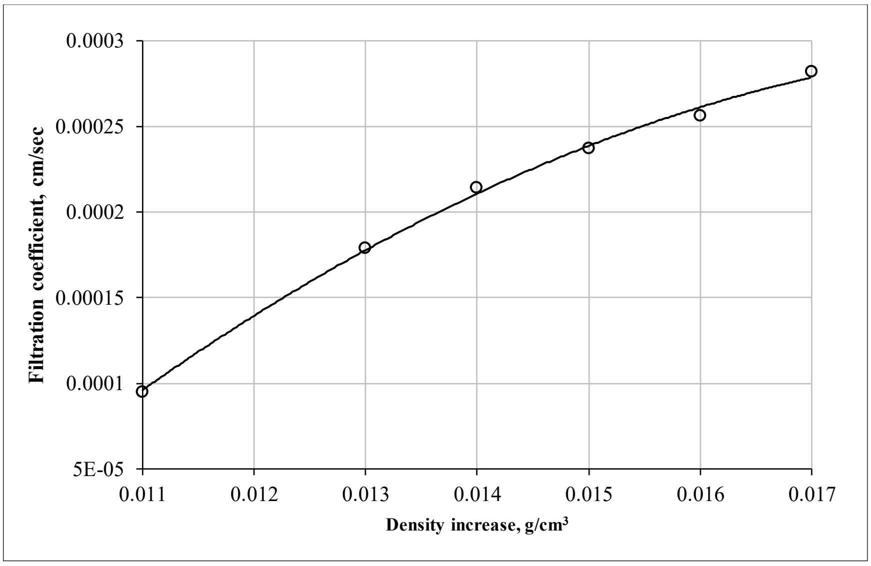

Figure 24. Dependence of the filtration coefficient k_f on the density increase Δ_ρ in samples containing fractions $m_{0.25-0.1}$

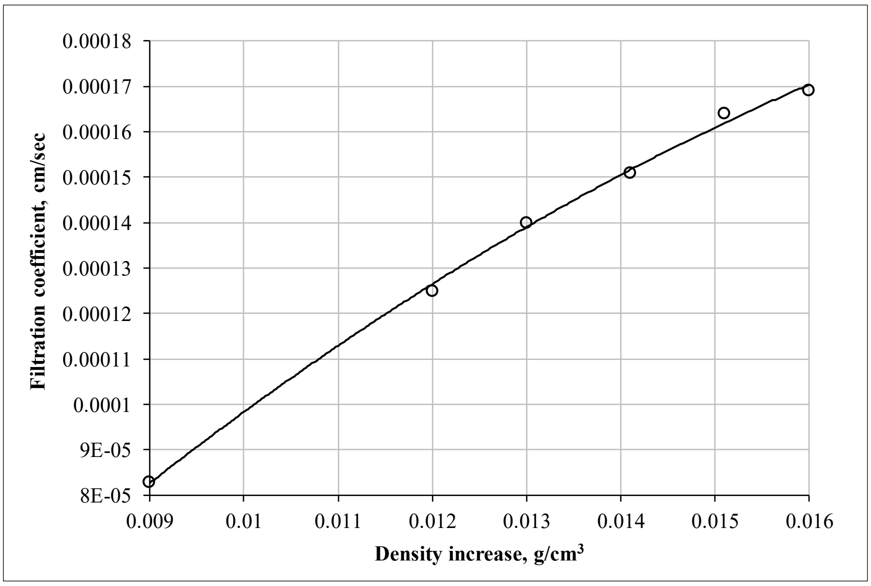

Figure 25. Dependence of the filtration coefficient k_f on the density increase Δ_ρ in samples containing fractions $m_{\leq 0.1}$

The graphs presented show the following quantitative patterns of the effect of density increase Δ_ρ on the values of the filtration coefficient k_f of fine earth:

- For samples including fractions m_{5-2}, an increase in density increase by 1.45-4.34 times causes an increase in the filtration coefficient from 419 × 10^{-6} cm/sec to 102 × 10^{-5} cm/sec (see Figure 20);
- For samples including fractions m_{2-1}, an increase in density increase by 1.31-4.27 times causes an increase in the filtration coefficient from 391 × 10^{-6} cm/sec to 816 × 10^{-6} cm/sec (see Figure 21);
- For samples including fractions $m_{1-0.5}$, an increase in density growth by 1.15-1.62 times causes an increase in the filtration coefficient from 195 × 10^{-6} cm/sec to 359 × 10^{-6} cm/sec (see Figure 22);
- For samples including fractions $m_{0.5-0.25}$, an increase in density growth by 1.17-1.50 times causes an increase in the filtration coefficient from 148 × 10^{-6} cm/sec to 318 × 10^{-6} cm/sec (see Figure 23);
- For samples including fractions $m_{0.25-0.1}$, an increase in density growth by 1.18-1.55 times causes an increase in the filtration coefficient from 95 × 10^{-6} cm/sec to 282 × 10^{-6} cm/sec (see Figure 24);
- For samples including fractions $m_{\leq 0.1}$, an increase in density growth by 1.33-1.78 times causes an increase in the filtration coefficient from 53 × 10^{-6} cm/sec to 235 × 10^{-6} cm/sec (see Figure 25)

The dependencies $k_f = f(\Delta_\rho)$, shown in Figures 20 and 21, are described by Equation 5, and in Figures 22 to 25 – by Equation 6.

$$k_f = u\Delta_p^2 - m\Delta_p + l, \tag{5}$$

$$k_f = t\Delta_\rho^2 - h\Delta_\rho + z, \tag{6}$$

where, u, m and l are coefficients taken from Table 9; t, h and z are coefficients taken from Table 10

Table 9. Coefficients u, m and l in Equation 5

Fraction	Values of the coefficients			The magnitude of the approximation reliability R^2
	u	m	l	
m_{5-2}	0.0063	0.0037	0.0005	0.9954
m_{2-1}	0.0556	0.0028	0.0004	0.9880

Table 10. Coefficients t, h and z in Equation 6

Fraction	Values of the coefficients			The magnitude of the approximation reliability R^2
	t	h	z	
$m_{1-0.5}$	-3.5314	0.1397	0.0010	0.9934
$m_{0.5-0.25}$	-3.2143	0.1250	0.0009	0.9976
$m_{0.25-0.1}$	-2.6071	0.1034	0.0070	0.9976
$m_{\leq 0.1}$	-0.5195	0.0255	0.0001	0.9981

4. Discussion

In order to assess the reliability of the obtained experimental data, they were compared with the results of the studies presented in Panov & Baranova [24]. The choice of these results was due to the fact that only they are to some extent acceptable for approximate comparison, whereas all the other above-mentioned research results (analyzed in this article) differ from our data by many initial factors adopted in the studies. It was found that the values of the filtration coefficient presented in Panov & Baranova [24] are close to the data in Table 2, related to fine earth samples with fractions $m_{1-0.5}$, $m_{0.5-0.25}$, $m_{0.25-0.1}$ and $m_{\leq 0.1}$ (Table 11). The difference between them reaches 12.63-14.87%. Moreover, the results obtained by the authors in Panov & Baranova [24] are higher than in our experiments. In our opinion, this is explained by the fact that in the experiments in Panov & Baranova [24], the samples tested were each formed from sand particles of the same size, while in our experiments, the samples were each formed from sand and clay particles of different (and smaller) sizes.

Table 11. Comparative values of filtration coefficient

Filtration coefficient values for fine earth with fractions (Table 2, at a weight content of 75%)			
$m_{1-0.5}$	$m_{0.5-0.25}$	$m_{0.25-0.1}$	$m_{\leq 0.1}$
0.000195	0.000148	0.000095	0.000053
Filtration coefficient values for homogeneous fractions with particle sizes [24]			
1.0	0.5	0.25	0.1
0.000224	0.000167	0.000107	0.000061

The research results indicate that the process of water filtration through fine earth samples causes certain structural changes in them, which are expressed in the rearrangement of solid particles, partial absorption of water by them and a decrease in the pore volume. These changes lead to a change in such physical characteristics of fine earth as density, moisture content and filtration coefficient. Moreover, these changes in the most important parameters characterizing the filtration and post-filtration state of fine earth samples are closely interconnected, as evidenced by stable correlation dependencies described by the corresponding second-order polynomial functions with high values of data approximation reliability. The test revealed that these dependencies can be described by other mathematical functions (linear, power or exponential), but with significantly lower values of approximation reliability R^2 (less than 0.8-0.9).

The established regularities are characterized by novelty and are in demand in practice. Thus, correlation Dependencies 1-6, obtained on the basis of the research results, can be used to determine the filtration coefficient k_f of fine earth depending on the weight number of fractions in it, as well as the increase in its moisture content Δ_w and the increase in density Δ_ρ. In this case, the weight amount of a particular fraction should be specified, and the parameters Δ_w and Δ_ρ should be assigned on the basis of the results of the corresponding filtration tests. By performing calculations for various options of fine earth fractions, its optimal composition can be established, at which the filtration coefficient k_{fo} will have a minimum value.

Relationships 1-6, as empirical models of fine earth filtration behavior, can be used as a tool for engineering soil mixture design. The correlation relationships under consideration are valid for all fine-grained components of coarse-grained soil with sandy loam aggregate.

Dependencies 1 and 2 can be written respectively as Equations 7 and 8 and used to determine the optimal weight quantity of fractions m_f^o based on the required value of the filtration coefficient k_{ft} of fine earth

$$m_f^o = \{b + [b^2 - 4a(d - k_{ft})]^{0,5}\}/2a \quad (7)$$

$$m_f^o = \{p + [p^2 - 4c(g - k_{ft})]^{0,5}\}/2c \quad (8)$$

where: *a, b* and *d* are the same as in formula (1); *c, p* and *g* are the same as in formula (2).

Correlation Dependencies 3 and 4 can be presented respectively in the form of Equations 9 and 10 and used to determine the values of fine earth moisture w_{kf} corresponding to the moment of completion of the filtration process:

$$w_{kf} = \left\{\frac{n+[n^2-4y(r-k_f)]^{0,5}}{2y}\right\} - w_{nf} \quad (9)$$

$$w_{kf} = \left\{\frac{j+[j^2-4x(v-k_f)]^{0,5}}{2x}\right\} - w_{nf} \quad (10)$$

where: w_{nf} - the importance of fine earth before the start of water filtration, %; *y, n* and *r* are the same as in Equation 3; *x, j* and *v* are the same as in Equation 4.

Similarly, based on Equation 5 and 6, we can obtain Equation 11 and 12 for determining the values of fine earth density ρ_{kf} , corresponding to the moment of completion of the filtration process

$$\rho_{kf} = \left\{\frac{m+[m^2-4u(l-k_f)]^{0,5}}{2u}\right\} - \rho_{nf} \quad (11)$$

$$\rho_{kf} = \left\{\frac{h+[h^2-4t(z-k_f)]^{0,5}}{2t}\right\} - \rho_{nf} \quad (12)$$

where, ρ_{nf} – density of fine earth before water filtration, g/cm^3; *u, m* and *l* are the same as in Equation 5; $t, h,$ and z the same as in Equation 6.

Equations 9 to 12 are recommended for use in predicting changes in the density-moisture state of fine earth in the dam body during non-standard filtration, i.e., in conditions where the decompression curve of water in the dam body changes its position as the level of its upper pool changes for a number of reasons, including seasonal shallowing.

Based on the results of the studies, it can be stated that the identified changes in the density and moisture content of fine earth as a result of water filtration through it will cause corresponding changes in its mechanical properties. These expected changes are the subject of further experimental studies. Establishing patterns of change in the deformation-strength characteristics (deformation modulus, internal friction angle and specific adhesion) of fine earth (of different fractional composition) during filtration and assessing the influence of these parameters on the values of its filtration coefficient will allow selecting the optimal composition of fine earth taking into account the transformations of its mechanical properties. This circumstance will contribute to increasing the filtration stability of earth dams and their components.

5. Conclusions

The laboratory studies allow us to draw the following main conclusions:

- The magnitude of the water level decrease during its filtration through fine earth depends on the duration of filtration, and this dependence is described by a linear function whose parameters change depending on the particle size and the weight of the fractions contained in the fine earth. The particle size and the weight of the fractions in fine earth also affect the rate of water level decrease during its filtration;
- The values of the fine earth filtration coefficient depend on the particle size and the weight of the fractions contained in it. The relationship between these parameters is described by Equations 1 and 2;
- The density and moisture content of fine earth increases as a result of water filtration. The increase in density and the increase in moisture content of fine earth depend on the size and weight of the fractions contained in it. There are dependencies between the filtration coefficient and the increase in moisture content, as well as between the filtration coefficient and the increase in the density of fine earth, described by Equations 3 to 6;
- Equations 7 to 12, obtained on the basis of correlation Dependencies 1-6, are recommended to be used at the stage of designing earth dams for selecting the optimal compositions of fine earth of soil mixtures used for their construction;

- The subject of further experimental studies is to establish the patterns of change in the deformation modulus, the angle of internal friction and the specific adhesion of fine earth (of different fractional composition) during filtration and to assess the influence of these deformation-strength characteristics on the values of the filtration coefficient.

6. Declarations

6.1. Author Contributions

Conceptualization, I.B. and K.S.; methodology, I.B.; software, N.S.; validation, I.B. and Y.A.; formal analysis, I.B.; investigation, K.S., Y.A., and N.S.; resources, I.B.; data curation, K.S., Y.A., and N.S.; writing—original draft preparation, K.S., Y.A., and N.S; writing—review and editing, I.B.; visualization, N.S.; supervision, K.S.; project administration, Y.A.; funding acquisition, I.B. and K.S. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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