Improving of the Method of Calculating of Linearly-Extended Constructions of the Perfect Watertight Type Constructed by the Method "Wall in the Ground" With Initial Filtration Gradient

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Abstract. There is calculation method of basic parameters of linear-extended anti-filtration structures taking into account the initial filtration gradient of the filling material of "wall" in two cases. The first one is that the "wall" is defective type and it overlaps water-yielding heavily filtrated stratum with embedment into the second weakly filtrated stratum. The second one is the particular case of the decision of the common task and is the most effective. The second "wall" is a "wall" of a higher kind with embedment into an aquitard. The offered calculation method bases on the model which takes into account the non-linear way of water filtration through the "wall". It lets to avoid the inaccuracies in calculations. The water filtration through the "wall" will take place when the excess gradient exceeds the initial gradient. The calculation method, described in regulatory documents, doesn't take into account the initial gradient value. It influences on the choise of "wall" construction parameters. Taking into account the initial filtration coefficient lets to increase the calculations accuracy of anti-filtration structures. If the initial filtration gradient value is neglected, the calculation result from the obtained formulas for particular case will coincide with values, obtained by formulas, described in regulatory document.

1. Introduction

The calculation methodology proposed below is based on a model different from what is recommended by the existing standards [1, 2] in that it considers the initial threshold level of filtration in writing diaphragm's material. Filtration of water through the diaphragm will only occur after the said threshold level is overcome and the surplus gradient exceeds the initial filtration gradient of the diaphragm – once it is overcome, filtration of water begins. Documents [1 and 2] use only the filtration ratio to describe the material, which is quite obviously insufficient. Some European nations, such as Germany, have regulated that the level on the diaphragm's outer side may be lower by up to 10 cm, or within 20 cm in some particular cases, whereas inflow of water into the pit over the diaphragm is restricted. Respective Russian regulations overlook such parameters, while commonly practiced methods of diaphragm parameter calculation tend to recommend oversized values. The issue of the non-linear nature of water filtration in low-permeability soils, considering the initial filtration gradient, was studied by: Karman, B.V. Deryagin, S.A. Roza, S.V. Nerpin, B.P. Gorbunov, M.Yu. Abelev and others. The writer adopted the same approach to the engineering problem in question.

It has to be said that issues related to impervious structures are covered in [6-19], where authors discussed the issues of technology improvement, researched parameters of ground waters moving around the impervious screen, factors bearing on production and filtration performance of aggregate materials and their composition, examined construction methods and problems related to organization of underground space.

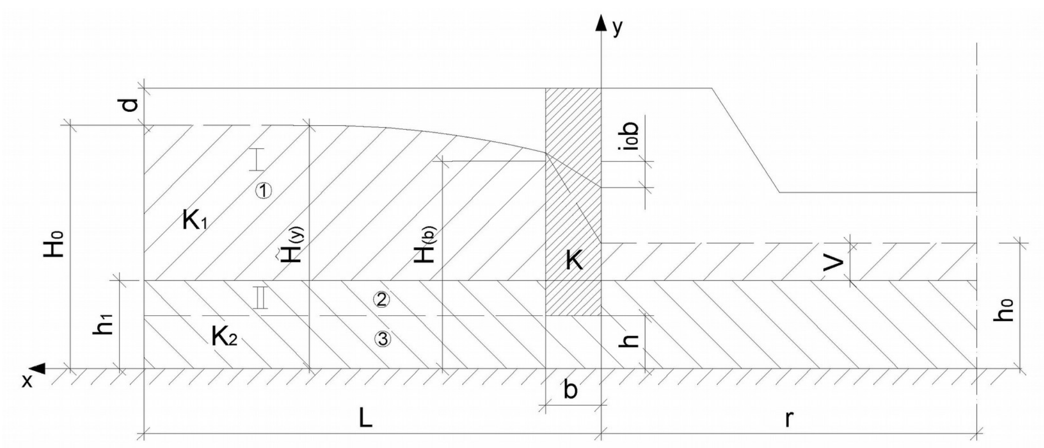
2. Research Objective

The objective is to estimate dependencies underlying design of linear-type impervious structures, considering the initial gradient of filtration. Another objective is to find the principal parameters: flow velocity, head distribution before the diaphragm and in the material thereof, width and characteristics of the aggregate, water inflow to the enclosed outline. If necessary, the diaphragm can be designed with zero water inflow. In an earlier study of the method, the author proposed a way of finding key parameters of an imperfect-design impervious structure with plane-radial one-dimensional filtration [3].

An imperfect design diameter is now examined in the environment of plane-parallel one-dimensional filtration. For the purposes of solution, we assume that the established filtration flow passing through the diaphragm is composed of three fragments: first is gravity filtration in the top layer, the other is under pressure around the bottom layer; the third fragment is pressure filtration constrained by the diaphragm base and the confining layer.

3. Results of the Study

Theoretical research resulted in estimated dependencies used to find key parameters needed to design impervious structures: flow velocity, water inflow, head distribution before the diaphragm and in the material thereof, width and characteristics of the aggregate. The study was assisted with a computer software pack; it calculated and analyzed the results for a wide range of soil conditions, with various engineering solutions of impervious structures, embedded in the low-impermeability layer based on the amount of water inflow to the enclosed outline.



Design diagram for the solution is represented in **Fig. 1**

The following conventions were used in the problem solution:

H_0 – static head (read from the reference plane of the confining layer); $H_{(b)}$ – head in section before the diaphragm; $H_{(y)}$ – head distribution in the diaphragm material; $\widetilde{H}_{(y)}$ – same but in the ground mass before the diaphragm; h_0 – head in the ground mass enclosed by the diaphragm around the pit as water level is ultimately lowered; h_1 – thickness of second layer (II); h_i – height of i-th (1, 2, 3) fragment; V-height from the second layer's roof to lowered water level in the pit; d – distance from ground surface to the static level; Z – diaphragm perimeter around the pit; L – distance from diaphragm's inner edge to the point where $\widetilde{H}_{(y)} = H_0$; b – diaphragm width; K, K_1, K_2 – filtration ratios of diaphragm's aggregate material (K) and soil (top K_1 and bottom K_2 layer); i_0 – initial filtration gradient of the diaphragm's aggregate material; $V_{x(i)}$,V_x – filtration rates in i-th fragment in the ground mass and in diaphragm material, respectively; q_1, q_2, q_3 – filtration rate per length unit of the diaphragm outline, filtered through fragments 1, 2 and 3, respectively; Q – total water filtrate into the diaphragm-enclosed ground mass; r – distance from diaphragm to the pit center.

Total water filtrate into the diaphragm-enclosed ground mass will be:

$$Q = (q_1 + q_2 + q_3)^* Z. \tag{1}$$

Amount of filtrate through the i-th fragment is found as:

$$q_i = h_i * V_{x(0)} . \tag{2}$$

Filtration rate through the i-th fragment is known from the following equations:

general velocity equation, for flat one-dimensional filtration:

$$\text{for } \left(\frac{dH}{dx} \geq i_0\right), V_x = -K\left(\frac{dH}{dx} - i_0\right), \tag{3}$$

$$\text{but for } \left(\frac{dH}{dx} \leq i_0\right), \quad V_x = 0,$$

and flow continuity equation:

$$\frac{d}{dx}(H \times V_x) = 0 \quad . \tag{4}$$

In the light of (3), equation (4) is going to appear as:

$$\frac{d}{dx}\left[H \times \left(\frac{dH}{dx} - i_0\right)\right] = 0 . \tag{5}$$

By integrating equation (5) by x, we can find head distribution in diaphragm material:

$$H \times \left(\frac{dH}{dx} - i_0\right) = C_1 , \tag{6}$$

where: C_1 - integration constant.

A singular water inflow filtered through the diaphragm body in the first fragment, according to (2), (3) and (6) shall be found to be:

$$q = H_{(b)} \times \left|V_{x(b)}\right| = H_{(b)} \times \frac{K \times C_1}{H_{(b)}} = KC_1 . \tag{6a}$$

Integration constant C_1 must consider (6); having divided our variables we get:

$$\frac{dH}{i_0} - \frac{C_1 \times dH}{i_0(i_0 H + C_1)} = dx , \tag{7}$$

In the first fragment, head H is read from the second layer's roof $H_{(0)} = h_0 - h_1$.

For this equation, the integral will be within the given range:

$$\int_{h_0-h_1}^{H} \frac{dY}{i_0} - \int_{h_0-h_1}^{H} \frac{C_1 \times dY}{i_0(i_0 Y + C_1)} = \int_0^x dx , \tag{8}$$

Thus the equation for C_1 will appear as:

$$\frac{H - h_0 + h_1}{i_0} - \frac{C_1}{i_0^2} \ln \frac{i_0 H + C_1}{i_0(h_0 - h_1) + C_1} = x . \tag{9}$$

Assuming in equation (9) that x = b, we get the ratio of head $H_{(b)}$ in the section before the diaphragm, and C_1:

$$\frac{H_{(b)} - h_0 + h_1}{i_0} - \frac{C_1}{i_0^2}\ln\frac{i_0 H_{(b)} + C_1}{i_0(h_0 - h_1) + C_1} = b\,. \qquad (10)$$

To find $H_{(b)}$ we need to know distribution of head in the ground mass before the diaphragm; seeing that $i_0 = 0$, equation (5) appears to be:

$$\frac{d^2\widetilde{H}_{(i)}{}^2}{dx^2} = 0\,. \qquad (11)$$

Distribution of head in the ground mass before the diaphragm is determined by integrating equation (11) with the premises that $\widetilde{H}_{(i)} = H_0 - h_1$:

$$\widetilde{H}_{(i)}{}^2 = C_1'(X - L) + (H_0 - h_1)^2\,. \qquad (12)$$

To express C_1' through C_1, we use the balance of flows q = q' in section x = b:

$$q = K \times C_1 = \widetilde{H}_{(b)} \times K_1 \frac{d\widetilde{H}_{(i)}}{dx} = K_1 \times \frac{C_1'}{2}\,, \qquad (13)$$

whence:

$$C_1' = 2\frac{K}{K_1} \times C_1\,. \qquad (14)$$

Now with substitute C_1' from (14) in (12), and assume that x = b, to find the head at the entry point of the diaphragm body:

$$H_{(b)} = \sqrt{2\frac{K}{K_1} \times C_1(b - L) + (H_0 - h_1)^2}\,. \qquad (15)$$

Reading the head from the confining layer, the entry point coordinate is:

$$H_{(b)} = \sqrt{2\frac{K}{K_1} \times C_1(b - L) + (H_o + h_1)^2} + h_1\,. \qquad (16)$$

For x = b, H = $H_{(b)}$, if we substitute $\widetilde{H}_{(b)}$ from equation (15) into (10), we end up with the final equation for b:

$$\frac{\sqrt{(H_0 - h_1)^2 - \frac{2K}{K_1} \times C_1(L - b)} - h_0 + h_1}{i_0} - \frac{C_1}{i_o^2}\ln\frac{i_0\sqrt{(H_0 - h_1)^2 - \frac{2K}{K_1} \times C_1(L - b)} + C_1}{i_0(h_0 - h_1) + C_1} = b \qquad (17)$$

Now we find a singular inflow and distribution of heads in the second fragment (assuming the flow is independent by the fragments). Thus, velocity is known from:

$V_x = -K\left(\frac{dH}{dx} - i_o\right)$, where head H is found separately for each fragment.

Head distribution in the diaphragm material and in the groundmass of the second fragment is found as:

$$H_{(y)} = (C_1 + i_0)x + h_0 = \left[\left[\frac{H_0 - h_0 - i_0 b}{b + K/K_2 \times (L - b)}\right]\right] + h_0\,, \qquad (18)$$

where: $$C_1 = \frac{H_0 - h_0 i_0 b}{b + K/K_2 \times (L - b)}\,. \qquad (19)$$

The singular water inflow *in the second fragment* is known from the equation:

$$q_2 = h_2 V_{x(0)} = (h_1 - h) \times K\left(\frac{dH}{dx} - i_0\right) = \frac{K(h_1 - h)(H_0 - h_0 - i_0 b)}{b + K/K_2 \times (L - b)}. \tag{20}$$

And finally, the singular water inflow *in the third fragment* should be found in the same way; for this, we use equation (5), which, assuming $i_0 = 0$ and h = const, appears to be:

$$\frac{d^2H}{dx^2} = 0 \tag{21}$$

We integrate (21), to get:

$$H = C_1 X + C_2 . \tag{22}$$

From our inputs $\begin{cases} x = 0; & x = L; \\ H_{(0)} = h_0; & H_{(L)} = H_{(0)} \end{cases}$

we find constants:

$$C_2 = h_0 \text{ and } C_1 = \frac{H_0 - h_0}{L}. \tag{23}$$

Finding head distribution *in the third fragment*:

$$H = \frac{H_0 - h_0}{L} X + h_0 , \tag{24}$$

Finding the singular water inflow *in the third fragment*:

$$q_3 = h_3 V_x = hK_2 \frac{dH}{dx} = \frac{hK_2(H_0 - h_0)}{L} . \tag{25}$$

Now let us take the practical approach and examine a case most frequently used in the construction sector.

Perfect design: A diaphragm embedded in the confining layer, considering initial gradient of the aggregate material, the head falling in the ground mass in the section before the diaphragm.

We find b from the transcendent equation (17), assuming that $h_1=0$:

$$\frac{Y - h_0}{i_0} - \frac{C_1}{i_0^2} \ln \frac{i_0 Y + C_1}{i_0 h_0 + C_1} = b , \tag{26}$$

where: $Y = \sqrt{H_0^2 - \frac{2K}{K_1} C_1 (L - b)}$.

Our singular water inflow will be:

$$q = K * C_1 \tag{27}$$

The head in the groundmass before the diaphragm is found from equation (16), assuming that $h_1=0$:

$$H_b = \sqrt{2\frac{K}{K_1} C_1 (b - L) + H_0^2} . \tag{28}$$

Considering the above, we propose a method to find the key parameters of diaphragm design and distribution of heads before the diaphragm. This method can prevent future adverse consequences and structural deformation in buildings or structures adjacent to the construction site. Some European nations, e.g. Germany, have regulated that the level on the diaphragm's outer side may be lower by up to 10 cm, or within 20 cm in some particular cases, whereas inflow of water into the pit over the diaphragm is restricted. Respective Russian regulations overlook such parameters, while commonly practiced methods of diaphragm parameter calculation tend to recommend oversized values. Error is caused by the fact that aggregate material of the diaphragm is described only by the filtration ration, while error actually depends on the level of initial filtration gradient and the diaphragm width, and tends to grow dramatically as they increase.

We have received certain dependencies (16, 17, 18, 20, 24, 25) based on the initial filtration gradient of the aggregate material in order to calculate an *imperfect-design diaphragm* that penetrates the heterogeneous water-saturated layer (strong filtration (I)), embedded (in the second layer h_1, weak filtration (II)). Efficiency *of this diaphragm type*, as supported by computer-assisted digital experiments, is ensured by varying diaphragm thickness b, and embedding depth in the second low-filtration layer h_1 (II). The second layer's filtration ratio must be lower than that of the strongly filtered layer (I) by the magnitude of five (10^{-5} cm/sec).

A series of partial solutions (26, 27, 28) has been produced for a *perfect-design diaphragm* embedded in the confining layer, as the most efficient option. As a particular case of general problem solution, should we neglect the initial filtration gradient (i_0 =0), the result of calculation to find the water inflow will match the results of the formulas recommended by the regulators [1, 2].

We need to emphasize that one may not neglect the initial gradient (i_0 = 0), as also stated by the above researchers. If water inflow calculation overlooks the initial filtration gradient of the aggregate, the error of its estimate for the pit will increase. In other words, as diaphragm thickness grows and the initial filtration gradient of the aggregate increases along with the flow's elevation in the ground mass relative to the confining layer, and as the difference of the heads (static and reduced) falls, all this generates an error in estimation of the amount of water inflow to the pit enclosed by the diaphragm. Quantitative evaluation of such errors and its determining factors is covered in depth in [4] on a calculation example of a perfect-design diaphragm embedded in the confining layer (with plane-radial filtration). As an illustration, we are going to quote one of the studies.

Conclusions:

1. Dependencies (16, 17, 18, 20, 24, 25) have been identified that consider the initial filtration gradient of aggregate material to make calculations for impervious structures *of an imperfect-design diaphragm* that penetrates the heterogeneous water-saturated layer (I - strong filtration), embedded in the second layer (II - weak filtration) h_1.

2. Efficient use *of imperfect design diaphragms*, as demonstrated with computer-assisted numeric tests, is ensured by varying diaphragm thickness b, and embedding depth in the second low-filtration layer h_1 (II), the second layer's filtration ratio must be lower than that of the strongly filtered layer (I) by the magnitude of five (10^{-5} cm/sec).

3. A series of partial solutions (26, 27, 28) has been produced for a *perfect-design diaphragm* embedded in the confining layer. The results matched those of the officially recommended formulas, if the initial gradient is neglected (i_0 =0) [1, 2].

4. Engineering calculations may not neglect the values of the initial filtration gradient of the aggregate material, as this causes overestimation of the diaphragm's design parameters, inaccurate head before the diameter, adoption of over-optimistic characteristics of the aggregate measurement, and too high estimated water inflow to the enclosed outline (pit).

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