Safety assessment of a dam made of ground materials

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Abstract. The Rogun HPP dam stability from ground materials is studied on the basis of numerical calculations of its spatial stress-strain state. The deformation and strength properties of materials composing the dam body defined in the triaxial compression devices were used in the calculations. Limit values of strength materials properties and controlled values of diagnostic indicators of a dam at which safety of its work is provided are established.

Introduction
In connection with the beginning of construction in the Republic of Tajikistan of a high earth-and-rock-fill dam, it is necessary to provide a scientific justification for its safe operation. The area of the Rogun HPP dam site, erected in difficult engineering-geological conditions, is composed of rock. The stone-earth dam is built on the Vakhsh river in a narrow gorge of V-shape, with steep slopes, which has a complex zigzag shape in the plan, which predetermines the study of its stress-strain state (SSS) and the stability assessment in the spatial formulation.

At present, the scientific substantiation of dam structures made of ground materials is usually carried out on the basis of numerical studies of their stress-strain state [1-3] with the use of modern provisions of soil mechanics [4]. At the same time, when describing the ground behavior under load by the equations of the plastic flow theory, the slopes stability of the soil dam is estimated within the framework of the general design scheme based on the development of plastic deformations analysis [5-8].

Materials and methods
The earth-and-rock-fill Rogun HPP dam body of with a height of 340m (refer with Figure 1) includes the central core made of loam, two transition filter layers made of sand, gravel and pebble, soil and retaining prisms that are backfilled with gravel with the additional rock mass load (refer with Table 1). The dam structure includes the dam of the first stage with a height of 130m, also backfilled with gravel with the additional rock mass load. As an antifiltration element in the dam of the first stage, it is proposed to use an asphalt concrete diaphragm. In the upper retaining part of the dam prism in the first phase of construction is also included a jumper with a height of 53 m from gravel-pebble soil. Antifiltration jumper elements are argil lo-arenaceous apron, injection curtain and polymer screen.
Mathematical model [4] formed within the framework of the plastic flow theory with hardening was used to describe the nonlinear deformability of ground materials.

**Table 1.** The main materials properties of the Rogun HPP

| Structural elements | Material  | $\rho$, [g/cm$^3$] | C, [MPa] | $T_{\phi}$ | Ff, [m/day] |
|---------------------|-----------|-------------------|----------|-----------|-------------|
| Retaining prism     | Gravel    | 2.25              | 0.06     | 0.98      | 86          |
| Core                | Loam      | 2.1               | 0.081    | 0.7       | 0.00026 - 0.0053 |
| Surcharging         | Rock mass | 2.08              | 0.1      | 0.98      | 430         |
| Transition zones    | Gravel    | 2.07              | 0.06     | 0.88      | 26          |
| Diaphragm           | Asphalt   | 2.49              | 0.375    | 0.81      | -           |

**Figure 1.** Design model. a – volumetric solid geometric model of the "rock base – dam" system, b – dam cross-section. (dam body materials are highlighted in color).

The model parameters are determined by standard three-axis tests and reflect the features of the ground dilatancy behavior, significantly affecting the plastic deformation processes of water-saturated grounds.

The method based on the numerical solution of the differential equations system of the quasi-two-phase soil grounds consolidation theory [9] was used to study the stress-strain state (SSS) of the Rogun dam. The equations resolving system composed for the whole set of finite elements approximating the computational domain, taking into account the state equations of all ground phases, initial and boundary conditions, fully characterize the quasi-two-phase grounds work under static conditions.
influences. At the same time, the factor of the compressible fluid filtration motion in the ground pores and the ground skeleton deformation properties are taken into account.

The dam construction, according to its construction scheme, was modeled by 21 building stages, including the dam construction of the first stage that was modeled by 10 building stages. The reservoir filling was modeled in accordance with the schedule of its filling, parallel to the dam construction. Hydrostatic pressure on the nucleus upper face was transmitted to the pore water and distributed over the core material skeleton as a volume force.

To estimate the stress state at each point of the soil body (by the approximation degree to the limit state), the static calculation results were used to determine the local factor of the shift margin by the equation:

$$k_i = \sigma_i^* / \sigma_i$$

where: \( \sigma_i^* = c + tg \varphi \sigma_{ef} \) is the limit value \( \sigma_i \); \( \sigma_{ef} \), \( \sigma_i \) are the invariants of the effective stress tensor; \( c \), \( tg \varphi \) are the strength parameters.

The key issue of the safety assessing of the structure in this case is to determine the safety factor of the overall stability of the structure, for which calculation it is necessary to bring the soil mass to destruction that can be achieved by gradually reducing the strength parameters values of the soils.

The total safety factor is determined by the dependence:

$$K_Z = \frac{c^*}{c} = \frac{tg \varphi^*}{tg \varphi}$$

where: \( c^* \), \( tg \varphi^* \) are the strength soil parameters values, when the calculations predict the soil massif destruction.

**Research result**

As the results of the performed static calculations showed, the main influence on the spatial stress-strain state formation of the earth-and-rock-fill dam is exerted by the dam materials heterogeneity, the dam construction phasing and the narrow winding canyon at the dam construction site. The above factors lead to the formation of a significantly heterogeneous spatial stress-strain behavior of the dam.

At the time of reservoir completion and filling, all components of the normal effective stresses are compressive. At sufficiently large values of the filtration coefficient of the core material, the values of the additional pore pressure are insignificant and by the time the reservoir is filled to the design level, the consolidation process is completed and a stabilized filtration regime is established.

With the accepted ground characteristics, the dam static stability and the strength of its core are provided. Local safety factors in all dam points \( kz > 1.0 \).

To determine the safety factor of the overall structure stability after the last construction stage (the dam construction for full profile and the reservoir filling), an additional calculations series was performed with a gradual decrease in the strength parameters of all materials of the Rogun HPP earth-and-rock fill dam.

As additional calculations have shown, the dam destruction occurs when the strength parameters are reduced more than 2.7 times. Under these conditions, in the upper part of the bottom retaining prism closer to the left side, the appearance of the limit stress state zone is traced, and below it a possible collapse zone is being formed. Thus, the total stability safety factor of the earth-to-rock-fill Rogun HPP dam under static effects for the initial strength and deformation characteristics of the dam body materials is \( Kz = 2.7 \).

According to the safety criteria determination methodology of hydraulic structures, the operational condition assessment of the structure and its safety should be carried out by comparing the measured diagnostic indicators with their criteria values established at the design stage of the structure.
The main controlled diagnostic indicators of the state of the earth-to-rock-fill Rogun HPP dam primarily include the values of vertical and horizontal displacements of its body. The calculations results of the strain-stress state analysis of the earth-to-rock-fill Rogun HPP dam under static effects can be considered as the first warning level of diagnostic indicators (K1), the excess of which indicates that in the course of subsequent operation there is a strain-stress state change of the dam in comparison with the results of the mathematical forecast.

As the second level of limit K2-values of diagnostic indicators at which operation of hydraulic engineering structures is inadmissible, calculations results of the strain-stress state of the earth-to-rock-fill Rogun HPP dam are accepted, when the safety coefficient value of the general stability is equal to the minimum standard value of 1.25 for the main combination of loadings. The criteria values of the controlled indicators for this level can be obtained from the static SSS calculation of the earth-to-rock-fill dam using the strength parameters of the dam body material reduced by $2.7/1.25=2.16$ times (refer with Figure 2).

![Figure 2](image_url)

**Figure 2.** Displacements in the dam cross-section with decrease in strength characteristics by 2.16 times. a - the horizontal displacement $U_x(m)$, b - is the vertical displacement $U_y(m)$.

**Summary**

As the calculations results with the accepted ground characteristics showed the dam static stability and the strength of its core are provided. Local safety factors at all points of the dam are greater than 1.0. At the same time, overall safety factor is 2.7.

As the maximum level of the monitored values of the diagnostic indicators, the SSS calculations results of the earth-to-rock-fill Rogun HPP dam are accepted, with decreased values of strength characteristics of body dam materials to the standard value of safety factor for the overall stability equal to $K_z^{min}=1.25$. 
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