Experimental studies to determine the initial filtration gradient in clays

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Abstract. As is known, bentonite clay with a high plasticity number of montmorillonite composition (Logosnoy deposit) is characterized in its natural occurrence by a filtration coefficient value of no higher than 0.001...0.001 m/day. When such lump clay is placed in a clay solution, as a result of lump soaking and swelling, the filtration coefficient value decreases by no less than an order of magnitude. This property of lump clay also creates a safety reserve for the anti-filtration properties of the curtain.

1 Introduction

where \( v \) is the filtration speed; \( k \) is the filtration coefficient; \( I \) ~ piezometric slope; \( I_0 \) ~ initial piezometric slope or resistance coefficient; \( n \) ~ constant.

Subsequently, the phenomenon of the initial filtration gradient was noted in the works of K.K. Gedoritsa, K.P. Lundina, K.I. Dobrovolksky and others.

A number of foreign works (P. Basak, D. Evans, X. Pascal, etc.) attempted to theoretically substantiate the causes of filtration anomalies during water movement in low-permeability clay soils at low pressure gradients. The deviation from Darcy's law and the manifestation of the initial filtration gradient is associated with the influence of the forces of molecular interaction of water with rock and the viscoplastic nature of water flow in ultra thin pore channels. Moreover, according to, for example, K. Tonsbo, in the region of anomalous gradients (large initial, but smaller gradients at which linear filtration is established), the relationship between filtration speed and pressure is parabolic. Deviations from Darcy's law

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are associated with the structural and mechanical properties of pore water, as well as the action of trapped air. At the same time, it is concluded that, regardless of the physical essence of the phenomenon, in natural conditions there is an initial gradient and at $I < I_0$ there is no movement of water in clay layers, i.e. they can be considered as aquitards.

It is interesting to note what values characterize the initial gradient according to the literature. In some works its value does not exceed tenths or hundredths; according to others, it is calculated in units; finally, for some authors the value of the initial gradient varies for montmorillonite clays from 50 to 100.

In the work, based on a review analysis of factual material (foreign research data), it is noted that the lower limit of applicability of Darcy’s law depends on the type of soil (the higher the surface activity, the higher the lower limit) and porosity (with an increase in the porosity of the same soil, this limit is reduced). At the same time, the authors emphasize the approximation and certain inconsistency of empirical data on the lower limit of applicability of Darcy’s linear law.

On the issue of the initial filtration gradient, the research of V.M. Pavilonsky deserves special attention. Based on the materials of his works, the author does not give an unambiguous answer to the question of whether the initial filtration gradient exists or does not exist. Thus, according to the results of a study of various lithological varieties (sandy loam, loam and clay), the phenomenon of an initial gradient was noted only in experiments with clays and loams. The issue of the initial filtration gradient in clays is discussed in the review article by I.A. Brilling, dedicated to the study of filtration in clays. The author of this article comes to the conclusion that there is no initial filtration gradient.

Thus, the results of published studies, for the most part, while confirming the presence in clayey rocks of the phenomenon of violation of Darcy’s linear law in the region of small pressure gradients, do not give an unambiguous answer to the question of the presence of an initial filtration gradient in clays. The value of the initial filtration gradient, according to works claiming its existence, varies widely from fractions of one to a hundred or more.

### 2 Materials and methods

When carrying out the experiments, the revealed patterns of changes in the permeability of clays under the influence of variable temperatures and mineralization were taken into account, which is directly related to the change in the state of water in the clays. As a result, the experiments included studying the lower limit of applicability of Darcy's linear law and identifying areas of possible existence of an initial filtration gradient.

When conducting experiments, analyzing and processing experimental data, the following initial premises were taken into account. As is known, Darcy's law establishes a linear relationship between the filtration rate $v$ and the pressure gradient $I$; the graph of the function $v = f(I)$ represents a straight line emanating from the origin. Further, if we consider the permeability coefficient $k_n$ to be a constant parameter independent of the pressure gradient, then the graph $k_n = f(I)$ would represent a straight line parallel to the abscissa (gradient) axis. For clays, due to the special properties of pore water noted above, in the region of small values of $I$, both a violation of the linear filtration law and a different nature of the dependence $k_n = f(I)$ are possible.

A violation of the linear law of filtration in clays associated with the initial gradient can manifest itself in the deviation of the graph $v = f(I)$ from the straight line emanating from the origin, and the cutting off of the segment corresponding to the value of the initial gradient on the abscissa axis.

During the experiments, the condition of equality of lateral and vertical pressure of hydraulic compression of the sample ($Pr = 3.2$ MPa) and constancy of temperatures for each degree of gradient pressure was strictly observed (in the region of minimum gradients,
temperature fluctuations were allowed within the range of no more than 0.2 °C into account the possible influence of side effects on the experimental results and, in particular, additional compaction of the samples and their filtration consolidation (changes in filtration parameters over time), the time of which can reach 20-40 days, the actual studies of the initial gradient were carried out after preliminary exposure sample in a given mode of pressure, temperature and mineralization for 30 days. The total duration of an individual experiment was at least 100-120 days.

The installation used a capillary flow meter with a resolution of ±0.0001 ml, which made it possible to determine the permeability of clays with an accuracy of 1-10 μm² within the time established by experience.

When conducting these studies, a stepwise change in gradients was carried out from large values to small ones, and in two experiments the gradients first increased from minimum to maximum (forward movement), then decreased (reverse movement). In the general case, the range of gradient changes ranged from 40 to 70. In the area of large gradients, the time for fixing the flow rate at each stage was limited to 1-2 days until 5-7 values of permeability coefficients are obtained, differing from each other by no more than 10%; at small gradient values, this time increased to tens of days.

A total of 11 experiments were performed, the data of which are given in Table. The hydraulic compression pressure of the sample in the experiments was 3.2 MPa.

<table>
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<td>Distilled water</td>
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</table>

3 Results and discussion

J p ≤ J

\[
J_p = \frac{\Delta h}{t}
\]

where J p is the calculated gradient value effective pressure of the filtration flow, \( J_p \) = permissible filtration flow gradient; \( \Delta h \) = level difference in front and behind the curtain thickness, m;
For the highest value of the dam height (24m), design elevation \( NPL = 130m \) and average depth \( GWL = 113.0 \) m (maximum level from the Central Fergana reservoir) \( \Delta h = 17m \) the maximum value of the calculated pressure gradient is equal to:

\[
\frac{17}{0.6} = 28.33m
\]

According to our research (see below), in soils with a filtration coefficient of up to 200 m/ day (for lump clay of the Central Fergana reservoir dam), the permissible pressure gradient \( J_{add} = 40 \) should be taken. Thus, the condition for the filtration strength of the curtain with a thickness of the curtain body of 0.6 m and filling the trench with ball clay is satisfied along the entire route of the anti-filtration curtain. For the conditions of maximum design head, that is, 28.33 < 40, respectively, is satisfied[1].

As is known, the initial filtration gradient in clays manifests itself in the fact that the movement of water in them begins only after the pressure gradient exceeds a certain critical value. According to experiments by V.M. Goldberg and N.P. Skvortsov, the initial gradient for clays varies from 10 to 100. For clays of the Logon deposit, which was used in the construction of the Central Fergana reservoir dam, is characterized by a plasticity number of up to 27, the initial filtration gradient ranges from 40 to 70. For the conditions under consideration at thickness curtain of 0.6 m and a maximum level difference of 17 m, the maximum possible pressure gradient is 28.33 m (17/0.6), which is lower than the minimum value of the initial filtration gradient.

With a thickness of the anti-filtration curtain of 0.6 m and filling it with lump clay, filtration through the body of the curtain is expected to be insignificant. This is also confirmed by the filtration calculations we carried out below, which were used to determine the position of the depression curve in the dam body.

![Fig. 1. Central Fergana reservoir dam with impervious curtain](image)

When performing filtration calculations of such dams, the virtual length method is used. For this purpose, a core with an average thickness \( \delta_{cf} \) and with a filtration coefficient \( K_i \) lead to a prism with a filtration coefficient \( K_f \). The virtual length of the core is determined by the dependence:

\[
\Delta L_h = \frac{K_{cf}}{K_{cf} + \delta_{cr}}
\]

Where:

\[
k'_{cr} = k_{cr} + \frac{2k_{oc} + \delta_{cr}}{\pi(H_h + H_n)} \ar c h \left( \frac{2\gamma}{\delta_{cr}} \right)
\]
\[
\delta_{\text{ср}, я} = \delta + \delta = \frac{0.6 + 0.6}{2} = 0.6 \text{M}
\]

After this replacement, we carry out the calculation as a homogeneous dam with layered drainage, as in the previous scheme[1].

\[
K' = 0.005 + \frac{2 \times 0.005 + 0.6}{\pi (11.2 + 0)} \ar ch\left(\frac{2 \times 45.9}{0.6}\right)
\]

inverse \( ar ch(x) = \ln(x + \sqrt{x^2 - 1}) \)

value of the hyperbolic cosine function is determined through the logarithmic function:\( ar ch\left(\frac{2}{\delta_{n}}\right) \)

From here we get:

\[
ar ch\left(\frac{2 \times 45.9}{0.6}\right) = ar ch(153) = \ln\left(153 + \sqrt{153^2 - 1}\right) = \ln(152.99) = 5.03
\]

Substituting into the formula we get:

\[
K' = 0.005 + \frac{2 \times 0.005 + 0.6}{\pi (11.2 + 0)} \times 5.03 = 0.006
\]

\[
\Delta L = \frac{7}{0.006} \times 0.6 = 700 \text{M}
\]

We carry out the calculation according to the method proposed by Prof. V.P. Nedriga . [1]

\[
q = \frac{H^2}{L_p + \sqrt{L_p^2 - m^2 + H^2}}
\]

\[
q = \frac{11.2^2}{766.03 + \sqrt{766.03^2 - 3^2 + 11.2^2}} = \frac{125.44}{1531.3} = 0.0819
\]

\[
L_p = 761.55 + 4.48 = 766.03 \text{M}
\]

Since \( m \geq 2 \), we take \( \beta B = 0.4; \)

\[
\Delta L_B = 0.4 \times 11.2 = 4.48
\]

\[
h_B = 3.5 \times 0.0819 = 0.287 \text{M}
\]

For \( m \geq 1 \) value \( f(m_2) = 0.5 + m_2 \)

\[
f(m_2) = 0.5 + 3 = 3.5
\]

Based on the data obtained, a depression curve was constructed:
As is known, clay with a high plasticity number of montmorillonite composition (Logon deposit) is characterized in its natural occurrence by a filtration coefficient value of no higher than 0.001...0.001 m/day. When such lump clay is placed in a clay solution, as a result of lump soaking and swelling, the filtration coefficient value decreases by no less than an order of magnitude. This property of lump clay also creates a safety reserve for the anti-filtration properties of the curtain.

Thus, the experience of using clay as an impervious curtain for the Central Fergana reservoir dam has shown its effectiveness.

4 Conclusion

As studies have shown, the filtration strength of the curtain material of the Central Fergana reservoir dam is ensured at a maximum pressure gradient equal to \( J_p = 28.33 \) m, which is lower than the minimum value of the initial filtration gradient (28.5<40).

As a result of a brief review of the literature, it was revealed that most of the authors of the books do not give an unambiguous answer to the question about the presence of an initial filtration gradient in clays.

Our experimental studies to determine the initial gradient in the clays of the Logonsky deposit showed that it is in the range of 40...70.

The experience of using clay as an impervious curtain for the Central Fergana reservoir dam has shown its effectiveness.

References


