Evaluation of stress state in rock mass surrounding underground structures of waterworks

LN Gakhova
Chinakal Institute of Mining, Siberian Branch Russian, Academy of Sciences, Novosibirsk, Russia
E-mail: gahoval@mail.ru

Abstract. Using the data of the numerical modeling of stress state in rock mass surrounding deep-level structures of waterworks, the author finds regular patterns and specific features of stress distribution under stage-wise underground construction. It is shown in the paper that as cross-section of an underground structure is enlarged, inelastic strain zones arise nearby the structures, and parameters of these zones are determined.

1. Introduction
When waterworks structures are arranged under the ground, the governing factor of stability for such structures is the effective stress state, and the role of the latter considerably grows with increasing depth. As a rule, stability of underground structures is evaluated using the estimates of stress state in surrounding rock mass. The classifications based on the analysis of mechanical properties of rocks may be inefficient in this case [1, 2]. Numerical modeling of stresses in integration with the full-scale observation of deformation processes in the vicinity of underground structures provides reliable estimation and prediction of stress–strain state during both construction and operation of underground waterworks [3, 4].

The sequence of formation of a mined-out void in surrounding rock mass for placement of waterworks structures is another determinant of their stability and a factor influencing stress state of rocks.

2. Numerical studies of the stress state and the results
This paper presents the analysis of changes in stress state of rock mass in the course of stage-wise construction of rock-fill embankment at Rogun Hydropower Plant, namely, powerhouse hall and transformer chamber, on the left-hand side of the Vakhsh River at a depth of 350 m. It is assumed that the transformer chamber (200 m long, 20 m wide and 40 m high) is completely formed, and cross-section of the powerhouse hall (length of 220 m, width of 22 m and maximum height of 78 m) is made in three stages: the first stage is formation of arch and cutting of 1/3 of the cross section; the second stage is cutting of 2/3 of the cross section; the third stage is full opening of the cross section.

The powerhouse hall and transformer chamber are arranged in hard rock mass composed of intercalating sandstone and siltstone. According to the data in [6], the rock layers are inclined at an angle of 70–75° relative to horizon. Sandstone and siltstone have uniaxial compression strength σ_c ranging from 100 to 200 and from 60 to 80 MPa, respectively [7].

The model of the linearly deformable medium assumes that the stratified rock mass is quasi-isotropic; the interfaces of the layers are free from sliding but in rigid cohesion. The calculations are performed using...
boundary integral equations [5]. The ratio of dimensions of the powerhouse hall and transformer chamber allows formulating plane stress problem.

For the numerical calculation of stresses in underground waterworks structures of hydroelectric power plants, in compliance with the research data on elastic, deformation and strength characteristics of enclosing rock mass [7], it is recommended to use: Poisson’s ratio $\nu = 0.26$, elasticity modulus $E = 3.5–4.5\cdot10^4$ MPa, cohesion $C = 0.41–0.7$ MPa, internal friction angle $\varphi = 35^\circ$. In situ stress state is assumed to be as follows [6]: $\sigma_x^0 = -35$ MPa, $\sigma_y^0 = -26$ MPa.

The calculated results are analyzed using numerical values of the stress tensor components ($\sigma_x$, $\sigma_y$, $\tau_{xy}$) and shearing stresses $\sigma_s$, which allows delineating potential zones of post-limit deformation based on comparison of the stresses $\sigma_s$ and cohesion of rock mass using the Mohr–Coulomb criterion [3, 4]:

$$\sigma_s = \frac{\sigma_1 - \sigma_3}{2\cos\varphi} + \frac{\sigma_1 + \sigma_3}{2}\tan\varphi,$$

where $\sigma_1 > \sigma_2 > \sigma_3$ are the principal stresses; $\varphi$ is the internal friction angle.

The distribution of the shearing stress in the roof, sidewalls and floor of the powerhouse hall void in Figure 1 agrees with the results of the transversely isotropic model of rock mass [6].

![Figure 1](image1.png)

**Figure 1.** Distribution of shearing stress (MPa) along the boundary of powerhouse hall.

Behavior of stresses in rock mass surrounding the powerhouse hall and transformer chamber during their construction is described in Figures 2, 3 and in the table below.

![Figure 2](image2.png)

**Figure 2.** (a) Horizontal and (b) vertical stresses (MPa) in surrounding rock mass after the first-stage cutting of cross section of powerhouse hall.
Figure 3. (a) Horizontal and (b) vertical stresses (MPa) in surrounding rock mass after the powerhouse hall void is cut out to the full cross section.

Table 1. Maximum and minimum stresses at the boundary of powerhouse hall during stage-wise cutting of its full cross section.

| Operation stage | Structural element of powerhouse hall | $\sigma_x$, MPa | $\sigma_y$, MPa |
|-----------------|-------------------------------------|-----------------|-----------------|
| I               | Floor                               | $-40$           | $0$             |
|                 | Right-hand sidewall                 | $0$             | $-25$           |
|                 | Roof                                | $-8$            | $0$             |
|                 | Left-hand sidewall                  | $0$             | $-27$           |
|                 | Floor                               | $-62$           | $0$             |
|                 | Right-hand sidewall                 | $0$             | $-16$           |
|                 | Roof                                | $-108$          | $0$             |
|                 | Left-hand sidewall                  | $0$             | $-12$           |
|                 | Floor                               | $-105$          | $0$             |
|                 | Right-hand sidewall                 | $0$             | $3.5$           |
|                 | Roof                                | $-126$          | $0$             |
|                 | Left-hand sidewall                  | $0$             | $-5$            |

In the roof and floor of the underground structures, concentration zones of $\sigma_x$ and $\sigma_y$ arise. As early as the first-stage cutting of cross section of the powerhouse hall, the stresses in the concentration zone are comparable with the ultimate compression strength of rocks whereas at the final stage of operation, $\sigma_x$ and $\sigma_y$ exceed $\sigma_c$ by 30–50%. The sidewalls are free from in situ stresses (Figures 2 and 3). As the void is enlarged, the compressive stresses $\sigma_y$ in the left-hand sidewall change from $-27$ to $-5$ MPa (see the table). In the right-hand sidewall the compressive stress $\sigma_y = -25$ MPa at the first stage pass into tensile stresses of 3.5 MPa at the final stage of the cross section cutting (Figures 1, 2b, table).

The elastic convergence of the sidewalls in the powerhouse hall (Figure 4) grows from 280 mm at stage I to 543 mm at the final stage (Figure 3a). The elastic floor–roof displacements are not higher than 50 mm.
Development of the inelastic strain zone in surrounding rock mass by stages of cutting the powerhouse hall until full cross section opening is depicted in Figure 5.

At stage I of the powerhouse hall cross section cutting, the inelastic strain zones extend to 1–2.5 m in hard rocks and to 5–6 m in damaged rocks. When the full cross section is opened (Figure 5c), the zones of inelastic strains in sidewalls extend to 1–3 m in hard rocks. In the pillar between the powerhouse hall and transformer chamber, the inelastic strain zones almost merge (Figure 5c). In the roof of the powerhouse void during its stage-wise cutting, $\sigma_z$ alter insignificantly.

3. Conclusions
The study has revealed the stress state behavior in rock mass during construction of underground waterworks structures at Rogun Hydropower Plant. In the powerhouse hall void cut to the full cross section:
— the sidewall rock mass is completely free from the action of in situ stresses;
— in the concentration zones, $\sigma_x$ and $\sigma_y$ exceed the ultimate compression strength of rocks by 30–50%;
— the inelastic strain zones embrace upperlying rock mass from the side of the transformer chamber;
— the convergence of sidewalls in the powerhouse hall reaches 543 mm.

The comparison of the calculations using the boundary integral equations and the data of the transversely isotropic model proves good agreement of the results and applicability of the boundary
integral approach to the analysis of stress state of rock mass surrounding underground structure of hydroelectric power plants.

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