Assessment of the safety of Rogun HPP dam in case of seismic impacts

Viatcheslav Orekhov¹ and German Alekseev²
¹ Research Institute of Bases and Underground Structures, 59 Ryazanskiy prosp., Moscow, 109428, Russia
² Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia

E-mail: ¹ v.orehov@rambler.ru ² alexeev_german@bk.ru

Abstract. The article considers the problem statement and the results of numerical studies of the formation of the stress-strain state of the rock-earthfill dam of the Rogun HPP under seismic impacts. In this case, the static stress-strain state of the dam is considered as the initial state. The purpose of this work is to assess the seismic stability of an ultra-high dam being built in a mountainous area with high seismicity. To study the stress-strain state of a rock-earthfill dam, we used a method based on the finite element solution of a system of differential equations for the dynamic theory of consolidation of quasi-two-phase ground media. To describe the nonlinear deformability of soil materials composing the body of the dam, we used a mathematical model formed in the framework of the theory of plastic flow with hardening. The calculations were performed in a spatial setting, taking into account the speed of propagation of the impact in the rock base. Packages of 3-component accelerograms synthesized for dam construction conditions were used as seismic effects in the calculations. To assess the safety of the rock-earth dam in case of seismic impacts, a calculation was made for the most dangerous impact when the strength characteristics of the dam body materials were reduced by 1.08. As shown by the results of the calculations in this case, after seismic excitation is not observed the appearance in the body of the dam areas of marginal soil conditions, the value of the total reserve coefficient is greater than the minimum standard value for a special combination of loads and seismic stability of the rock-earthfill dam is provided.

1. Introduction
Currently, an ultra-high dam of Rogun HPP (Hydro Power Plant) is being built in the Republic of Tajikistan. The construction area has a high-altitude strongly dissected terrain and high seismicity. The highest intensity of seismic impacts of the design level of MDE (Maximum Design Earthquake) at the construction site is 9 points. The 340m high rock-earthfill dam is being built on the Vakhsh river in a narrow V-shaped gorge with steep slopes, which has a complex zigzag shape in the plan, which determines the study of its stress-strain state and the assessment of seismic stability in the volume formulation.

The scientific justification of dam structures made of soil materials is usually performed on the basis of numerical studies of their stress-strain state [1-15] using modern provisions of soil mechanics [16-17]. For seismic calculations, it is also advisable to perform calculations taking into account the
interaction of the dam with the reservoir [1] and the speed of propagation of the impact in the rock base [18].

2. Methods
To study the stress-strain state of the rock-earthfill dam of Rogun HPP, the method [19] was used, based on the finite element solution of the system of differential equations of the dynamic theory of consolidation of quasi-two-phase ground media [20]. To describe the nonlinear deformability of soil materials composing the body of the dam, we used a mathematical model formed in the framework of the theory of plastic flow with hardening [16], the parameters of which are determined by standard three-axis tests of soils and reflect the features of the dilatation behavior of the soil, which significantly affect the processes of plastic deformation of water-saturated soils. The finite element model of the rock-earthfill dam of Rogun HPP is shown in figure 1.

In the calculation model, the construction of the dam and the filling of the reservoir, according to the design schemes, were simulated by 21 calculation stages. The results of static calculations of the stress-strain state of Rogun HPP dam are presented in [21]. When calculating the seismic impact, the static stress-strain state of the dam is considered as the initial one. The approach of seismic impact to the dam in the calculations was set on the X-axis from the downstream side. The value of the approach angle of the seismic impact front is 45 degrees. The speed of propagation of the seismic impact front along the rock base when approaching the rock-earthfill dam is 2800 m / sec.

A package of 3-component accelerograms synthesized in Institute Gidroproekt for the construction conditions of Rogun HPP dam was used as seismic effects in the calculations. The package consisted of 10 calculated accelerograms of different frequency composition with the maximum values of the amplitudes of horizontal accelerations along the dam site and vertical accelerations of 0.54 g (g - acceleration of free fall). Across the dam site, the maximum impact accelerations were 0.46 g.

![Figure 1. Three-dimensional finite element model of the dam. Downstream view.](image)

For estimation of the stress state (by the extent of approximation to the limit state) in each point of soil mass determining local shear safety factor based on the results of dynamic calculations. The total safety factor is determined from the relationship:

\[ K_z = \frac{c^{**}}{c} = \frac{tg\varphi^{**}}{tg\varphi} \]

where \( c^{**} \) and \( tg\varphi^{**} \) are values of soil strength parameters, at which calculations predict failure of soil mass.
3. Research result

As a result of computational studies of the stress-strain state of the rock-earthfill dam of Rogun HPP, it was found that the largest values of the maximum displacements of the dam and their residual values were obtained from the calculation of the MJ 475 accelerogram (Figure 2).

The results of dynamic analysis of the rock-earthfill dam for assigned 3-component seismogram showed that within the set problem the seismic load mainly affects the dam longitudinal horizontal (along axis X) oscillations. At that, as a result of seismic load the dam has about 13 oscillations. Maximum horizontal displacement of the dam crest center toward the downstream side is about 1.17 m, toward the upstream side – about 1.22 m (Figure 3). Maximum vertical displacement of the dam crest center is about 0.91m, and longitudinal oscillations of the dam crest are insignificant. At that, oscillations in these directions damp actually just after seismic impact.

![Figure 2. Three-component accelerogram Mj475.](image)

After the end of the earthquake the maximum residual horizontal dam displacement along axis X (about 0.54m) in the analysis is predicted in the upper part of the downstream shell near the core; at that, the value of maximum displacement of the upstream shell slope central part toward the upstream side is about 0.46m (Figure 4).

As a result of seismic impact the upstream shell and the core have the greatest additional settlement. Maximum residual vertical displacement of about 0.98m (additional settlement due to seismic impact) by calculations is predicted on the dam crest from the side of the upstream shell. At that, there observed slipping of the upstream shell material against the core material and the core material against the downstream shell material (Figure 5) accompanied by tilting of the dam crest toward the upstream side (maximum value of the difference in settlements of the end points width-wise the crest is 0.47m).

![Figure 3. Displacement U (m) of the middle of the dam crest during seismic impact.](image)
Figure 4. Additional horizontal displacements $dU_x$ (m) in the dam due to seismic impact. Top view.

Figure 5. Additional vertical displacements $dU_y$ (m) in the dam cross section due to seismic impact.

However, in spite of shell shear along the core and occurrence of horizontal displacements of the upstream shell surface toward the upstream side no potential dangerous collapse surface is formed in the upstream shell body.

As a result of seismic impact, the nature of stress distribution in the dam body and their values changed slightly relative to the static state [21].

In General, as well as after the static calculation, after of the seismic impact calculation are not projected to occur in the dam body zones limit state of the soil. The local safety factors everywhere greater than 1.0 Despite a slight increase (compared to the static condition) the intensity of shear deformation in the core of the dam and adjacent transition areas, their values are far from the ultimate. The intensity of shear deformation in thrust wedges also significantly below the limit (and on the
slopes of a dam close to zero), which also indicates no occurrence of the limit state zones of soil in the process of seismic impact.

To assess the safety of the rock-earthfill dam of Rogun HPP under seismic impacts, a calculation was made for the most dangerous impact of Mj475 with the strength characteristics of the dam body materials lowered by 1.08.

As shown by the results of calculations, at the end of the seismic impact, there is no occurrence of zones of the limiting state of the soil in the body of the dam, the local reserve coefficients are always greater than 1.0 (Figure 6). Thus, the seismic stability of Rogun HPP rock-earthfill dam is provided, and the value of the total reserve coefficient is greater than the minimum standard value for a special combination of loads Kz>1.0625.

Figure 6. Local safety factors in the dam cross section after seismic load at 1.08 times decrease of strength characteristics

4. Conclusions
As a result of MDE level seismic load assigned by three-component seismogram taking into account the velocity of seismic waves propagation in rock foundation the additional development of plastic deformations occurs in the dam and sliding of material of the upstream shell relatively the core material is observed.

Seismic stability of rock-earthfill dam of Rogun HPP is provided. The value of overall safety factor is more than minimum standard value at unusual load combination.

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