The nature of the dynamic stress field formation around the underground hydraulic mine workings

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Abstract. The article discusses the features of the formation of a dynamic stress field and manifestations of rock pressure around hydraulic tunnels. The results of the calculation of the dynamic stresses in the rock mass of the surrounding hydraulic tunnels, the turbine hall, the transformer room of the Rogun HPP are presented. Analytical studies are confirmed by data obtained as a result of observations of the behavior of workings under dynamic loads in production conditions at the construction of hydroelectric power plants. The influence of blasting operations on the development according to the form adopted in hydraulic engineering was also considered. Based on the studies carried out in the chamber sections of the turbine hall and the transformer room of the Rogun HPP, it was found that the maximum and minimum principal stresses $\sigma_1 \land \sigma_3$ are horizontal, while the stress $\sigma_1$ in direction coincides with the longitudinal axis of the turbine hall, and $\sigma_3$ with its transverse axis the average principal stress $\sigma_2$ is vertical.

1. Introduction

During the construction of hydroelectric power plants, a significant number of underground workings for various purposes are being built. The cross-section of underground structures is given various shapes, while they reach large parameters. For example, the tunnels of the Nurek and Rogun HPPs have a cross-sectional area of 125-150m².

Under conditions of dynamic manifestations of rock pressure, the task of forecasting and ensuring the stability of mine workings becomes much more complicated.

When elastic waves act on underground structures, a time-varying stress state arises in it, which can be investigated using solutions of dynamic problems of the theory of elasticity. The magnitude of stresses depends on the ratio of the transverse dimensions of underground mine workings and the length of seismic waves.

Such loads are the source of the formation of a dynamic stress field around underground structures. Stress field parameters affect the degree of stability of underground structures.
The complex of theoretical and experimental studies carried out under the leadership of V. L. Trushko made it possible to identify important regularities in the formation of the total stress field from static and dynamic influences. Dynamic phenomena during the development of ore deposits are characterized by energies from $10$ to $10^8$-$10^{10}$ J with a wavelength of several tens of Hertz and an array oscillation duration up to 10-12 sec. According to these parameters, dynamic phenomena of a mining and geotechnical nature occupy an intermediate position between earthquakes (high-energy phenomena over $10^8$ J) and massive explosions (phenomena of energy with wavelengths of several meters and duration of exposure up to 1-2 sec) [1].

As a rule, such workings are designed for a significant service life, therefore they are laid in hard rocks, the breaking of which is carried out exclusively due to the energies of the explosion, and at present, the simultaneous explosion of a significant amount of explosives is widely practiced.

2. Dynamic stress fields around underground workings

During blasting operations both on the surface and underground conditions, it is necessary to take into account their influence on the stability of underground workings, especially under cyclic dynamic loads, since the latter is functionally dependent on a number of mining factors [2].

The features of the dynamic manifestations of rock pressure at great depths, on the one hand, are expressed in the transition to the limiting state of significant zones around the workings, and on the other hand, in the increase in the strength of rocks with depth exceeding the increase in gravitational forces. This is the reason, at first glance, of the paradoxical phenomenon of a decrease in the number of rock bursts with increasing depth of development. The concentration of stresses directly at the contour of a solid massif contributes to the manifestation of spalling phenomena on the contour of the mine (peeling, shot), not avalanche destruction (rock burst). The conditions for the manifestation of a rock burst in brittle rocks appear when a disturbed (fissured) zone is formed around a mine working. In this case, the stresses in the near-contour part decrease, the maximum stresses move away from the excavation contour, the disturbed rocks form a damper zone (plug), which creates a support for the elastically deforming part of the massif. Violent destruction of the extremely stressed part of the massif becomes possible with a decrease in the resistance of the damper zone (removal of its part) or an increase in the concentration of stresses in the region of their maximum location (with the imposition of the reference pressure of the workings), leading to an increase in shear forces.

The existence of dynamic manifestations on the excavation contour (peeling, shot, intensive ash formation) is directly related to the presence of tensile stresses on the excavation contour, the occurrence of which is caused by its unevenness, as well as the presence of brittle fracture centers due to the heterogeneity of the mechanical properties of the rock mass. The destruction of the rock masses occurs through the joint action of separation and shear until the formation of peculiar domes in the workings, contributing to the transition of the centers of destruction into a state close to all-round compression. In the case of manifestation of plastic properties by rocks or weakening at the contour part of the rock mass by seismic action, the maximum stress is moved away from the mine contour, which helps to eliminate the conditions for the occurrence of these phenomena [3-5].

The deformation of the excavation contour is predetermined by the movement of the particles of the rock mass when a compression wave passes through it. A certain combination of explosion parameters and physical and mechanical properties of rocks affects the degree of deformation of the rock mass enclosing the mine, which manifests itself in the form of cracking, if the tensile force exceeds its tensile strength. The consequence of this is a decrease in the bearing capacity of the cladding and lining, which leads to an increase in the cost of construction. Therefore, solving the problem of stability of underground structures under dynamic loads is of certain theoretical and practical interest.

The operability and durability of an underground structure are determined by the correct choice of loads acting on their lining during construction and operation. At the same time, the load on the lining of an underground structure substantially depends on the reaction of the lining, its bearing capacity, and its working resistance.
The simplest formulation of the requirements for the compiled mathematical model of an underground structure and certain design loads corresponds to the following scheme (Figure 1).

Figure 1. Scheme for determining the design loads on the underground structure.

A mine working with a contour $L$ lies at a depth of $H$ from the earth's surface. If it is known that the influence of the lining reaction of a mine working stops at the height $H_0$ below it at the depth $H_0'$ and to the sides at the distance $B_0$, then the load independent of the lining reaction (along the vertical $\gamma H$ and linear $\lambda \gamma H$, where $\gamma$ – the volumetric weight of the rock, $\lambda$ – the lateral expansion coefficient) acts only on the contour of the ABCD area. The study of the interacting system "rocks-lining" in the field of ABCD is the subject of numerous studies of rock pressure. With their help, it has been established that the size of the ABCD depends both on the physical and mechanical properties in this area, and the mechanical characteristics of the underground structure itself.

The main driver of rock pressure is gravity. Geotechnical processes, changes in the temperature of the upper layers of the earth's crust, as well as production activities for the construction of underground and aboveground structures are additional excitatory, which have different performance, duration and strength of action [6].

Dynamic and, in particular, seismic methods based on the theoretical relationship between the speed of propagation of seismic waves in the rock and the seismic modulus of elasticity $E_{seism}$ have now more and more application in the practice of studying the properties of rocks [7]. The speed of propagation of waves of an artificially created impact in the rock varies depending on the degree of fracturing or weathering of the rock, the presence of water in the rock mass or pores and other features of the rock and allows you to establish contact planes between soft soils and rock, as well as between rocks of various nature. The magnitude of the seismic modulus of elasticity differs from the modulus of elasticity determined by static methods, and the transition from $E_{seism}$ to the required in the static calculations of the structures $E_{stat}$ presents still known difficulties, which are resolved to one degree or another in each individual case by means of an appropriate set of studies [8-9].

The analysis of various methods and criteria for assessing the state of stability of mine workings in rocks under conditions of dynamic manifestations of rock pressure showed that the most acceptable in practical terms is the one proposed by O.V. Timofeev criterion $P$ reflecting the ratio of stresses acting in the massif surrounding the mine and the resistance of rocks in the massif:

$$P = \frac{G_m \cdot K_1 \cdot K_2}{R \cdot K_s \cdot \xi},$$  \hspace{1cm} (1)

where $G_m$ – the magnitude of stresses in an intact mass in a given direction; $K_1$ – the the coefficient of stress concentration from mining a given working; $K_2$ – the coefficient of stress change from the
influence of other workings; \( R \) – the rock compressive strength of the sample; \( K \) – the rock structural weakening coefficient; \( \xi \) – the coefficient of long-term strength of rock in the massif [4].

3. Calculation of dynamic stresses

Here we calculate the dynamic stresses in the rock mass of the surrounding hydraulic tunnels under the conditions of the Rogun HPP during an earthquake with a force of 9 points at \( T_0 = 0.5 \text{s} \), which propagates two types of elastic waves, longitudinal (extension and compression waves P) and transverse (shear waves S) (see Figure 2). The propagation velocities of these waves are different, they are [1]:

\[
\varphi_p = \sqrt{\frac{E * g}{\gamma}} \cdot \frac{1 - \mu}{(1 + \mu) \cdot (1 - 2\mu)}; \tag{2}
\]

\[
\varphi_s = \sqrt{\frac{E * g}{2\gamma(1 + \mu)}} = \varphi_p \cdot \sqrt{\frac{1 - 2\gamma}{2\gamma(1 + \mu)}}. \tag{3}
\]

![Figure 2. Stress waves in the rock mass propagating from the source of the earthquake: 1 - longitudinal; 2-transverse.](image)

Seismic waves are distinguished by a large wavelength, significantly exceeding the dimensions of the cross-sections of underground structures, as a result of which the task of calculating underground structures for seismic effects is reduced to solving two quasi-static problems (with respect to two waves, Figure 3).

![Figure 3. Quasi-static stress field in the rock mass, equivalent to the action of longitudinal (a) and transverse (b) waves.](image)

The dynamic stress field in the array is replaced by the equivalent quasi-static extreme values of the normal shear stresses applied to infinity, determined by the expressions.

\[
G_{max} = \pm \frac{1}{2\Pi} * A * K_1 * \gamma * \varphi_p * T_0 * K_n = \pm P \tag{4}
\]

\[
\tau_{max} = \pm \frac{1}{2\Pi} * A * K_1 * \gamma * \varphi_s * T_0 * K_n = \pm S \tag{5}
\]
where $A$ - the conditional seismic acceleration of rock particles in fractions of g (g-acceleration of free flow); the coefficient $A$ takes values 0.1; 0.2; 0.4, respectively, for the design seismicity 7, 8, 9, points; $K_1$ – the coefficient taking into account the permissible damage of tunnel lining ($K_1 = 0.25$); $T_0$ – the predominant vibrations of rock particles (s), determined from seismic data, and in their absence taken equal to 0.5s; $K_2$ – the coefficient taking into account the depth of the construction; $\gamma$ – the rock characteristics $0.0262 MN/m^3$, $f = 5 – 6$, $\varphi = 45^\circ$, $\mu = 0.24$.

$K_h = 1 – 0.005H$ with $H \leq 100m$;
$K_h = 0.5$ with $H > 100m$.

Hence, for the average hardness of rocks in the conditions of the Rogun hydroelectric power plant:

$$\vartheta_p = \sqrt{\frac{300*10^2 * 9.8}{0.0262} * \frac{1-0.24}{(1+0.24)*(1-2*0.24)} } = 4050 m/s;$$

$$\vartheta_s = 4050 * \sqrt{\frac{1-2*0.24}{2*(1-0.24)} } = 2369 m/s.$$

Further, according to the formula (4), we determine the maximum dynamic stresses in the array in the X, Y coordinate system (the X axis coincides with the direction of wave propagation), then,

$$\sigma_{by} = \sigma_{max}$$

$$\sigma_{ef} = \lambda \cdot \sigma_{max}$$

$$\tau_{xy} = \tau_{max}$$

where,

$$\lambda_1 = \frac{\mu}{1-\mu}$$

For a 9-point earthquake $A=0.4$, $AK_1=0.40.25=0.1$; we accept $K_h=0.5$, as $H=312m$.

We put the values for the average hardness of the rocks in the formula (4) and in the above formulas and get the following (table 1):

$$\sigma_{by} = \frac{1}{2*3.14} * 0.1 * 0.0262 * 4050 * 0.5 * 0.5 = 0.422 MPa;$$

$$\sigma_{ef} = \frac{10.24}{1*0.24} * 0.422 = 0.133 MPa;$$

$$\sigma_{by} = \frac{1}{2*3.14} * 0.1 * 0.0262 * 2369 * 0.5 * 0.5 = 0.247 MPa.$$

### Table 1. The results of the above calculations.

| Rocks                     | Category | $\gamma$, MN/m$^3$ | $E$, 10$^4$ MPa | $\nu_p$, m/s | $\nu_s$, m/s | $\mu$ | $\sigma_{by}$ | $\sigma_{ef}$ | $\tau_{xy}$ | $\sigma_1$ | $\sigma_2$ | $\theta$ |
|--------------------------|----------|---------------------|-----------------|---------------|---------------|-------|---------------|---------------|-------------|------------|------------|---------|
| Siltstone, claystone, sandstone | VI       | 0.0262              | 300             | 40            | 23            | 0.24  | 0.422         | 0.133         | 0.247       | 0.564      | 0.01       | 59°7'    |
Let us further define the principal stresses in the massif and their directions with respect to the X-axis (angle $\theta$) according to the formula (8).

$$
\frac{\sigma_1}{\sigma_2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_y - \sigma_x}{2}\right)^2 + \tau_{xy}^2},
$$

We put the values of the quantities for the average hardness of rocks in this formula and, as a result, we get:

$$
\frac{\sigma_1}{\sigma_2} = \frac{0.422 + 0.133}{2} \pm \sqrt{\left(\frac{0.422 - 0.133}{2}\right)^2 + 0.247^2} = 0.564 -0.018.
$$

The angle of inclination of the main axes of the initial stresses to the coordinate axes in this case is determined by the formula (9).

$$
\theta = \frac{1}{2} \arctg \frac{2\lambda m}{1 - \lambda^2},
$$

$$
\theta = \frac{1}{2} \arctg \frac{-2 \times 0.247}{0.422 - 0.133} = 59^\circ 7',
$$

$$
tg 2\theta = \frac{2\tau_{xy}}{\sigma_y + \sigma_x}.
$$

4. Discussion

According to the results of geophysical research methods, the velocities of longitudinal waves $V_p$ in the pillar in 2005 were in the range from 2000 to 5000 m/s, the modal value of $V_p$ in this case was 3500 - 3750 m/s. In 2009, before the resumption of construction work, the range of P-wave velocities in the pillar of the turbine hall and the transformer room of the Rogun HPP remained unchanged, and the modal value shifted to the interval 3250 - 3500 m/s. This testifies to some unloading of the pillar during the absence of man-made impacts. In 2013, after intensive tunneling works carried out in the vicinity of the turbine hall and the transformer room, changes occurred in the high-speed structure of the rear pillar: the upper value of the speed range increased to 5750 m/s, and the modal value, respectively, increased to 3750 - 4000 m/s [10].

As a result of the analysis and determination of the results of a sufficiently large number of tests, it was found that the stress state of the rock mass around the turbine hall of the Rogun HPP can be approximately characterized by the following components of the main normal stresses:

$$
\sigma_1 = \sigma_{max} = 11.7 \text{MPa}; \sigma_2 = \sigma_{max} = 11.7 \text{MPa}.
$$

The maximum and minimum principal stresses $\sigma_1 \wedge \sigma_3$ are horizontal and oriented respectively perpendicular and parallel to the longitudinal axis of the machine room, the average principal stress $\sigma_2$ is vertical [10].

A number of works have been devoted to the study of the influence of dynamic pulses on cylindrical holes both in our country and abroad.

From the point of view of the correctness of the formulation of the problem and the logical course of its solution, one should point out the work of Durell and Riley "Distribution of stresses at the boundary of a circular hole in a plate during the passage of a long-duration stress pulse", which was taken into account in the study of the dynamic stress field around underground workings [11].

In contrast to the aforementioned work, the impact of blasting operations on a single mine and on a series of workings in the form adopted in hydraulic engineering, in the far and near spheres of action of the charge explosion was also considered. When solving the problem, specific mining conditions were taken, which received certain quantitative dependencies.
The problem to be solved can be briefly formulated as the establishment of the dependence of the nature of the stress field formation around the underground hydraulic structures from the explosion of the charge produced in the rock mass, at a considerable distance from the working in the vicinity of the working.

As a result of solving the problem, radial and tangential displacements of the mine contour were obtained, depending on the parameters and the type of disturbance wave (flat or spherical), the shape of the cross-section of the mine and the physicomechanical properties of rocks, and the degree of stress state of the rock mass and rock pillars was determined in different time periods [12-13].

Analytical studies are confirmed by data obtained as a result of observations of the behavior of workings under dynamic loads in production conditions at the construction of hydroelectric power plants [14].

The research results can be used in determining the optimal parameters of drilling and blasting operations, as well as in calculating linings of hydraulic structures taking into account dynamic loads.

The first studies to determine the natural stress state of the rock mass in the area of the turbine hall of the Rogun HPP were carried out in the late 1970s. The research was carried out in four chambers, equipped in an exploration adit on the left bank of the Vakhsh river. In these chambers, the Academy of Sciences of the Republic of Kyrgyzstan conducted experiments with the method of unloading a well and ultrasonic studies in wells drilled along and across the bedding of rocks [15-16].

The results of research carried out by various scientific organizations at different times are shown in Table 2. However, based on fundamental research, it is known that natural tectonic stresses, after fixing all workings, are restored to their original value in a relatively short period of time.

| Company                      | Year | Vertical Stress, MPa | Horizontal Stress, MPa |
|------------------------------|------|----------------------|------------------------|
| Tashhydroproect              | 1976 | 26.0                 | 35.0                   |
|                              | 1978 |                      |                        |
| NIS Hydroproect              | 1990 | 14.0                 | 18.0                   |
| Kyrgyzstan (unloading method) | 1970 | 10.5                 | 18.2                   |
| Kyrgyzstan (ultrasound)      | 1979 | –                    | 24.0                   |

The strength and deformation (elastic) properties of the rocks that make up the rock mass surrounding the engine ash mine are shown in Table 3.

| Rocks                        | Resistance | Deformation modulus, MPa | Strength, f |
|------------------------------|------------|--------------------------|-------------|
|                              | \(\sigma_{\text{comp}}\), MPa | \(\sigma_{\text{tens}}\), MPa | MPa         |
| Sandstone (K1ab2)            | 65.0 – 150.0 | 7.5 – 150               | 8500        | 6 – 7       |
|                              | 107.5           | 107.5                   |             |             |
| Siltstone (K1ab1)            | 40.0 – 118.0   | 5.0 – 6.0               | 5500        | 5           |
|                              | 79.0           | 5.5                     |             |             |
| Lenses of faults and breaks  | –             | –                       | 2000        | 2           |

From the given data and approximate calculations, it follows that taking into account the redistribution and concentration of stresses in the vaults, with an increase in the depth of excavation, loads arise that transform the ultimate strength of the rock, especially in the vault key.

In his research G.A. Markov [17] said that with actively acting tectonic forces, the horizontal components of the stress tensors can significantly exceed the vertical components determined from
gravity calculations. Depending on the ratio of the acting stresses and the compressive strength of the rock, the resolution process can occur at a decaying, constant or increasing rate. The results were obtained on the increase in the intensity of brittle fracture in time in the region of extreme deformation of the rock, i.e. given that \( \sigma \geq \frac{\sigma_{\text{compr}}}{1 - \frac{\sigma_{\text{compr}}}{\sigma_{\text{compr}}}} \). Under these conditions, destruction is observed with an increasing rate. So with respect to \( \theta \), the destruction rate is 0.3 m per year, and at \( \theta \geq 2 \) the speed of this process exceeds 2 m/year.

Extreme tension in the vault reduces it. The studies of creep, passing into brittle fracture of the rock, of G.A. Markov and other prominent scientists, it is necessary to take measures to radically reduce the displacement of the walls of the turbine hall of the hydroelectric power station [15-17].

Comprehensive studies of rock masses that contain the main underground structures of the Rogun HPP carried out in recent years have made it possible to clarify the current state of these masses and update the characteristics of their elastic, deformation and strength properties obtained at the technical design stage.

With dynamic phenomena a static non-equal-component stress field takes place around the workings of seismic waves, as a result of which a cyclic immersion of the rock mass occurs for 1–12 s with the number of cycles reaching 300–500. This not only causes an increase in stress concentration in some zones in the vicinity of the mine, but also causes oscillatory processes that provoke dangerous resonance phenomena in the rocks of the roof [18-20].

Tectonic faults play an important role in the formation of the stress-strain state of the rock mass, and there are many unresolved issues in the problems under consideration.

5. Conclusion

Based on the studies carried out, the following conclusions were made:

1. On the basis of the calculation results, it is concluded that the higher the dynamic stresses in the rock mass, the stronger the rock mass composing it (the higher the deformation modulus). With the simultaneous action of longitudinal and transverse waves in the rock mass, tensile stresses can arise even in the compression phase of the longitudinal wave;

2. The research results can be used in determining the optimal parameters of drilling and blasting operations, as well as in calculating linings of underground hydraulic structures, taking into account dynamic loads;

3. In recent years, comprehensive studies of rock masses containing the main underground structures of the Rogun HPP have made it possible to clarify the current state of these masses and update the characteristics of their elastic, deformation and strength properties obtained at the stage of the technical design;

4. On the basis of the studies carried out, the features of the stress state of the array in the chamber sections of the turbine hall and the transformer room of the Rogun HPP were revealed, and an assessment of the stresses acting on this section was given. It was obtained that the maximum and minimum principal stresses \( \sigma_1 \) and \( \sigma_2 \) are horizontal, while the stress \( \sigma_1 \) in direction coincides with the longitudinal axis of the turbine hall, and \( \sigma_2 \) with the transverse axis, the average principal stress \( \sigma_3 \) is vertical;

5. High tectonic stresses with a predominance of horizontal components on vertical ones create exorbitant loads in the arch-forming rock, cause the phenomenon of creep, which can go into the phase of brittle fracture;

6. Consider the issue of measures to reduce tectonic stresses recovering during the long-term operation of the structure, taking into account scientifically based recommendations;
7. Ensure the reliability and regularity of observations of the displacements of the turbine room walls and the periodic determination of the values of the acting tectonic stresses;
8. To reduce the intensity of seismic vibrations, it is proposed to switch to seismic-safe technology in the application of such blasting schemes in which its maximum mass blasted simultaneously would not exceed the calculated value, and the deceleration time would fluctuate within the optimal range of 25-50 ms.

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