

# Spatial seepage mathematical model of earth-fill dam in complicated topographic and engineering-geological conditions

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**Abstract.** The seepage regime system of dam-foundation bed mainly determines the safe operation of such structure as an earth-fill dam. This work describes the spatial seepage mathematical model of the earth-fill dam system – foundation bed as applicable to high rock-filled dam of Rogun HPP. Resumption of construction of this hydro-project was necessitated by refinement of parameters of the system seepage flow: the position of the seepage surface, the values of the seepage discharge, the values of the seepage gradients and seepage velocities. The studied project is characterized by rather complicated topographical and engineering-geological conditions.

## 1. Introduction.

One of the most important problems in justification of high earth-fill dams safe operation is forecasting of the seepage regime of the system «structure-foundation bed» [1]. Possible resumption of construction of Rogun HPP, as well as introduction of technological changes into the design seepage control devices of the structure raised the problem of the need in simulation of the seepage regime with regard to new conditions.

The objective of investigation is creation of a spatial mathematical model of the seepage regime of the system «earth-fill dam – foundation bed», differing in the complicated topographic and engineering-geological conditions. This model permitted to obtain a detailed picture of the seepage regime: the position of the phreatic surface in the earth-fill dam body and dam-site sides, distribution in the design area of seepage heads, head gradients and seepage velocities. There are considered the diagrams with different design variants of the seepage control element: the inclined core with a fracture in the upper and lower parts (old variant) and the inclined core without fractures (new variant). The computations were performed in a 3D setting with regard to spatial work of the structure and the effect of rock foundation bed.

## 2. Methodology.

Recently for solving the seepage problems in the classic setting use is made of a considerable number of multipurpose software systems, based on the finite elements method, such as: Plaxis, Midas, ModFlow, Fidesis, etc.

As it is known, solution of the problem of unstable seepage in the spatial setting is based on solution of the main differential equation of the theory of seepage (Poisson equation)[2]:

$$\frac{\partial}{\partial x} \left[ K_x \left( \frac{\partial H}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ K_y \left( \frac{\partial H}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[ K_z \left( \frac{\partial H}{\partial z} \right) \right] - \mu \frac{\partial H}{\partial t} = 0 \quad (1)$$

Where  $H = f(x, y, z, t)$  – the sought head function in the design area, changing in time  $t$ ;  $K_x, K_y, K_z$  – seepage intensity coefficients (towards coordinate axes);  $\mu$  – coefficient of soil water yield.

In this work use is made of analogy between the seepage problem, described by equation (1) and the temperature problem based on solution of differential equation of thermal conductivity [3]:

$$\frac{\partial}{\partial x} \left[ \lambda_x \left( \frac{\partial T}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ \lambda_y \left( \frac{\partial T}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[ \lambda_z \left( \frac{\partial T}{\partial z} \right) \right] - \frac{\partial t}{\partial \tau} = 0 \quad (2)$$

Where  $T = f(x, y, z, \tau)$  – the sought temperature function;  $\lambda_x, \lambda_y, \lambda_z$  – the coefficients of temperature conductivity of the material (towards coordinate axes no);  $\tau$  – time.

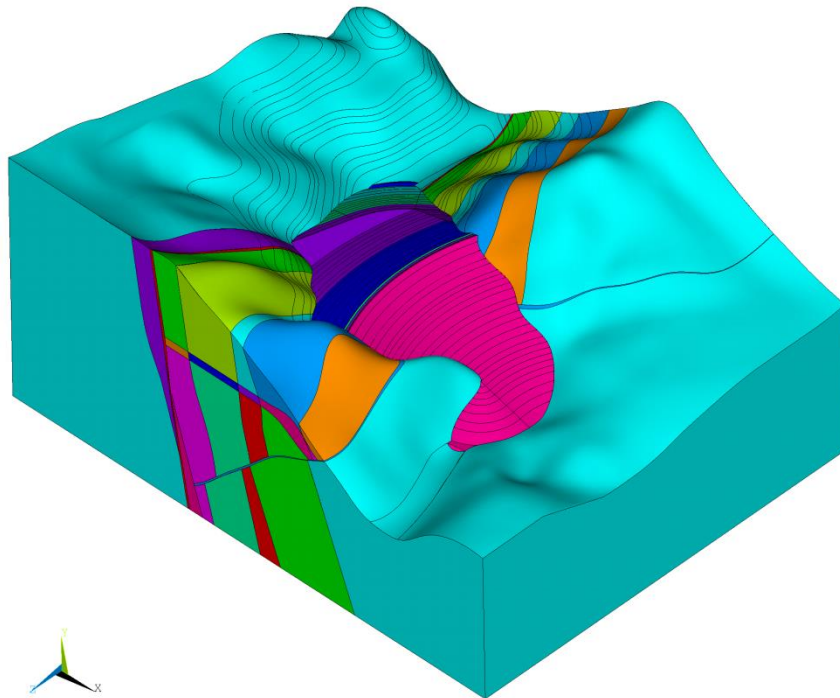
Use of this analogy permits to obtain the exact solution of the seepage problem at setting the corresponding boundary conditions. Thus, for solution of the seepage problem it is possible to use the multipurpose industrial software systems [4-6].

To find a solution in this work used was made of the system of mathematical simulation ANSYS APDL [7-10], permitting to solve seepage problems [11, 12] using the method of temperature analogy. This software system, in its base, includes the methods of finite element simulation, permits to solve interdisciplinary problems and take into account the complicated profile of hydraulic structures and their foundation beds [13-15]. Before in using this system there were performed the investigations with verification of the obtained results [16-21].

### 3. Investigations results.

The 3D geoseepage model of Rogun HPP was elaborated on the basis of the existing information on the geological structure of foundation bed and project drawings of the old and new projects. For obtaining a comparative analysis of the change of the seepage regime in the earth-fill dam body there were elaborated two models, differing in geometry of the seepage control element. For the first variant there was considered the inclined core without fractures (new project), for the second one – the inclined core with fractures in the upper and lower parts of the core (old project). The general view of the simulated mathematical model is given in fig. 1, and includes: the rock foundation bed, the upstream and downstream prisms of the rock earth-fill dam, seepage control element in the form of the core, two layers of transition zones, upstream and downstream cofferdams.

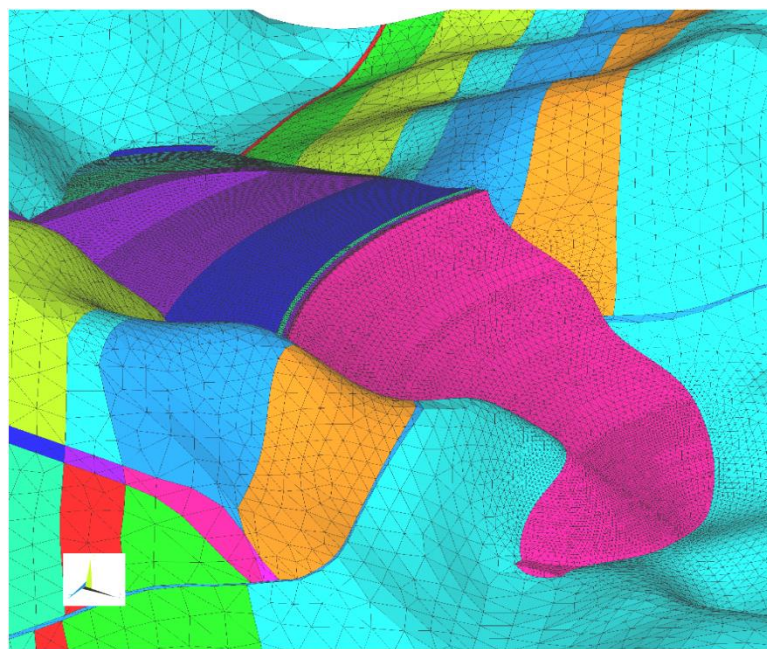
In multivariant calculations the rock mass seepage properties were accepted on the basis of old data without regard to the possible anisotropic seepage in faults and cracks which may introduce essential change into the foundation bed seepage regime. The effect of these features will be considered in further work. This study paid the most attention to the seepage through the earth-fill dam body.



**Figure 1.** Solid body approximation of Rogun HPP geoseepage model.

The size of built in the model of the design area in plan is 1,8 km by 2,3 km, the total area of the design zone is 4,14 km<sup>2</sup>. From below the design zone is limited by absolute elevation + 500 m. The earth-fill dam length in crest is 610 m, the dam maximum height – 340 m with absolute elevation 1300 m. The central core is filled with loam, transition zones are of sand-gravel pebble, the material of retaining prisms – gravel-pebble with rock surcharge embankment.

The elaborated geoseepage mathematical model was approximated by 2 073 055 finite elements of first order of precision, with linear description of the shape function (figure 2). Maximum thickening of the finite element of flow net diagram was performed in the dam core to determine the exact position of phreatic surface. The average size of the finite element at the foundation bed is 20 m, in the core 1 m, in the retaining prisms – 7 m. Calibration of the mathematical model was performed according to the data of Nurek HPP, then multivariant investigations were fulfilled.

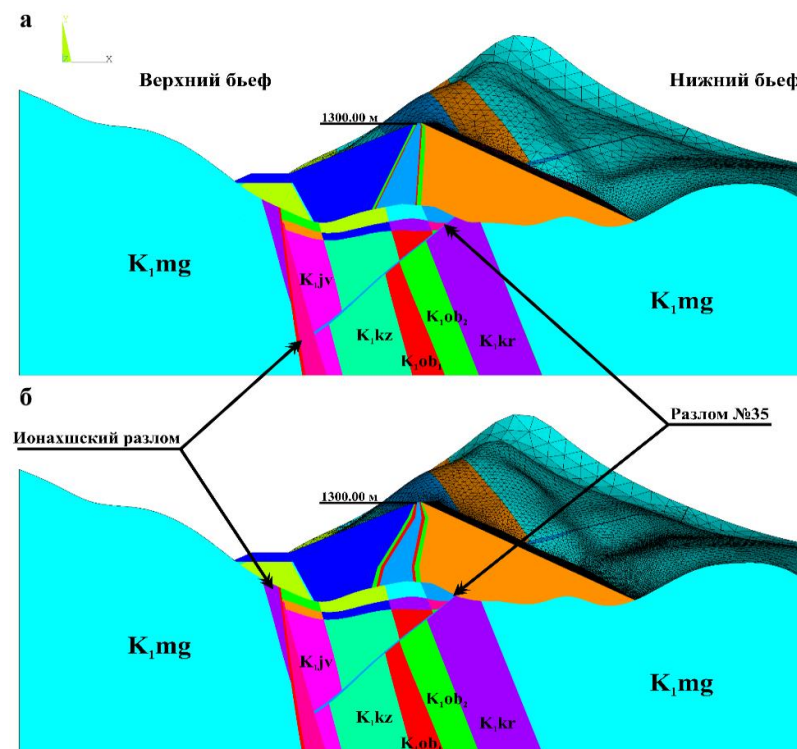


**Figure 2.** Finite-element approximation of Ragun HPP earth-fill dam

Sections by the elaborated simulation models with the inclined core without fractures (new project) and with the inclined core with fractures in the upper and lower parts (old variant) are given in figure 3.

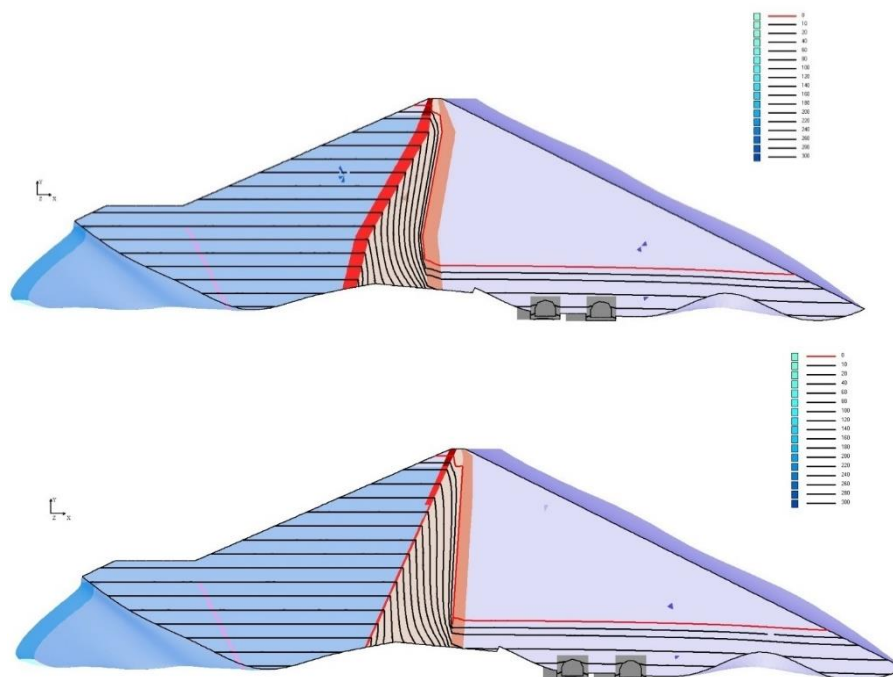
Design studies were performed for the case of stable steady-state seepage at different elevations of the upstream level. In total eight calculations were done at the following values of the upstream water level elevation: 1123 m; 1150 m; 1175 m; 1185 m; 1210 m; 1236 m; 1250 m; 1290 m. The downstream level therewith was considered constant with elevation 983 m.

On the upstream side on the model nodes the boundary condition was assigned of I order ( $H = \text{NWL}$ ). On the downstream side, there was also assigned the boundary condition of I order, with the head invariable value ( $H = \text{DSL} = 983.00 \text{ m}$ ). Over the boundaries of the design area there was assigned the particular case of the boundary condition of II order – impermeability ( $Q = 0$ ). For construction of a drawdown curve and correct consideration of movement of the seepage moisture between the seepage point and DS side (these are the nodes of the dam core, of downstream slope, or bank abutment) there was superimposed the condition:  $H_i = H_z^i$  where где  $H_z^i$  – coordinate of i-th node relative to the level of DSL. In geoseepage model it was accounted for the only impact created by reservoir without additional precipitation and seepage feed.



**Figure 3.** Sections in Rogun HPP geoseepage models on the side of the right bank: a – new project; b – old project

The results of investigations are given for the variant with maximum value  $NWL=1290$  m. (figure 4).



**Figure 4.** Isolines of piezometric heads on the geoseepage model at NWL 1290 m, a - variant No.1; b – variant No.2



The performed calculations permitted to perform the following feature of the seepage regime, which could not be obtained on its 2D models. The taking into account of the foundation bed natural complicated profile and the spatial work of the dam seepage control elements permitted to obtain the following conclusion: on the downstream side over the retaining tunnels the area appears with a higher water level as compared to the plane solution (figure 4). This is explained by accumulation of the water infiltrating through the core and by the complicated terrain natural backwater.. This effect is observed in two elaborated mathematical models at NWL rise up to elevations over 1236 m, then with further reservoir impounding up to elevation 1190 m, the suction is possible of seepage flow at the earth-fill dam downstream slope.

Comparison of first and second variants of the core geometry shows that in the second project there is observed the even distribution of piezometric heads in the dam core which shows the optimality of the accepted design. The analysis of velocity gradients shows improvement of the seepage picture in the dam core, there is observed a lesser zone of higher velocities, a lower concentration in the change point of the dam core inclination.

#### 4. Conclusions

- 4.1. Change of Rogun HPP dam core geometry design resulted in more even distribution of pressures in the core and in disappearance of the velocities gradients concentration thus improving the structure operation conditions.
- 4.2. In connection with the fact that the dam calculation was performed without regard to the drainage devices, the seepage flow suction to the downstream slope is possible. It is desirable to upgrade the elaborated model due to accounting for seepage control elements in the dam foundation bed..
- 4.3. There is need in additional investigations in 3D setting with regard to the complicated anisotropic work of the foundation bed rock mass, wherein a greater attention will be paid to the seepage properties of rocks and faults.

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