Stress-strain state of rock mass and lining when constructing underground turbine hall of hydropower plant

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Abstract. Numerical modeling was performed for stress-strain state of the rock mass and lining of underground turbine hall of Rogun hydropower plant. The hall is located in a rock mass at great depths. Numerical modeling was conducted using the method of boundary integral equations based on the model of linearly elastic quasi-isotropic medium. The character and features of forming inelastic deformation zones near the contour of turbine hall cross-section are found. The regularities of distribution of rock mass and lining stress-strain state are determined as well.

1. Introduction
The stability of underground hydrotechnical structures during their construction is largely determined by the stress-strain state (SSS) acting in the surrounding rock mass, with its role significantly increasing in the deep subsurface conditions. Evaluation of the underground structures stability requires taking into account specificity of the formation of stress conditions in their peripheral zone. Methods of the SSS numerical simulation with integrated full-scale studies of deformation processes in the vicinity of underground hydraulic structures allow obtaining reliable estimates and predicting their structural elements state both during construction and operation [1, 2].

Underground structures of the rockfill embankment (dam) of Rogun hydropower plant (HPP) (Figure 1), specifically, the turbine hall and transformer room, are emplaced in the rock mass at a depth of 350-420 m. Surrounding rocks jointing and loss of stability in the vicinity of their outcrops have become a topical issue in the construction and utilization of hydropower and other underground engineering structures. Stability of underground structures can be secured by the lining (rock support), which prevents rock mass deformations and failure in the outcrop zones. Given that underground construction works disrupt the pre-existing state of equilibrium (e.g., in-situ stresses), the stress regime of lining-rock mass interactions has to be readjusted until new state of equilibrium is attained. Evaluation of the strain-stress state of both lining elements and rock mass is therefore critical for ensuring stability of the complex of underground hydrotechnical structures located at great depths.
This paper analyzes interactions between the lining and surrounding rock mass of Rogun hydroelectric power plant and structural elements of underground structures with an aim to obtain the parameters necessary for estimation of the converging sidewall and lining surfaces of the turbine hall. Since location of the transformer room near the turbine hall appreciably influences the SSS of the surrounding rock mass, the calculations were performed with account of the completely open cross section of the transformer room.

2. Modeling and test results

Results of the SSS numerical simulation analysis performed for surrounding rock mass in the vicinity of the turbine hall (Rogun HPP) suggest the developing zones of inelastic deformations near its sidewall surfaces (Figure 2). These zones were dislodged deep into rock mass even at the initial stage of opening the cross section of the turbine room: from a depth of 1–2.5 m (in hard rock mass), down to 5–6 m (in damaged zones) (Figure 2a). At the final stage of the cross section opening, the zones of inelastic deformations practically merge with the zones formed in rock mass surrounding the transformer room, specifically along its periphery (Figure 2b). It is therefore necessary to analyze the variations in the lining capability of keeping the rock masses from failure (load-bearing capacity), which should be maintained throughout the facility operating time.

In most research works [3–8], both surrounding rock mass and lining material are interpreted as elastic isotropic materials. The magnitude of stresses and deformations arising at the lining–rock mass interface depends on (i) the technology of the lining construction; (ii) physical and mechanical properties of rock mass and lining; and (iii) the initial stress state of hard rocks [4, 6, 7].

The SSS analysis for surrounding rock mass and lining elements of the turbine hall of Rogun HPP emplaced in hard country rock, which is composed of interbedding sandstones and siltstones
representing hard rock with a uniaxial compressive strength $\sigma_{\text{cont}}$ which is equivalent to 100–200 MPa (sandstones) and 60–80 MPa (siltstones) [9].

In the applied model of linearly deformable medium hosting the laminated rock mass and taken as quasi-isotropic medium [1], the lining is assumed to be continuously contacting with the surrounding rock face along the entire outer contour (Figure 3), i.e. continuity condition is fulfilled on the stress and displacement field type vectors along the contact line [1].

![Figure 3](image)

**Figure 3.** Horizontal $\sigma_x$ (a, c) and vertical $\sigma_y$ (b, d) components of the stress tensor (MPa) of the surrounding rock mass and lining in the case of the cross section of the turbine hall partially (a, b) and completely (b, d) open.

The problems were solved with the use of the boundary integral equations method for piecewise homogeneous media [1, 2, 10] in the plane formulation, inasmuch as the relationships between geometric dimensions of the turbine hall allow solving the problem of SSS of the surrounding rock mass and lining under plane strain condition. The parameters accepted for calculating SSS of the
structural elements of underground structures are [9]: Poisson’s ratio \( \nu = 0.26 \), modulus of deformation \( E = 3.5 \times 10^4 \text{ MPa} \), cohesive strength of rock mass \( C = 0.41 \text{ – 0.7 MPa} \), internal friction angle \( \varphi = 35^\circ \). Parameters of the natural stress field [11] include: \( \sigma_{x0} = -35 \text{ MPa}, \sigma_{y0} = -26 \text{ MPa} \). The lining thickness over the entire surface of the underground structure opening was assumed to be 1 m; concrete used as the lining material characterized by Poisson’s ratio \( \nu = 0.25 \) and modulus of deformation \( E = 3 \times 10^4 \text{ MPa} \). The calculated numerical values of the stress tensor components \( (\sigma_x, \sigma_y, \tau_{xy}) \) and normal tangential stresses \( \sigma_\theta \) are used to analyze the bearing capacity of lining in the normative documents [5, 6].

The mechanism of SSS formation in the surrounding rock mass in the vicinity of the turbine hall and the lining (when its cross-section is partially and completely open) is illustrated by the results presented in Figure 3. The values of the stress components \( \sigma_x, \sigma_y \) on the lining surface are shown along its inside contour.

Figure 4 shows plots for tangential normal stresses in the lining structural elements corresponding to final construction stage of the turbine hall (Figures 4a and 4b). The \( \sigma_x, \sigma_y \) stresses concentration zones tend to develop in the roof and soils of the surrounding rocks mass in the vicinity of the turbine hall (Figure 3). Due to high horizontal stresses in the roof and vertical stresses in its side walls, the turbine hall is characterized by high stresses in its arch lining (up to 100 MPa at the final stage of construction).

As is the case with the surrounding rock mass, compressive stresses \( \sigma_\theta \) acting in the arching part of lining are the highest, while on the inside surface compressive \( \sigma_\theta \) appears greater, than on the outside surface of the lining (Figure 4). Since it was assumed that the concrete lining is not reinforced, the maximum compressive stresses \( \sigma_\theta \) significantly exceed the compressive strength of concrete. The inside surfaces of the sidewall lining are from the action of \( \sigma_\theta \) stresses which pass into tension when the cross-section completely opens (Figure 4b).

**Figure 4.** Diagrams of normal tangential stresses (MPa) on the outside (a) and inside (b) lining surface after the cross section of the turbine hall opens completely.

Elastic convergence for the side wall surfaces in the surrounding rock mass in the vicinity of the turbine hall at its width of 22 m is equal to 543 mm (Figure 5) (the lining-corrected parameters are: 20 m and 448 mm), while displacement of the lateral surface contour \( (U_x, \text{ mm}) \) outlying from the...
transformers room is more appreciable, than in its proximity (292 and 251 mm, respectively, in the surrounding rock mass). For comparison, the turbine hall side walls convergence obtained for the transversal-isotropic model of the surrounding rock mass is 435 mm (234 and 201 mm) [11].

Figure 5. Elastic displacements (mm) in the horizontal $U_x$ direction after the turbine hall cross section is completely open.

with prediction of the convergence (approaching) of its side surfaces. For this purpose, we investigated convergence as the displacement value-time and displacement velocity-time functions. The non-attenuating relaxation process of a rock massif under constant external forcing is generally described by a logarithmic function [12]:

$$y(t) = a \ln(t + b) + c,$$

(1)

where $a$, $b$, $c$ are the coefficients determined from the observation results interpolation by this function using the least squares method. The attenuating relaxation process is described by the exponential function [12]:

$$y(t) = a_1(1 - e^{-a_2 t}),$$

(2)

where $a_1$, $a_2$ are the coefficients determined from the observation results interpolation by the exponential function using the least squares method.

Figure 6 shows results of the extrapolation of the observed convergence increments for gate 4 of the turbine hall of Rogun HPP. The application of function (1), which reflects the non-attenuating process, showed that until 2016, the data of convergence observations are interpolated to an accuracy of ± 3 ± 6 mm (standard deviation, SD); by the end of 2018, the interpolation error has reached 9 m. The SD error of the interpolated valued obtained by function (2) reflecting attenuating process is in excess of 16–20 mm.

Figure 6. Results of the convergence increments extrapolation by the attenuating and non-attenuating functions for gate 4.

Judging from the extrapolation results, we can thus argue about the non-attenuating convergence process in the turbine hall walls in the area of gate 4, indicating that we deal with manifestations of
rheological behavior of the surrounding rocks and lining. In the absence of the data on rheological properties of rocks, the approach formulated in [6] can be used to determine the lining bearing capacity, taking into account the maximum stress values recommended in the Russian Building Codes (SNiP) [5], while the span of safe (accident-free) operation of underground structures can be determined from the yearly convergence increment value.

3. Conclusions
Based on the numerical simulation results and using a quasi-isotropic model of rock mass, the specific SSS distributions are established for the surrounding rock mass and the turbine hall lining in the underground conditions of the Rogun hydropower plant structures. Normal tangential stresses in the vault lining (on its inside surface) can exceed the uniaxial compression strength of the surrounding rock mass. The sidewall surfaces of the turbine hall are free from the stresses acting in the intact rock masses. In the middle part of the sidewall lining surfaces, the horizontal tensile stresses are acting at the final construction stage of the turbine hall. Estimation of increments in the converging side surfaces of the turbine hall showed that in the area of gate 4, the process of convergence of its side surfaces was non-attenuating at the end of 2018, which is interpreted as rheological behavior of surrounding rocks and lining.

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