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Criteria for modelling flow movement in filtering structures of railway earthworks

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ABSTRACT The article presents the derivation of similarity criteria for laminar, turbulent, and transitional regimes of filtration flow in pipeless French drain systems. In recent years, coarse-grained materials have been widely used in the construction of railway embankments to protect slopes from erosion and wash-outs and to build filter trenches. The patterns of filtration flows in both cases are the same as in pipeless French drainage systems; however, not all of the calculation dependencies required for practical use can be obtained theoretically, and it is then necessary to use either mathematical methods or, more often, physical modelling. In particular, it is not possible to theoretically obtain dependencies for determining flow depths when there is no water level at the downstream end of the outlets. Until now, research has been conducted primarily by hydraulic engineers for filtration flows through embankment dams. In this case, the filtration usually behaves as a laminar flow. In the outlet sections of filter trenches and pipeless drains, the flow is generally turbulent, while at the section just before the outlet the flow is transitional. Until recently, these cases remained outside the focus of filtration specialists. There were no criteria for modelling. In this article, these criteria are derived from the equations of filtration flow motion in drains for all three regimes: laminar, transitional, and turbulent. Verification of the obtained similarity criteria was carried out for a 14 metre long pipeless French drain laid in a trough. The article presents a water surface profile designed using a theoretically justified calculation relationship. The same figure also shows points obtained by measurements in specific sections of the filtration flow in the trough. As can be seen from the figure, the agreement of the results is quite satisfactory.

KEYWORDS: pipeless French drain; filter trench; filtration flow; modelling criteria; filtration regime; physical modelling; hydraulic calculation; crushed stone; railway earthworks

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Научная статья

Критерии моделирования при движении потоков в фильтрующих сооружениях земляного полотна

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АННОТАЦИЯ Представлен вывод критериев подобия при ламинарном, турбулентном и переходном режимах движения фильтрационного потока в бесполостных дренах. В последние годы при строительстве земляного полотна железных дорог находят широкое применение крупнозернистые материалы для защиты откосов от

размывов и сплывов и при устройстве фильтрующих прорезей. Закономерности движения фильтрационных потоков в обоих случаях те же, что и в бесполостном дренаже, однако не все необходимые для практиков расчетные зависимости могут быть получены теоретическим путем, и тогда приходится использовать методы либо математического, но чаще всего физического моделирования. В частности, не представляется возможным теоретическим путем получить зависимости для определения глубин потоков, когда со стороны устьев уровень воды в нижнем бьефе отсутствует. До настоящего времени исследования проводились в основном гидротехниками для фильтрационных потоков через грунтовые плотины. При этом имеет место обычно ламинарный режим фильтрации. В устьевых участках фильтрующих прорезей и бесполостных дрен имеет место, как правило, турбулентный режим, а перед устьевым участком — переходный. Эти случаи до последнего времени оставались вне поля зрения специалистов по фильтрации. Критерии моделирования отсутствовали. В статье эти критерии получены из уравнений движения фильтрационных потоков в бесполостных дренах для всех трех режимов: ламинарного, переходного и турбулентного. Проверка полученных критериев подобия была проведена для бесполостной дрены длиной 14 м, уложенной в лоток. Приведена кривая свободной поверхности, построенная с использованием теоретически обоснованной расчетной зависимости. На этом же рисунке нанесены точки, полученные путем измерения глубин в определенных сечениях фильтрационного потока в лотке. Как следует из рисунка совпадение результатов вполне удовлетворительное.

КЛЮЧЕВЫЕ СЛОВА: бесполостная дрена; фильтрующая прорезь; фильтрационный поток; критерии моделирования; режим фильтрации; физическое моделирование; гидравлический расчет; щебень; земляное полотно.

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INTRODUCTION

Over the last 20 years, coarse-grain materials have been increasingly in use in railway construction in Russia for building filter trenches that are nothing more than a pipeless French drainage system. In a pipeless French drain, the water-conveying cavity is filled with high-filtration, coarse-grained material [1–5]. Coarse-grained materials are also used to protect slopes of earthworks against erosion and wash-outs. The patterns of filtration flow movement in both cases are the same as in the case of a pipeless French drainage system. However, it is not always possible to theoretically obtain the required calculation dependencies for practical use, and it is then necessary to use experimental research methods. In particular, it is not possible to theoretically obtain relationships for determining depths at the outlets of the flows when no water level on the downstream side is available. Hydraulic engineers dealing with filtration flows in embankment dams were the first to face the problem. All solutions were mainly obtained by physical modelling. However, it should be noted that in soils the filtration flow is laminar. Transitional flow prevails in coarse-grained materials, and turbulent flow is usually found in outlet sections. For some time, these cases have not been given focus.

In railway transport, pipeless French drainage systems are built using the same fractions as those used for the ballast section. The results of the calculations show [4] that due to low slopes of railway tracks and, hence, those of pipeless drains that are laid with the same gradient, the flow is transitional along a significant portion of the drain length. Consequently, the hydraulic calculation of pipeless drains should use a differential equation in the following form:

$$\frac{dh}{dS} = i - \frac{q'}{K_L \cdot \omega} \cdot S - \frac{(q')^2}{K_T^2 \cdot \omega^2} \cdot S^2, \qquad (1)$$

where h is the depth of the filtration flow in a given flow section, m; i is the slope of the bottom of the pipeless drain; q' is the specific inflow to the drain, m^2/s; S is the distance from the drain head to the section in question, m; K_L and K_T are the permeability coefficients of the fill material for laminar and turbulent flows, respectively, m/s; and ω is the filtration flow section area in the given flow section, m^2 (*Fig. 1*).

Equation (1) is only solved for four shapes of the cross-section of a pipeless French drain: rectangular,

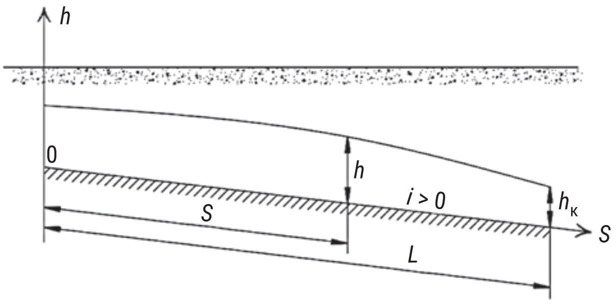

Fig. 1. Design model of water movement in a pipeless drain

triangular, trapezoidal, and combined. Besides, pipeless drains are longer and as the flow rate and velocity of the filtration flow in a pipeless drain increase, seepage often goes through all the three flow regimes, from laminar to turbulent. Each regime has its own similarity criteria, and all the criteria can be obtained by using equation (1). This is due to the fact that under a certain regime, each right-hand term of the equation is the principal member [5]. Let us use this to derive the necessary similarity criteria. It is particularly relevant to obtain calculation dependencies for determining cross-sectional shapes such as triangular, at the outlet sections of a drain.

Determining h_c for a pipeless French drainage is similar to finding the seepage interval for groundwater [6] that seeps through an earth cofferdam with no backwater on the downstream side. In general, the structure of the formula for seepage height h_s (an analogue of h_c) looks as follows:

$$h_c = \beta \cdot \frac{q'}{K_L}, \tag{2}$$

where β is the coefficient; and q' is the specific flow rate across the seepage area, m²/s.

The coefficient β varies over a wide range. Thus, in [6–8], β is equal to 0.44, and according to P.Ya. Polubarinova-Kochina, β is equal to 0.74. According to V.A. Ionat, for drains laid on impervious material, β is equal to 0.5. All this suggests that physical model-based studies are necessary, which requires similarity criteria.

An example of using similarity criteria in an analysis of the fluid flow in granular layers is found in [9].

Papers [10–12] discuss hydrogeological models that resemble the flow in a pipeless French drainage system. More data on turbulent filtration flow is found in [13]. Articles [14, 15] provide additional information about the height of the seepage interval, a known value of which allows for the correct assessment of the position of depression curves in various cases, as will be shown in this work.

FINDINGS

Testing equation (1) confirms that in the case of a laminar flow, the role of the last term is very small due to the low filtration velocity, and then, with an accuracy quite sufficient for practical purposes, the filtration flow movement obeys the following equation written for a drain of rectangular cross-section:

$$\frac{dh}{dS} = i - \frac{q'}{K_L \cdot b \cdot h} \cdot S, \tag{3}$$

where b is the drain width; and h is the water depth in the cross-section in question.

Then for both actual and model conditions, we get:

$$\frac{dh_A}{dS_A} = i_A - \frac{q'_A}{K_{L_A} \cdot b_A \cdot h_A} \cdot S_A; \tag{4}$$

$$\frac{dh_M}{dS_M} = i_M - \frac{q'_M}{K_{L_M} \cdot b_M \cdot h_M} \cdot S_M. \tag{5}$$

Let us introduce to equation (4) the scaling factors for the similarity of the actual flow to the model flow in a pipeless French drain:

$\alpha_S = \frac{S_A}{S_M}$ — for flow length;

$\alpha_b = \frac{b_A}{b_M}$ — for flow width;

$\alpha_h = \frac{h_A}{h_M}$ — for flow depth;

$\alpha_{K_L} = \frac{K_{L_A}}{K_{L_M}}$ — for filtration coefficients in laminar flow;

$\alpha_i = \frac{i_A}{i_M}$ — for drain slopes; and

$\alpha_{q'} = \frac{q'_A}{q'_M}$ — for specific inflow to the drain.

If we model without scale distortion, then $\alpha_S = \alpha_h = \alpha_b$ and $\alpha_i = \alpha_A/\alpha_M = 1$.

In equation (4), let us express all the characteristics of the flow using the corresponding characteristics of the model flow and the scaling factors:

$$\frac{\alpha_h}{\alpha_S} \cdot \frac{dh_A}{dS_A} = \alpha_i \cdot i_M - \frac{\alpha_{q'} \cdot q'_M}{\alpha_{K_L} \cdot K_{L_M} \cdot \alpha_b \cdot b_M \cdot \alpha_h \cdot h_M} \cdot \alpha_S \cdot S_M. \tag{6}$$

According to the hydraulic modelling theory, the relationships between like forces at all homologous points of the actual and model flows are the same. Following this rule, we divide each term of equation (6) by the corresponding term in equation (5) and equate the results. As a result, after making the appropriate reductions of the equal-magnitude scaling factors and substituting the remaining scaling factors with their expressions in terms of characteristics of the actual and model flows, we obtain:

$$\frac{q'_A}{K_{L_A} \cdot b_A} = \frac{q'_M}{K_{L_M} \cdot b_M} \text{ or } \frac{q'}{K_L \cdot b} = U_L = \text{idem} \tag{7}$$

for both the actual and model flows at all homologous points. When condition (7) is satisfied, model flow depth h_M at any homologous flow section will be similar to the actual flow, i.e.:

$$h_A = \alpha_h \cdot h_M.$$

At the head of a pipeless French drain with small bottom slopes, the filtration flow is usually laminar, while at the outlet it is turbulent. The flow between the head and the outlet section of the drain is transitional. Let us first obtain the modelling criteria for the turbulent regime and then move on to the transitional one. As was mentioned above, in the case of a turbulent filtration flow in a pipeless French drain, equation (1) for a rectangular cross-section is as follows:

$$\frac{dh}{dS} = i - \frac{(q')^2}{K_T^2 \cdot b^2 \cdot h^2} \cdot S^2. \tag{8}$$

After doing all the necessary rearrangements and reasoning as in the case of the laminar flow, we finally obtain the following similarity criteria for the turbulent flow:

$$\frac{q'}{K_T \cdot b} = \sqrt{U_T} = \text{idem}. \qquad (10)$$

The mechanical similarity of flows will be maintained if criterion (9) is rewritten as follows:

$$\frac{q'}{K_T \cdot b} = \sqrt{U_T} = \text{idem}. \qquad (10)$$

In the case of a transitional flow, all the terms in equation (1) are significant, albeit to a different degree, depending on to which of the two critical Reynolds numbers (Re_L for laminar flow and Re_T for turbulent flow) Re is closer in magnitude for a given flow section of the filtration flow in a pipeless drain.

Let us write equation (1) for a pipeless Frencdrain of rectangular cross-section in full, in order to obtain similarity criteria for the transitional regime for both the actual and model flows:

$$\frac{dh_A}{dS_A} = i_A - \frac{q'_A}{K_{L_A} \cdot b_A \cdot h_A} \cdot S_A - \frac{(q'_A)^2}{K_{T_A}^2 \cdot b_A^2 \cdot h_A^2} \cdot S_A^2; \tag{11}$$

$$\begin{aligned} \frac{dh_M}{dS_M} - i_M - \frac{q'_M}{K_{L_M} \cdot b_M \cdot h_M} \cdot S_M - \\ - \frac{(q')^2}{K_{T_M}^2 \cdot b_M^2 \cdot h_M^2} \cdot S_M^2. \end{aligned} \tag{12}$$

Using the scaling factors introduced earlier and given that $\alpha_i = 1$ and $\alpha_S = \alpha_h = \alpha_b$, we rewrite equation (11) for the actual flow to express in it all the characteristics of the flow using the corresponding characteristics of the model flow and all the scaling factors:

$$\begin{aligned} \frac{\alpha_h}{\alpha_S} \cdot \frac{dh_A}{dS_A} = \\ = \alpha_i \cdot i_M - \frac{\alpha_{q'} \cdot q'_M}{\alpha_{K_L} \cdot K_{L_M} \cdot \alpha_b \cdot b_M \cdot \alpha_h \cdot h_M} \cdot \alpha_S \cdot S_M - \\ - \frac{\alpha_{q'}^2 \cdot (q'_M)^2}{\alpha_{K_T}^2 \cdot K_{K_M}^2 \cdot \alpha_b^2 \cdot b_M^2 \cdot \alpha_h^2 \cdot h_M^2} \cdot \alpha_S^2 \cdot S_M^2. \end{aligned} \tag{13}$$

By viding all the terms of equation (13) term by term by the corresponding terms of equation (12) and equating them with each other, and after making the appropriate reductions, we obtain the following expression:

$$\left. \begin{aligned} U_L &= \frac{q'}{K_L \cdot b} = \text{idem} \\ U_T &= \left(\frac{q'}{K_T \cdot b} \right)^2 = \text{idem} \end{aligned} \right\} \tag{14}$$

However, criteria (14) can only be met simultaneously if the scaling factors α_{K_L} and α_{K_T}, are equal, which is hard to achieve in practice. The discussion above shows that if a transitional flow is present in a pipeless French drain, then at the outlet section, where the flow rate is maximum and the water depth is minimal, the flow is either turbulent or close to turbulent. In this case, as a result of modelling, it is sufficient to ensure that values of criterion U_T in the actual and model flows are equal for the turbulent regime.

For a hydraulic calculation of pipeless French drains, we have obtained calculation relationships in order to design water surface profiles, including the transitional flow for the following cross-sections (rectangular, triangular, trapezoidal, and combined). The calculation relationship for the rectangular cross-section was obtained first. Then it was established that the surface profile shape does not depend on the movement regime throughout the drain length. *Fig. 2* shows

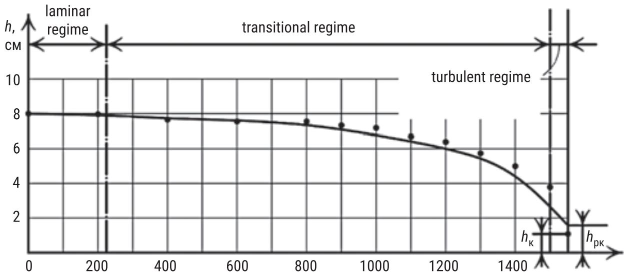

Fig. 2. Calculated surface profile in a pipeless French drain (i = 0; experiment No. 10) – test points

Table 1

Filtration characteristics of granite crushed stone

d_{17}, cm	η	ψ	*n*	d_u, cm	K_L, cm/S	K_T, cm/S	c_0,	Re_L	Re_T
2.45	1.54	1.68	0.48	0.829	312.8	10.8	78	14.8	352

Table 2

Relative lengths of sections with different flow regimes in an experimental pipeless French drain, %

Experiment No.	Drain slope	Filtration regime		
		laminar	transitional	turbulent
10	0.00	15.6	83.5	0.9

a surface profile designed on the basis of the calculation by the formula derived for the transitional regime for bottom slope $i = 0$, and test points are plotted in the same figure. The calculated surface profile was designed for a pipeless French drain laid in a trough, and the calculations took into account the effect of near-wall filtration. The experimental and calculated data agree well with each other. *Table 1* shows the characteristics of crushed stone, and *Table 2* lists the relative lengths of sections with different filtration regimes as a percentage of the total length of the experimental pipeless drain. It is no coincidence that all researchers only sought to obtain relationships for determining seepage height h_S, and in this case, it is the water depth at the drain's outlet. Here, only one similarity criterion is required.

The following designations are used in *Table 1*: d_{17} is the diameter of particles, finer than which 17 per cent, by mass, of particles are contained in crushed stone; η is the coefficient of heterogeneity (grain size inhomogeneity) of crushed stone; ψ is the coefficient of particle shape; n is porosity; d_u is the calculated diameter of the filtration passage; c_0 is the Chezy coefficient; and Re_L and Re_T are the critical Reynolds figures for laminar flow and turbulent flow, respectively.

Table 2 shows the dimensions of drain sections with different flow regimes.

CONCLUSIONS

1. All the problems of filtration for determining the water depth at outlet sections of flows use calculation relationships obtained experimentally, and for laminar filtration flow only. In the case of filter trenches in railway earthworks and pipeless French drainage systems, the flow regime at the outlet is usually either transitional or turbulent. No similarity criteria for these cases have been obtained earlier.

2. When slopes of pipeless French drains and filter trenches are small, which is the case for railways, a turbulent regime is found at the outlets of drains and flows. In this case, only one criterion is to be observed in modelling. Considering that in outlet sections, flow velocities are the highest and under certain conditions seepage damage (contact erosion) is possible, it is important to be able to determine the flow depth at the drain outlet. There are no theoretical calculation relationships for determining h_c, but flow depths at the outlet of pipeless French drain systems h_c can be determined by modelling.

REFERENCES

1. Zhinkin G.N., Grachev I.A. *Features of railway construction in areas of permafrost and swamps: a textbook*. Moscow. Lan. 2020:420. (In Russ.).

2. Shtykov V. I., Ponomarev A. B., Yanko Yu. G. Discussing the calculation of erosion rates in the design of filtering structures in cohesive soils. *Proceedings of Petersburg Transport University*. 2021;18(2):303-312. (In Russ.) DOI: 10.20295/1815-588X-2021-2-303-312. EDN: OVVRLC. (In Russ.).

3. Shtykov V.I., Ponomarev A.B., Yanko Yu.G. Specifics of rockfill dam hydraulic calculations in clay soils. *Proceedings of Petersburg Transport University*. 2025;22(1):228-237. DOI: 10.20295/1815-588X-2025-1-228-237. EDN: ZNYWRP. (In Russ.).

4. Shtykov V.I., Ponomarev A.B. Hydraulic calculation of non-cavity triangular cross-section drains in transient regime. *Proceedings of Petersburg Transport University*. 2019;16(3):523-532. DOI: 10.20295/1815-588X-2019-3-523-532. EDN: ZQMGCB. (In Russ.).

5. Shtykov V.I., Gordienko S.G. Cavity-free drainage: hydraulic justification, calculation and operational efficiency. Saint Petersburg. 1997:223. EDN: ZIWSFB. (In Russ.).

6. Klimentov P.P., Kononov V.M. *Dynamics of groundwater: [Textbook for geological exploration colleges]*. 2nd ed. Moscow. Vysshaya Shkola. 1985:383. (In Russ.).

7. Balykov B.I. Experimental studies of similarity conditions for physical and mechanical properties of non-cohesive soil samples. *Izvestia VNIIG im. B.E. Vedeneeva*. 1979;135:5-13. (In Russ.)

8. Poltavtsev V.I., Spitsyn I.P., Vinnikov S.D. *Hydrological laboratory modeling*. Poltavtsev V.I., ed. Leningrad. Leningrad Polytechnic Institute. 1982:142. (In Russ.).

9. Kravtsov M.V., Kravtsov A.M. General equation of the hydraulic friction law for hindered falling of an individual ball and fluid motion in granular layers. *Energetika. Proceedings of CIS higher education institutions and power engineering associations*. 2015;(3):85-96. EDN: TXJDPP. (In Russ.).

10. Mitrushkin D.A., Tomin P.Y. Calculation of filtration flows in fractured-porous media with cavities. *Georesursy, geoenergetika, geopolitika*. 2014;1(9):13. EDN: SIUYUT. (In Russ.).

11. Anakhaev K.N., Anakhaeva K.K. Simulation of filtration flow seepage through sloped soil slope. *Power Technology and Engineering (Gidrotekhnicheskoe Stroitel'stvo)*. DOI: 10.34831/EP.2023.29.23.006. 2023;(11):36-40. EDN: LWEZRR. (In Russ.).

12. Bublik S.A., Semin M.A. Analysis of approaches to the calculation of groundwater filtration flows in modeling artificial frozen walls formation. *Fluid Dynamics*. 2023;16(1):46-60. DOI: 10.7242/1999-6691/2023.16.1.4. EDN: GSSLUU. (In Russ.).

13. Gasanov I.R. On the determination of hydraulic resistance in the turbulent regime of fluid filtration in a porous medium. *Young Scientist*. 2019;2(240):20-22. EDN: YTVCBN. (In Russ.).

14. Bukhartsev V.N., Petrichenko M.R. Translational invariance of the Dupuit formula and determination of the seepage gap height. St. Petersburg State Polytechnical University Journal. 2012;3-2(154):194-199. EDN: PESLGF. (In Russ.).

15. Petrichenko M.R., Zaborova D.D., Kotov E.V., Musorina T.A. Formation of a seepage gap in a rectangular jumper. *Power Technology and Engineering (Gidrotekhnicheskoe Stroitel'stvo). 2018;(10):49-52. EDN: YNAWUH. (In Russ.).*

ЛИТЕРАТУРА

1. *Жинкин Г.Н., Грачев И.А.* Особенности строительства железных дорог в районах распространения вечной мерзлоты и болот: учеб. пособие. М.: Лань, 2020. 420 с.

2. *Штыков В.И., Пономарев А.Б., Янко Ю.Г.* О расчете размывающих скоростей при проектировании фильтрующих сооружений в связных грунтах // Известия Петербургского университета путей сообщения. 2021. Т. 18. Вып. 2. С. 303–312. DOI: 10.20295/1815-588X-2021-2-303-312. EDN: OVVRLC.

3. *Штыков В.И., Пономарев А.Б., Янко Ю.Г.* Об особенностях гидравлического расчета фильтрующих насыпей в связных грунтах. // Известия Петербургского университета путей сообщения. 2025. Т. 22. Вып. 1. С. 228–237. DOI: 10.20295/1815-588X-2025-1-228-237. EDN: ZNYWRP.

4. *Штыков В.И., Пономарев А.Б.* Гидравлический расчет бесполостных дрен треугольного поперечного сечения при переходном режиме // Известия Петербургского университета путей сообщения. 2019. Т. 16. Вып. 3. С. 523–532. DOI: 10.20295/1815-588X-2019-3-523-532. EDN: ZQMGCB.

5. *Штыков В.И., Гордиенко С.Г.* Бесполостной дренаж: гидравлическое обоснование, расчет и эффективность действия. СПб., 1997. 223 с. EDN: ZIWSFB.

6. *Климентов П.П., Кононов В.М.* Динамика подземных вод : [Учеб. для геол.-развед. техникумов]. 2-е изд., перераб. и доп. М.: Высш. шк., 1985. 383 с.

7. *Балыков Б.И.* Экспериментальные исследования условий подобия физико-механических свойств образцов несвязного грунта // Известия ВНИИГ им. Б.Е. Веденеева: сб. науч. трудов. 1979. Т. 135. С. 5–13.

8. *Полтавцев В.И., Спицын И.П., Винников С.Д.* Гидрологическое лабораторное моделирование / под ред. В.И. Полтавцева. Л.: Ленингр. политехн. ин-т, 1982. 142 с.

9. *Кравцов М.В., Кравцов А.М.* Общее уравнение закона гидравлического сопротивления при стесненном падении одиночного шара и движении жидкости в зернистых слоях // Энергетика. Известия высших учебных заведений и энергетических объединений СНГ. 2015. № 3. С. 85–96. EDN: TXJDPP.

10. *Митрушкин Д.А., Томин П.Ю.* Расчет фильтрационных течений в трещиновато-пористых средах с кавернами // Георесурсы, геоэнергетика, геополитика. 2014. № 1(9). С. 13. EDN: SIUYUT.

11. *Анахаев К.Н., Анахаева Х.К.* Моделирование высачивания фильтрационного потока через наклонный грунтовый склон // Гидротехническое строительство. 2023. № 11. С. 36–40. EDN: LWEZRR.

12. *Бублик С.А., Семин М.А.* Анализ подходов к расчету фильтрационных течений подземных вод при моделировании формирования ледопородных ограждений // Вычислительная механика сплошных сред. 2023. Т. 16. № 1. С. 46–60. DOI: 10.7242/1999-6691/2023.16.1.4. EDN: GSSLUU.

13. *Гасанов И.Р.* Об определении гидравлического сопротивления при турбулентном режиме фильтрации флюида в пористой среде // Молодой ученый. 2019. № 2(240). С. 20–22. EDN: YTVCBN.

14. *Бухарцев В.Н., Петриченко М.Р.* Трансляционная инвариантность формулы Дюпюи и определение высоты промежутка высачивания // Научно-технические ведомости Санкт-Петербургского государственного политехнического университета. 2012. № 3-2(154). С. 194–199. EDN PESLGF.

15. *Петриченко М.Р., Заборова Д.Д., Котов Е.В., Мусорина Т.А.* Образование промежутка высачивания в прямоугольной перемычке // Гидротехническое строительство. 2018. № 10. С. 49-52. EDN: YNAWUH.

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