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MATHEMATICAL MODELING OF THE STRESS-STRAIN STATE OF CONCRETE DAM AND ROCK FOUNDATION CAUSED BY TECTONIC FAULT SLIP

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Abstract. The multilevel finite element technique for determination of dam-foundation stress-strain state under tectonic fault slip is developed. Computational model includes an active fault, dam and foundation. The methodology is used to calculate stress-strain state of concrete structures and foundation of Sayano-Shushenskaya HPP under Borusskiy fault presumable slip.

1. Introduction

Earthquakes often cause seismic discontinuities. Mutual displacements of the rupture banks causes changes in the stress-strain state of a rock foundation and the dam itself. The article is devoted to development of the methodology for assessing the stress-strain state of construction-foundation system caused by tectonic displacements [1]. The technique is based on the principles of fragment calculations. The series of sequential stress-strain calculations for a set of embedded models are performed using a recurrent algorithm. Stress-strain state estimates, obtained by calculation with the model i, are used as the boundary conditions for the calculation of the embedded model $i + 1$, that has more detailed finite element mesh.

The first model contains the part of the Earth crust with the considered fault and the dam. The impact here is being set as a relative displacement of the rupture banks (displacement dislocation). The last of the models (n-model) is a detailed model of the concrete dam with all main concrete structures and its foundation. The use of «intermediate» models $2 \div (n-1)$ provides the required accuracy and reduces the number of degrees of freedom (DOF) to an acceptable level in each of the models.

The developed methodology is used to research an impact of presumable fault slip in the nearest potentially active fault (Borusskiy fault [2, 3]) on the stress-strain state of Sayano-Shushenskaya dam. The corresponding calculations are made using the finite element program Abaqus 6.13.

2. Computational models

A three-model system is adopted for evaluation of the stress-strain state of Sayano-Shushenskaya dam caused by dislocation in Borusskiy fault (Fig. 1).

Model 1 represents the Earth crust section of 70x70 km and 40 km depth (Fig. 1a). Finite element mesh includes 4078651 elements, 1811675 nodes and it has 5435025 DOF.

Model 2 (Fig. 1b) represents the "extended" area of the dam foundation. It makes possible taking into consideration the length and the depth of faults and breaks located directly under the foot of the dam. Second model dimensions are 5.5x6 km in plan with 2.5 km depth. Finite element mesh contains 1455052 elements, 1500669 nodes and 4502007 DOF.

Model 3 represents the detailed computational model of dam-foundation system. Its dimensions are 1.5x2 km in plan and 1 km depth (Fig. 1c). Finite element mesh consists of 859961 elements, 329160 nodes and has 1213914 DOF.

Figure 1 illustrates the hierarchy of the models, the position of the model 2 inside the model 1 and the model 3 inside the model 2. The cross-section of the main fault is also pointed in the figure.

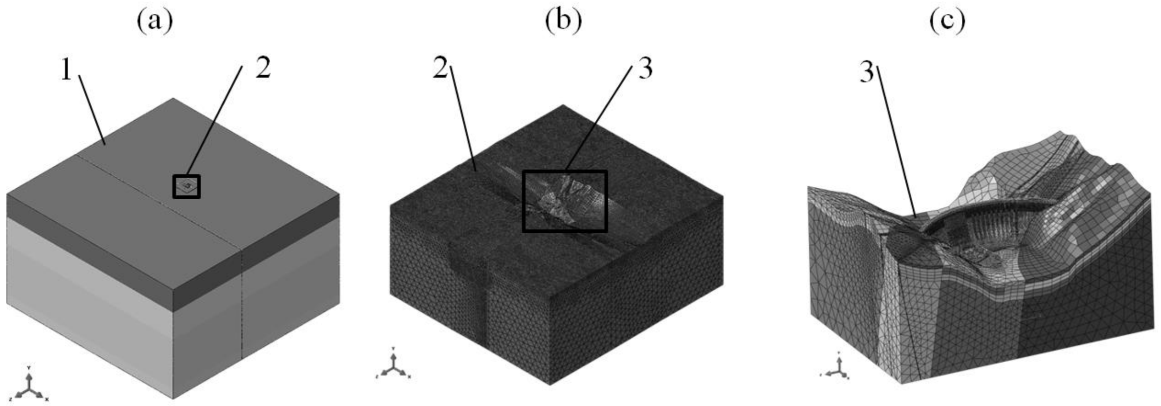

Fig. 1. Computational models: 1 – model 1; 2 – model 2; 3 – model 3.

The model 3 includes all main concrete structures of Sayano-Shushenskaya HPP: the concrete arch-gravity dam, powerhouse, the divide wall and the model of the rock foundation. Engineering-geological information given in [3, 10, 11] is used for the model developement. Previous model of the dam created and verified by VNIIG [10] was modified in accordance with the specifics of the calculations performed. Foundation scheme was implemented based on structural model built by TSSGNEO [11]. The model takes into account the spatial position and modes of occurrence of mainly rock types, spatial location and structure of the IV order subvertical tectonic faults and their influence zones. Foundation (excluding the fault and fault influence zones) were modeled using linear elastic material. Faults and its influence zones were modeled using Mohr-Coulomb elastic-plastic material. During the calculations elastic-plastic Drucker-Prager material was also used to provide better convergence [12, 13].

3. Determination of geometry and magnitude of mutual displacements of the presumable seismogenic rupture

Geometrical characteristics of the rupture and the magnitude of the relative displacement of its banks are used as boundary conditions for the analysis of stress-strain state of the first model (the largest one).

The following values are estimated: 1) maximum displacement at the ground surface $D^0_{\max}$ (m); 2) Average displacement at the ground surface D^0_{av} (m); 3) maximum displacement on the surface of the rupture $D^s_{\max}$ (m); 4) average displacement on the surface of the rupture D^s_{av} (m); 5) the length of the rupture on the ground surface L^0 (km); 6) maximum length of the rupture below the surface $L^s_{\max}$ (km); 7) depth or rupture W (km); 8) area of the rupture S (km^2).

When determining these parameters, the magnitude of a potential earthquake in Borusskiy fault was taken as $\boldsymbol{M_w} = 6$, focal depth of 10 km [3].

Empirical regression relations are commonly used for geometric characteristics of rupture and its banks mutual displacement estimation. These equations demonstrate the relations between the characteristics of the rupture to the earthquake magnitude M [4-9].

Relations published in different sources often lead to different results. The main reason for that is that different authors use different seismic catalogs [4-9]. According to [8, 9] "for seismic events with magnitudes from 5.7 to 8, there is no systematic difference between the values of magnitude M_s, where M_s is determined based on intensity of the surface waves and the magnitude $\boldsymbol{M_w}$, where $\boldsymbol{M_w}$ is calculated based on seismic momentum M_0". We assume M_s = $\boldsymbol{M_w}$ = 6 for further calculations.

The aim of the work is the determination of conservative estimates of the stress-strain state. Therefore when estimating the characteristics of possible rupture the highest values obtained according to [4-9] were adopted (so-called "envelope estimation") [4]. It was also taken into account that the seismic momentum $M_0 = \iint_s \mu D ds$ satisfies the relation $2\lg M_0 - 18 = 3M_W$ [6], where S is the area of rupture, μ – shear modulus, D – mutual displacement of the rupture banks.

Thus, vertical cross-section of the 1st model is presented on Fig. 2. The rupture constructed depth W is 15.75 km, area S is 148 km^2. For both shear and upthrow earthquakes maximum displacement in point A on the ground surface is $D^0_{\max} = 2$ m. Maximum displacement on the surface of the rupture is $D^s_{\max} = 2{,}6$ m. Average displacement on the surface of rupture is $D^s_{av} = 1{,}04$ m.

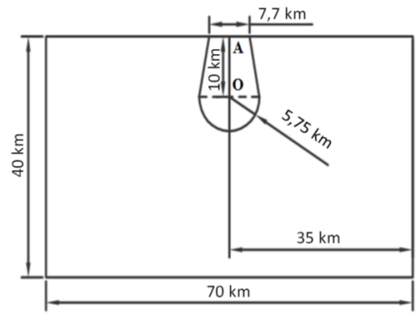

Fig. 2. Scheme of the rupture used for displacement dislocation modelling.

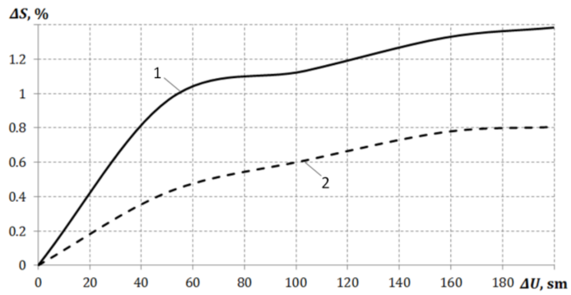

Fig. 3. Disturbed dam-rock contact area Δs versus shear displacement ΔU in tectonic fault for 10th (curve 1) and 18th (curve 2) sections of the dam.

4. Results and conclusions

In the present study calculations of the stress-strain state of the dam-foundation system under static (gravity and hydrostatic) and tectonic loads are made. Calculations are performed for Sayano-Shushenskaya HPP dam. Tectonic loads were modelled as for displacement in Borusskiy fault; throw-up and shear slip are considered. The influence of tectonic displacement on stability of the concrete dam is estimated. The important factor characterizing stability of the dam is the area of undamaged contact on rock-concrete contact surface [14]. In the present study the value of 1.2 MPa for tensile strength was used for contact surface. The maximum allowable disturbed contact area was set as 5 % of the total area of the section base. In this case (see Fig. 3) results indicate that if displacement on the ground surface is less than 2 m (corresponding to an earthquake with magnitude 6) then the dam section stability conditions are not violated.

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