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INVESTIGATION OF CLAY SOIL MECHANICAL SUFFOSION PROTECTED WITH A FILTER

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Abstract

This article analyzes the relationship expressing the connection between the quantitative characteristics of suffosion in soils and the key factors affecting them. These factors underlie the methodology for selecting materials for the core of earth dams, filters, and drainages. The test equipment and methodology used to model the joint work of the clay core and the dam's sand filter, which has a crack in the core, are presented. Experimental results reflecting the changes in the mass and concentration of particles carried out with the water flow during the suffosion process, depending on time, are presented.

Keywords: suffozion, granular composition, hydraulic gradient, critical gradient, reverse filter, arch formation.

Introduction

It is known that, as a result of filtration performed by the mass of the soil, soil–rock and basement, filtration forces are generated that can affect the soil skeleton. These forces are able to compromise the stability of slopes or cause local deformations of soil, as well as mechanical suffosion or colmatage. Mechanical suffosion refers to the displacement of fine particles through the pores formed by coarse particles under the influence of filtration flow in the soil mass. There are two types of mechanical suffosion: internal and external. During internal suffosion, fine soil particles move through the pores of the soil mass and can either move to the surface or remain inside and cause colmatage. The area of soil where suffosion occurs experiences changes in granulometric composition, density, deformation, and strength properties. Suffosion is a time-varying process. When fine particles are removed from the soil, the gradient of the filtration flow increases, which in turn increases suffosion. It weakens the soil structure and could even cause soil collapse.

During colmatage, the reverse process occurs. Internal suffosion may occur at the point of contact between the two soils with different granulometric compositions. Additionally, the soil contact layers may not exhibit suffosion processes. However, at the point of contact, there is a significant flow of fine particles from one layer into larger pores.

During external suffosion, the filtration flow carries some soil particles to the surface through the soil pores. It causes the size of the surface pores to increase and the suffosion to spread deeper into the soil. All of this typically leads to changes in the tension-deformation state of the local areas of the soil filtering mass, including the accumulation of particles, which ultimately results in the formation of sediments or filtration extrusions [1, 2, 3].

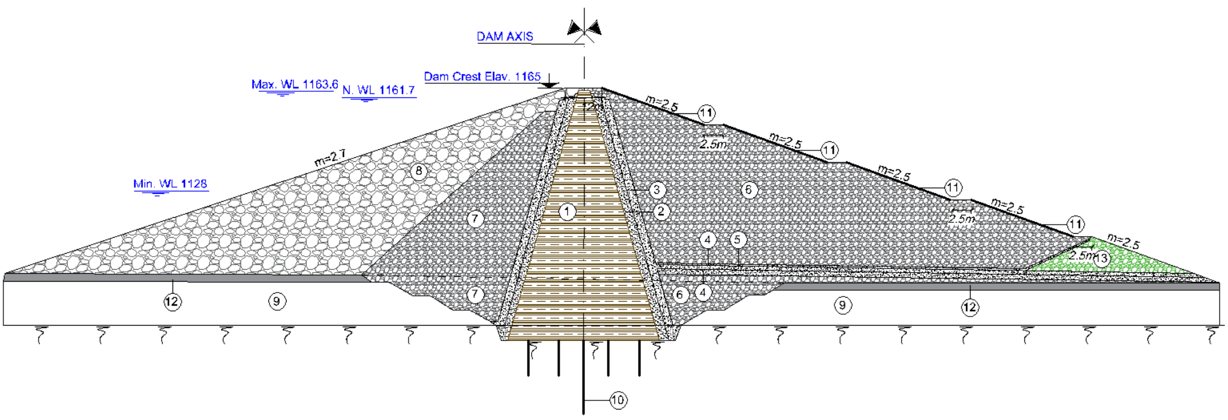

Fig. 1 Cross-section of the reservoir dam

1 - core from sandy clay soils, 2 - 1st layer of transition zone fine sand, 3, 4 - second layer from gravel ballast, 5 - drainage, 6 - river sediments, 7 - internal rockfill, 8 - external rockfill, 9 - conglomerates, 10 - cement curtain, 11 - sod covering, 12 - apron, 13 - embarkment

The problem of filtration deformations and stability in hydro-technical structures is possible by selecting the soil material used in the dam, filters, the transitional zone, and the drainage composition. It helps prevent or minimize mechanical suffosion (Fig. 1).

According to an assessment of the soil suffosion used as a foundation or building material for dams as well as method selection [4. 5], the main factors affecting soil suffosion are granulometric composition, filtration rate, and pressure gradient. If the protected soil is unbounded, its resistance to suffosion is determined by the grain masses and the tension of the grain system. Therefore, the process of internal suffosion depends on the movement and distribution of diffusing particles in the pores of the protective soil and filter.

If the protective soil is bonded, the process is complicated because the formation of particles requires additional energy and certain conditions that depend on several factors, such as the plasticity number, fluidity index, optimal humidity, moisture content of the protective ground during compaction, etc. [6, 7, 8, 9].

Given the influence of these factors on suffosion, studying their effects requires laboratory testing methodology and process modelling.

In the scientific literature, the internal suffosion of an earthen dam with a granular filter is typically divided into several stages:

- occurrence of a crack in the core,
- decay of fine-grained material under the influence of water flow from the crack walls,
- movement of particles subjected to suffosion to the filter,
- accumulation or release of these particles in the filter,
- continuation of suffosion with depletion of material stability or elimination of the crack and restoration of core body [6, 10].

Conflict Setting

The work aims at analyzing the relationships that express the connections between the primary factors that affect the quantitative characteristics of the suffosion in soils, which serve as the basis of the methodology used in selecting core soil for dams, filters, and drainage materials [5]. Additionally, the article aims to present a testing device and method that can be used to simulate a dam crack, and the joint operation for modelling the clay core and the sand filter. The study aims to align the results that reflect the change in mass and concentration of particles performed with the water flow during suffosion over time.

Research Results

Determination of the diameter of filtration pores in unbounded soils.

The diameter of the filtration pores in the soil is a crucial calculation parameter for selecting the composition of filter soil and solving questions related to the suffosion and filtration strength of soil structures. This diameter is determined using the formulas developed by A.N. Patrashev and M.P. Pavchich [5].

$$d_0 = 7{,}12\sqrt{\frac{\nu \cdot k}{n \cdot g \cdot \varphi}}, \qquad (1)$$

$$d_0 = c\frac{n}{1-n}d_{17} \qquad (2)$$

$$c = 0.455\sqrt[6]{\eta}$$

where ν - is the kinematic coefficient of water viscosity, k - the filtration coefficient, n - the soil porosity, g - is the free fall acceleration, φ - is the coefficient taking into account the shape and roughness of the soil particle, d_{17} - is the particle diameter, with the smallest containing 17% of the soil's mass.

Determination of the calculation parameters of the particles forming bridges in the contact zone between the protected soil and filter.

The calculated particle diameters that form bridges are determined by the condition that they do not collapse. To prevent fine particles of the protected soil from penetrating the pores of the coarse filter soil, a stable bridge needs to be formed from the fine particles that penetrate the filter pores in the contact zone. To prevent soil grains from entering the pores of the reverse filter first layer, it is important to select a grain size composition for the filter that will allow for the formation of stable bridges from the fine particles of the protected layer in the contact zone.

Numerous experiments conducted on reverse filters have shown that stable bridges are formed when the diameter of the filter is not more than 1.8 times larger than the diameter of particles that cause bridge blockages. The condition of not penetrating the filter pores of protected soil particles is as follows:

$$\frac{d_0}{d_{0i}} \le 1{,}8 \tag{3}$$

or

$$d_{0i} \ge 0{,}555\, d_0, \tag{4}$$

where d_0 -is the filter pore diameter in the contact zone of the soil contact zone protected by the filter, d_{0i} –is the diameter of the grains forming bridges.

Inserting (1) and (2) into (4), we will get the following calculation formulas for d_0 [5].

$$d_{0i} \ge 3{,}95\sqrt{\frac{\nu \cdot k}{n \cdot g \cdot \varphi}}, \tag{5}$$

$$d_{0i} \ge c_1 \frac{n}{1-n} d_{17}, \tag{6}$$

$$c_1 = 0{,}2526\,\eta \tag{7}$$

where n - is the filter porosity, k and η are the filtration and inhomogeneity coefficients.

Determination of suffosive particle diameters.

Mechanical suffosion can develop in sandy soil in the presence of particles where the diameter is less than the soil maximum filtration diameter $d_{0i}^{\max}$. Soil particles with a diameter less than the diameter of their filtration passage are called suffosive particles. They remove from the ground with a seepage, if

$$D_{ci} < d_0^{\max}, \tag{8}$$

where D_{ci} – is the diameter of suffosive particles.

The maximum diameter of the filtration passage is determined by the following relationship:

$$d_0^{\max} = 7.12\chi\sqrt{\frac{\nu \cdot \kappa}{ng\varphi}}, \tag{9}$$

$$d_0^{\max} = \chi c \frac{n}{1-n} d_{17}, \tag{10}$$

where χ is the soil's particle arrangement asymmetry coefficient, it mainly depends on the soil inhomogeneity.

In case of filter soil inhomogeneity coefficient $\eta \le 25$,

$$\chi = 1 + 0{,}05\eta,$$

for $\eta > 25$

$$\chi = 0{,}35\left(3 + \sqrt[3]{\eta \ell g \eta}\right).$$

The diameters of particles that can move in the pores of the protected soil and emerge on its unprotected surface, i.e., in the absence of a reverse filter, are determined by the following relationship:

$$d_0^{\max} = \le 0{,}77 d_0 \tag{11}$$

or

$$d_0^{\max} = \le \frac{\chi \cdot c}{1{,}3} \frac{n}{1-n} d_{17} : \tag{12}$$

As previously mentioned, when the soil is protected by a reverse filter, stable bridges are formed in the contact zone. Disrupting these bonds requires a greater filtration flow than removing particles of the same size to the soil free surface. In other words, the particles that form the bridges limit the removal of fine particles from the protected soil.

The diameter of the suspended particles in the area adjacent to the protective filter of the soil is determined based on the following conditions:

$$d_0^{\max} \leq 0{,}77\, d_0, \tag{13}$$

$$d_0 < \zeta d_{0i}, \tag{14}$$

where ς is the Slichter coefficient, which is determined by the arrangement of grains in the soil. The first condition(13) is considered ….., while the second condition (14) is considered sufficient [5]. This means that if $0{,}77\, d_0 > \varsigma d_{0i}$, then the particles with a diameters smaller than ςd_{0i} can be removed from the soil protected by the filter, and when $\varsigma d_{0i} > 0{,}77\, d_0$, then the particles with the diameter satisfying the condition (13) will be removed from the protected soil.

Determination of critical suffosion speed and critical gradients.

The filtration rate at which the maximum balance of **suffosive** particles is disturbed is known as the **suffosion** critical speed.

The critical suffosion speed depends on various factors, including the size of the extracted particles, the soil filtration coefficient, its porosity, and the nature of the particle distribution that are exposed to the filtration flow.

The critical speed of suffosion can be determined using the following formula by A.N. Patrashev [5]:

$$V_{KP} = \varphi_0 d_{ci} \sqrt{\frac{n_r g k_r}{\nu}} \tag{15}$$

where φ_0 is the critical speed coefficient

$$\varphi_0 = 0{,}60 \left(\frac{\gamma_r}{\gamma_B} - 1 \right) f_* \sin(30^0 + \frac{\theta}{8}), \tag{16}$$

where f* - is called the friction coefficient. It depends on the shape of the suffosive particles and how they are distributed within the pores. The critical suffosion speed in the area of contact with the soil protected by the reverse filter is determined by the following formula:

$$V_{KP} = 0{,}32 d_{cr} \varphi_0 \sqrt{\frac{n_r g}{\nu}} k_r \tag{17}$$

where - d_{cr} is the diameter of soil particles forming bridges, and $0{,}32\, d_{cr} = d_{ci}$ - is the diameter of soil suffosive particles that can leave the contact zone at a speed of $V. > V_{KP}$.

Determination of critical pressure gradient.

The suffosion critical gradient is determined by the following expression derived from formula (15):

$$i_{KP} = \varphi_0 d_{ci} \sqrt{\frac{ng}{\nu k_r}} \quad (18)$$

or by the following formula proposed by Privedni:

$$i_{KP} = \frac{\alpha\varphi_0}{\varepsilon d_{17} \sqrt[6]{\eta}} d_{ci} \quad (19)$$

where α - is a coefficient that characterizes grain roughness, ε - is the porosity coefficient, η -is the inhomogeneity coefficient, and d_{ci} is the diameter of suffosion grains.

The critical pressure gradient in the zone protected by the reverse filter can be calculated using the following formula:

$$i_{KP}^{\max} = 0{,}32\varphi_0 d_{cr} \sqrt{\frac{ng}{\nu k_r}} \quad (20)$$

or

$$i_{KP}^{\max} = \frac{0{,}32\alpha\varphi_0}{\varepsilon d_{17} \sqrt[6]{\eta}} d_{cr} \quad (21)$$

By applying the formulas and standards that were developed for designing dams, the curves of the grain-size distribution of the soils used in the construction of the Vedi reservoir dam project were constructed (Fig. 2). These curves were used to determine the suffosion strength parameters of the core transfer layers [11].

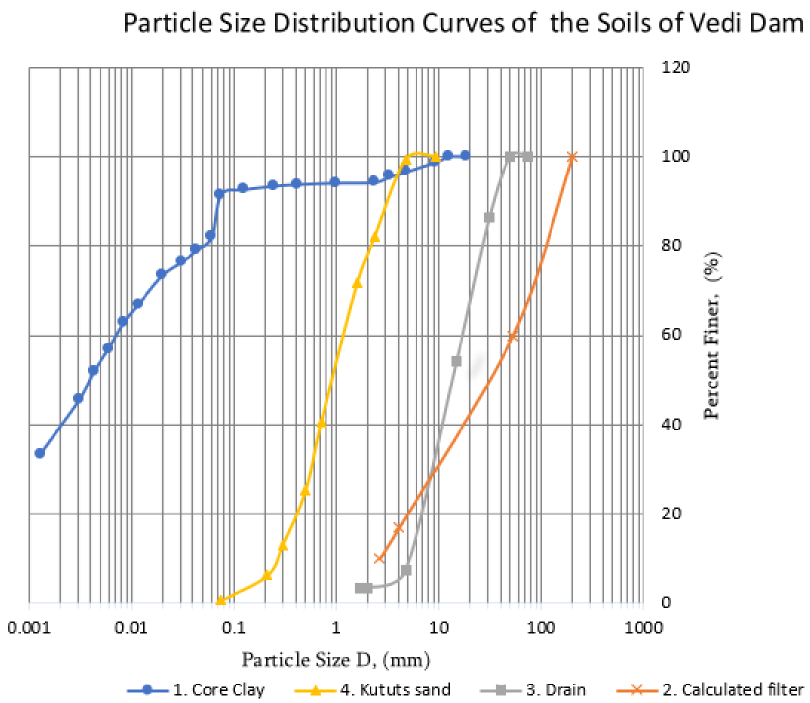

Fig. 2 Grain size distribution of earthen dam

1 - of core soil, 2 - soil of Kotuts river, 3 - grain size distribution of transfer zone soil, 4 - filter soil grain size distribution (calculated)

A study was conducted to experimentally evaluate the suffosion stability of the clay core protected by a sand filter using the aforementioned soils.

Test equipment and test methodology

Tests to study the filtration of high dams are typically conducted in a laboratory setting. In order to evaluate the suffosion stability of soil protected by a non-suffosable filter, studied the amount and concentration of particles removed by a concentrated flow of water passing through a crack in the soil and the protective filter [12, 13]. The laboratory test device used to study the sufficient stability of the soil is shown in Fig. 3.

The test device used in the study is a cylinder made of organic glass with an inner diameter of 118 mm and a height of 270 mm. The lower part of the cylinder contains a disc with 8 mm holes (2). The upper part of the cylinder is closed by a disc (4), in which the water inlet valve (9), the air removal valve, and the pressure gauge (8) are installed. A ring (3) connects the disk (2) at the bottom of the cylinder to the disk (4) at the top with rods (5) that are aligned with the disk holes. The test device is hermetically sealed due to the rubber ring inserts (7) placed in the holes on the lower part of the ring (3) and the upper part of the disk (4). The pressure gauge (8) measures the actual water pressure on the sample, while the water drained from the perforated disk (2) represents the actual water consumption. This drained water also contains particles removed from the sample as a result of suffosion. To estimate the number and size of the extracted particles, a suitable sieve (11) is placed under the test device.

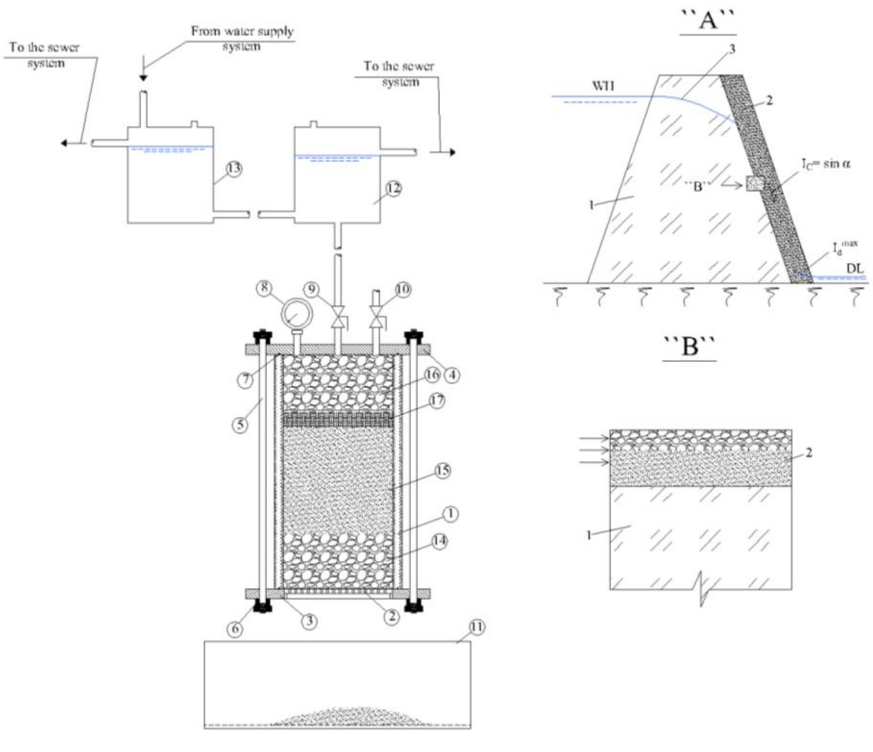

Fig. 3 Experimental setup for studying the properties of soil suffosion protected by a filter
1 - glass cylinder, 2 - holeplate, 3 - ring, 4 - disc, 5 - rod, 6 - screw, 7 - rubber ring insert, 8 - pressure gauge, 9 - inlet valve, 10 - air removal valve, 11 - sieve, 12 - water container, 13 - communicating vessels, 14 - bottom drainage layer, 15 - filter layer, 16 - gravel, 17 - clay layer

Container (12) placed above the test device provides constant water pressure on the sample. The water level in the container can change within 5 meters, allowing us to create a hydraulic gradient by adjusting the height of the test device filled with the sample. During the experiment, the constant water level in the container (2) is maintained through the communicating vessel (13) placed above it.

To obtain a sample that matches the original construction of the dam core soil, the bottom of the testing device filled with 5.5 cm of gravel. Next, the first layer of the dam filter, which is 14 cm thick, is placed on the gravel by compacting it. The clay layer of the embankment core, which has a thickness of 3 cm, is then placed on top of the filter layer under optimal moisture conditions and compacted. Lastly, a 5.5 cm thick clay layer is placed on top of the clay layer to prevent direct impact from the water jet on the clay.

The conducted experiments have shown that the clay used in the core of the reservoir has filtration coefficient of$\approx 1.0x10^{-9}$ m/s, which is considered practically impermeable. Therefore, if the core is built using the proper technology, the occurrence of suffosion in the filter layer due to the flow of the water filtered by the core is practically not observed.

Our study on filter bed sand suffosion has revealed that uneven deformations in narrow canyons with steep slopes installed in high dams with a thin core, as well as seismic phenomena, can result in the appearance of a separate local crack in the core. Such cracks are not desirable, especially on the lower side of the core in the contact part of the transfer zone (Fig. 4 a).

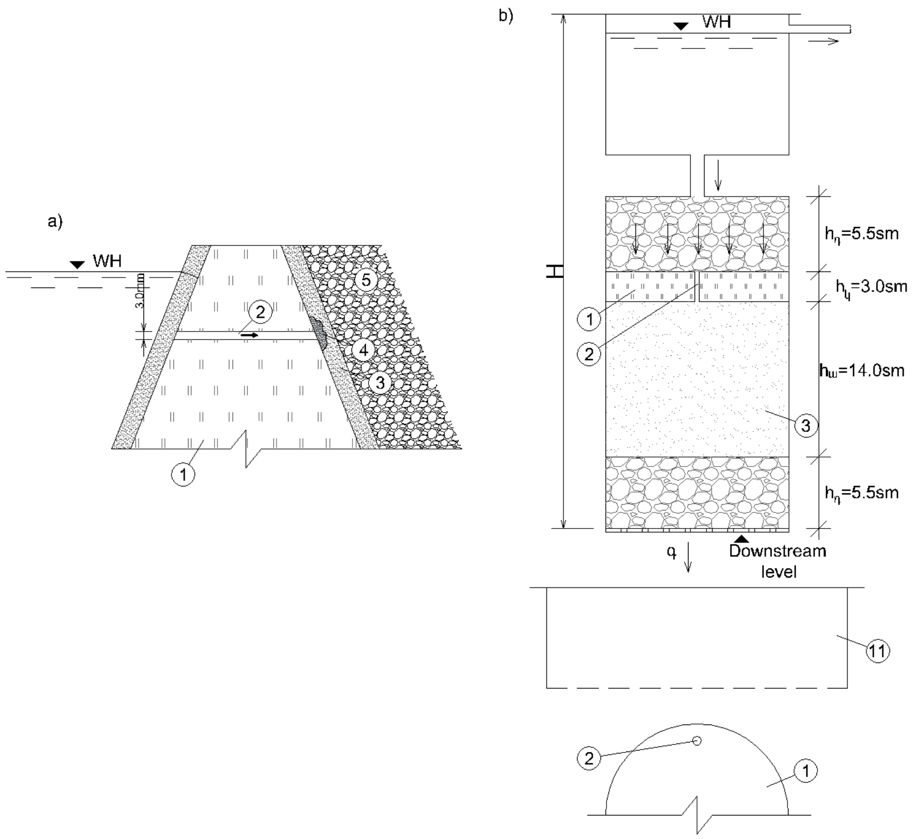

Fig. 4 Study of suffosion scheme at the cracked core

a - core original scheme, b - core scheme of the corresponding sample,
1 - clay core, 2 - crack, 3 - transition zone, 4 - colmatage site, 5 - dam prism

To prevent the contact zone of the core from being washed by the particles from the crack filtration flow, the transfer zone filter must be designed so that the core particles transported by the filtration flow do not pass through the filter layer but are colmataged at the crack exit. Figure 4 shows the schemes revealing the occurrence of cracks and colmatage in the core, as well as the regeneration of the latter.

A completely different scenario should be expected when the clay layer entering the construction system consisting of different layers has a discontinuity (crack). The flow of water passing through the layer and reaching the filter will be significantly different from the flow passing through the layer without a discontinuity, both in terms of pressure and the movement of particles. Considering this circumstance, a vertical hole with a diameter of 3 mm was inserted into the clay layer during sample preparation. This hole allows the flow of water passing through the clay layer to be directed to the filter through the hole. The hole diameter was selected based on the clay particle grain size composition [14]. Our experience indicates that we are dealing with an external suffosion of clay that develops on the walls of the hole.

During the suffosion test, water under a pressure of 4.5-5 atmospheres was pumped from the water inlet valve of the test device onto the concrete constitutive layer. For getting accurate readings for the manometer, the construction layer of gravel placed above the clay layer was de-aerated at the beginning of the experiment. During the experiment, the filtration flow passing through the crack passes through the sand filter and is collected by the drainage layer in the flow measuring container (11). Filtration flow rates were recorded every 2 minutes during the experiment. The mass of particles passing through the sample was estimated every 2 minutes in the stream of water passing through the sample.

The amount of water flow and the mass of particles removed from the test sample were recorded every 2 minutes during the experiment. To evaluate the intensity of suffosion, the concentration of solid particles in the flow was calculated over time

$K = f(t)$.

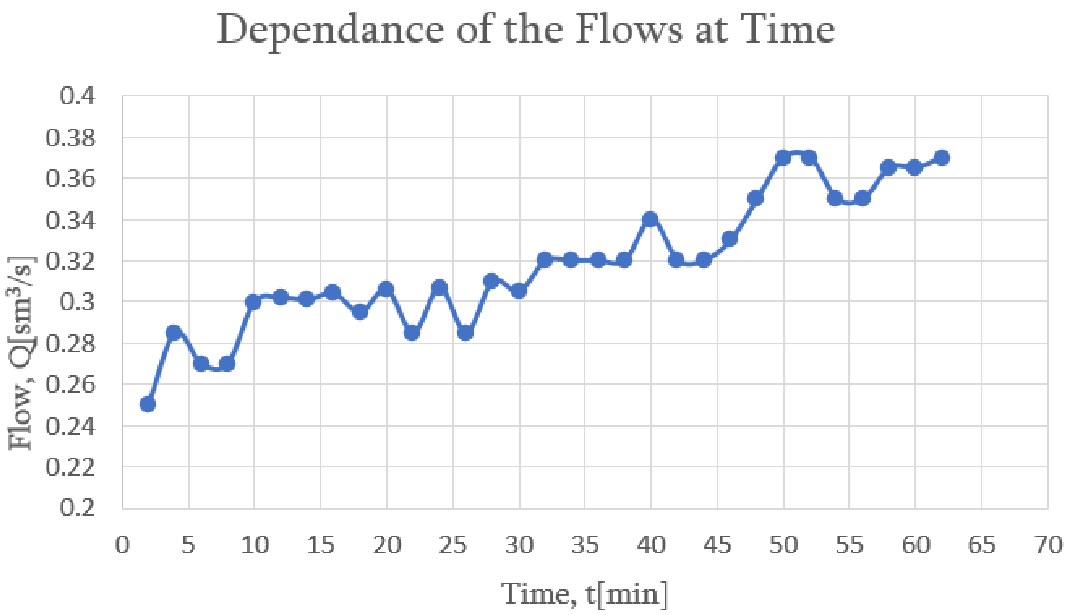

Fig. 5 Graph of specific filtration output: $q = f(t)$

At the end of the experiment, the mass of particles accumulated on the N200 sieve (hole diameter 0.075 mm) in the water flow during the experiment is evaluated.

The experiment resulted in obtaining value for the filtration output $q = f(t)$ (Fig. 5) and the concentration of particles undergoing suffosion $K = f(t)$ (Fig. 6) over time under conditions where a crack was present in the core.

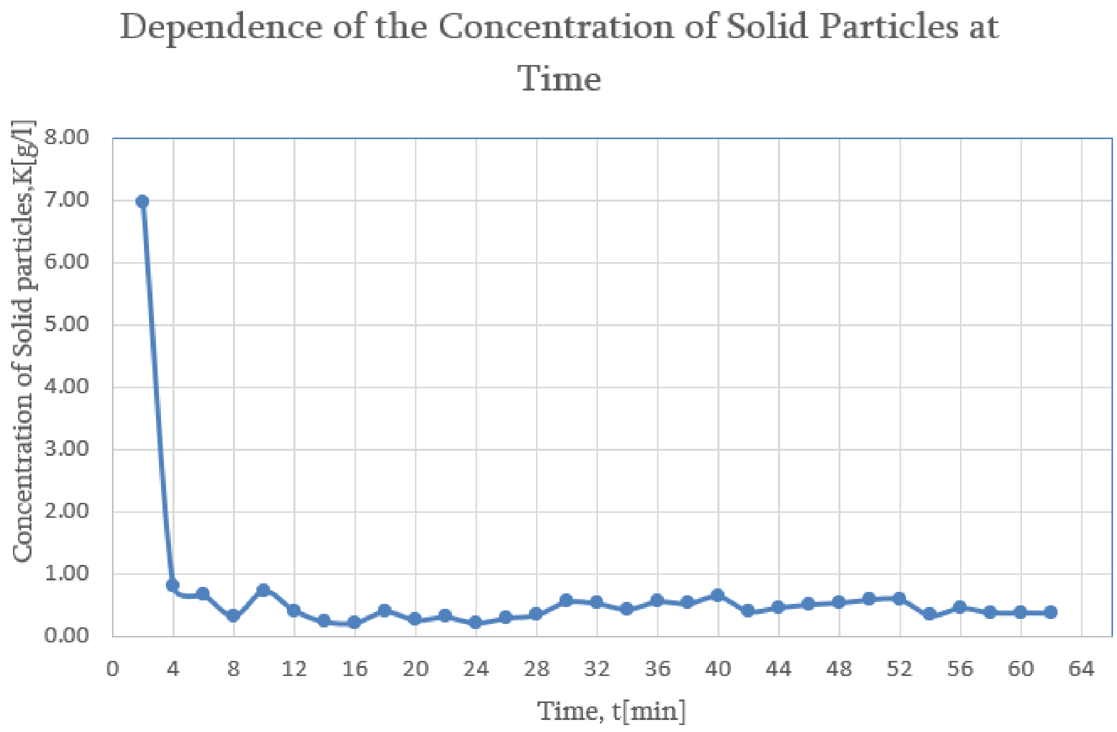

Fig. 6 $K = f(t)$

As shown in Fig. 5 and Fig. 6, the filtration efficiency in the core crack increases significantly over time, from 0.25 cm3/s to 0.37 cm3/s in 60 minutes. When the particles undergo suffosion, their concentration initially drops sharply from 7 g/l to 0.9 g/l and then decreases further to 0.4 g/l during the observed period.

Conclusion

The physical and mechanical parameters of the soil tested are consistent with the physical and mechanical characteristics of soils provided as examples in the technical specifications for the Vedi reservoir construction project. The gravel indicators and sand filter installed in the dam core are consistent with the filtration indicators proposed by Sherhardt. The suffosion studies conducted on the dam core and transition zone soils indicate that the system is free from suffosion risks without core continuity.

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Պետրոսյան Տ.Լ., Մանուկյան Ս.Բ., Խաչատրյան Է.Հ., Նամաթյան Ն.Տ.
Ճարտարապետության և շինարարության Հայաստանի ազգային համալսարան

Աշխատանքում վերլուծվել է գրունտներում սուֆոզիայի գործընթացի քանակական բնութագրերի վրա ազդող հիմնական գործոնների միջև գոյություն ունեցող կապերն արտահայտող առնչությունները, որոնք ընկած են գրունտային պատվարների միջուկի, ֆիլտրերի և դրենաժների նյութերի ընտրության մեթոդիկայի հիմքում: Ներկայացվել է փորձասարքը և մեթոդիկան, որի միջոցով կարելի է մոդելավորել պատվարում ճաք ձևավորված կավային միջուկի և ավազային ֆիլտրի համատեղ աշխատանքը: Բերվել են ստացված փորձարարական արդյունքները, որոնք ներկայացնում են սուֆոզիայի գործընթացում ջրի հոսքի հետ դուրս բերվող մասնիկների զանգվածի և կոնցենտրացիայի փոփոխությունը ժամանակի ընթացքում:

Բանալի բառեր. սուֆոզիա, հատիկաչափական կազմ, հիդրավլիկական գրադիենտ, կրիտիկական արագություն, հակադարձ ֆիլտր, թաղակապություն:

ИССЛЕДОВАНИЕ МЕХАНИЧЕСКОЙ СУФФОЗИИ ГЛИНИСТОГО ГРУНТА, ЗАЩИЩЕННОГО ФИЛЬТРОМ

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В работе проанализированы закономерности, выражающие связи, имеющиеся между основными факторами, влияющими на количественные характеристики суффозионного процесса в грунтах, лежащие в основе методики выбора материалов ядра грунтовых плотин, фильтров и дренажей. Представлено испытательное оборудование и методика, с помощью которых можно смоделировать совместную работу глинистого ядра и песчаного фильтра плотины, имеющую трещину на ядре. Представлены полученные экспериментальные результаты, отражающие изменение массы и концентрации частиц, выносимых с потоком воды в процессе суффозии с течением времени.

***Ключевые слова*:** суффозия, гранулометрический состав, гидравлический градиент, критическая скорость, обратный фильтр, сводообразование.

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