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Methodology of Planning an Experiment for the Analysis of the Filtration Flow Gradient Based on Low-Pressure Hydraulic Structures

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ABSTRACT: This article examines the application of dimensional theory and experiment planning to study the filtration flow gradient. A criterion dependence was obtained, on the basis of which the experimental plan was developed. An analysis of the significance of factors was conducted, a regression model was proposed, and methods for optimizing parameters were considered.

I. INTRODUCTION

At present, low-pressure hydraulic structures are widely used in water management and land reclamation. In hydraulic engineering construction practice, these structures have such advantages as high material resources, labor intensity and high costs, as well as the absence of a long construction process, the possibility of construction in different climatic, geological, and hydrogeological conditions and on different soil bases, low environmental impact, and the unchanging hydrological and ice regimes of the reservoir. Therefore, low-pressure hydraulic structures built from concrete and soil materials play an important role in managing the use of surface waters not only for irrigating agricultural crops but also in other socio-economic spheres of the country [1-2].

There are cases of decreased reliability of low-pressure hydraulic structures due to prolonged continuous operation, insufficient volume and quality of repair work. At the same time, neglecting various factors influencing their operation leads to a decrease in the level of reliability of the structures' operation, causing serious damage to structures and elements [3].

When ensuring the safety of low-pressure hydraulic structures, it is permissible to investigate the filtration regime. Determining the output gradient at the base of low-pressure hydraulic structures in complex engineering-geological conditions is currently relevant, and the presented work allows us to determine this problem using the regression method (Figure 1).

II. METHODS

In hydraulic engineering practice, numerous works have been published on the issues of filtration in the body and foundation of the structure, as well as on the issues of reducing the energy of the filtration flow, anti-filtration measures, and safety related to filtration. However, there are no works aimed at determining the yield gradient in the foundation of low-pressure hydraulic structures used in complex engineering-geological conditions.

Hydrodynamic processes in porous media play a key role in engineering calculations. For effective control of filtration parameters, it is necessary to establish the dependence of the flow gradient on the physical characteristics of the medium and the experimental conditions. In this work, the dimensional analysis method was used to obtain a criterion dependence, and an experiment was planned to construct a mathematical model [4-10].

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The original functional dependence has the form:

$$J=\varphi(L, n_1, n_2, n_3, \omega, v, g, \gamma_1, \gamma_2, \gamma_3, \gamma_4, H) \quad (1)$$

where: J – gradient of pressure; n_1 – loess porosity coefficient; n_2 – loam porosity coefficient; n_3 – sand porosity coefficient; ω – cross-sectional area of flow; v – kinetic viscosity of water; g – acceleration due to gravity; γ_1 – specific gravity of loess; γ_2 – specific gravity of loam; γ_3 – specific gravity of sand; γ_4 – specific gravity of water; H – water pressure; L – length of the structure.

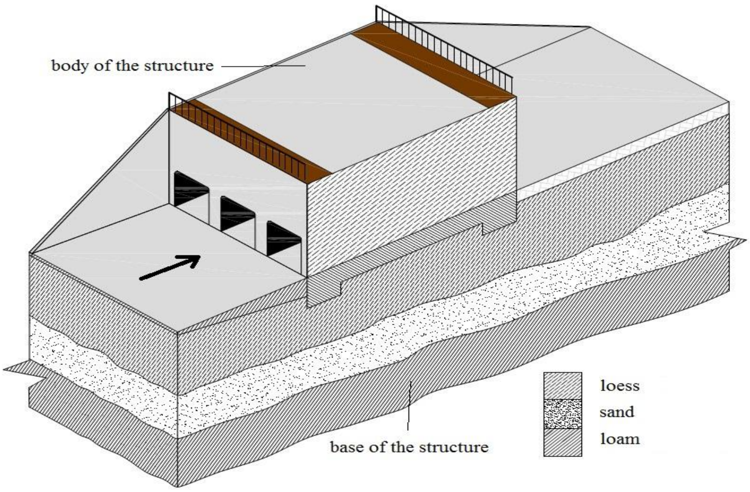

Fig. 1 Low-pressure hydraulic structures erected in complex engineering-geological conditions

III. RESULTS

There are only 12 variables, their dimensionality depends on three main variables. Therefore, according to the π-theorem, 9 dimensionless complexes can be formed.

Using the π-theorem, a dimensionless relationship was obtained:

$$J = \varphi\left(n_1, n_2, n_3, \frac{\omega}{L^2}, \frac{Hg}{v^2}, \frac{\gamma_1}{\gamma_4}, \frac{\gamma_2}{\gamma_4}, \frac{\gamma_3}{\gamma_4}\right) \quad (2)$$

This form expresses the dependence of the flow gradient on the dimensionless parameters characterizing the pressure filtration process under the structure.

Experiment planning is aimed at determining the dependence of the J gradient on the factors influencing it. The main goal is to reduce the number of experiments, obtain accurate data, and identify the most significant parameters.

Selection of factors and levels of variation. Eight main factors influencing J have been identified, each varying at three levels: minimum (-1), average (0) and maximum (+1).

Possible experiments for conducting experiments:

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- fractional factor experiment 2^{k-p}, where: p – number of contracted factors;
- Pfaffen Plan - a combined method of reducing experiments;
- Box-Benkin plan - used for nonlinear dependencies.

Since the number of factors is sufficiently large (k=8), the full factorial experiment 2^8=256 experiments is too cumbersome. Therefore, the fractional factor experiment 2^{8-3}=32 experiments is used.

Experiment planning matrix. Example of several experiments (Table 1).

Table 1

Experiment	n_1	n_2	n_3	$\frac{\omega}{L^2}$	$\frac{Hg}{\nu^2}$	$\frac{\gamma_1}{\gamma_4}$	$\frac{\gamma_2}{\gamma_4}$	$\frac{\gamma_3}{\gamma_4}$	J
1	-1	-1	-1	-1	-1	-1	-1	-1	?
2	+1	-1	-1	-1	-1	+1	+1	+1	?
3	-1	+1	-1	-1	+1	-1	+1	+1	?

The value of J is measured experimentally.
After conducting the experiments, we construct a regression model of the form:

$$J = a_0 + a_1 n_1 + a_2 n_2 + a_3 n_3 + a_4 \frac{\omega}{L^2} + a_5 \frac{Hg}{\nu^2} + a_6 \frac{\gamma_1}{\gamma_4} + a_7 \frac{\gamma_2}{\gamma_4} + a_8 \frac{\gamma_3}{\gamma_4} \quad (3)$$

The a_i coefficients are determined by statistical methods (the least squares method), significance testing (Student's criterion, Fisher's criterion), and model adequacy assessment are conducted.
If the relationship is nonlinear, we use the quadratic model:

$$J = a_0 + \sum a_i X_i + \sum a_{ij} X_i X_j \quad (4)$$

where: X_i – coded variables.
Optimizing parameters. By analyzing model coefficients, the most significant factors are determined. Optimization methods (gradient discharge, Lagrange method) are used to determine the best conditions for pressure filtration.

IV. CONCLUSION

The application of dimensional theory and experiment planning methods made it possible to obtain a criterion dependence and construct an adequate mathematical model for estimating the flow gradient. The developed approach can be applied in engineering practice when designing filtration structures.

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