Investigation of the stress-strain state of a gravity dam made of cement-sand and gravel (CSG)

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Abstract. The article presents studies of the stress-strain state of a gravity dam of a homogeneous symmetrical profile made of cement-sand and gravel (CSG) on a rocky base. When performing computational studies, the method of full factorial experiment (PFE) was used. Based on this method, we take three variations factors the dam height, slope ratio, and the modulus of deformation of the dam. Calculations were carried out using the CRACK software package. The results allow us to optimize the dam profile (CSG) in a real project and evaluate the reliability of dam structures of this type.

Keywords: Cemented sand and gravel dam (CSG dam), stress-strain state, Theory of experiment planning, the method of full factorial experiment, Software package "CRACK.

1 Introduction

Cement-sand and Gravel Dam (CSG dam) is a new method of dam construction with unique technological characteristics, which occupies an intermediate position between the basis of a gravity dam made of rolled concrete and the rock-fill dam, by obtaining raw natural materials locally and reusing otherwise discarded materials, which has a high construction speed, energy saving and environmental protection, economy, efficiency, safety and reliability [1, 2, 15].

The initial concept of CSG dam was brought up by J. M. Raphael [1] early in 1970. It was then followed by French and Japanese researchers to develop and build hard fill dams, and symmetrical trapezoid dams in Greece, Japan and Turkey [4-11]. In recent years, with the improvement of the technology of construction of dams from materials (CSG), about 10 dams of this type with a height of 20 to 100 meters have been built, such as the dams Nagashima, Tobetsu in Japan in figure 1, Oyuk, Cindere in Turkey, and many studies have also been conducted on the construction materials of dams in Turkey, the Dominican Republic,, Philippines, Iran, and other countries [17- 20].

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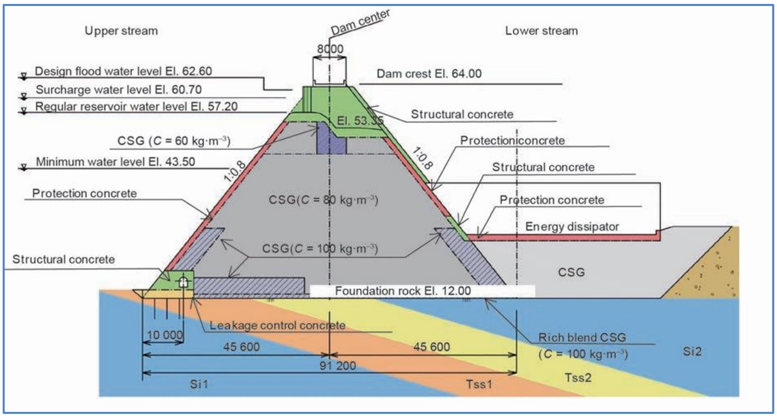

Fig. 1. Tobetsu dam in Japan (H = 52 m)

The material used for constructing such dams is generally termed as (CSG) (cemented sand and gravel) with a maximum aggregate size less than 80 mm.

The cost-effectiveness of a symmetrical trapezoid dams from a (CSG) consists in the cheapness of the material, because the filler is soil taken near the construction site, which does not require processing, sorting, washing, fractionation, soil with the small of cementitious material (50~80 kg/m^3) [16]. Compared to (CSG) material with conventional concrete and even roller compacted concrete (RCC), it contains much less cement (typically less than 40 kg/m3), effectively avoiding the common temperature control problem among concrete dams. Thus, the (CSG) dam inherited both the technical advantages of the simple and rapid construction of rock-fill dams and the stronger structural integrity of concrete dams [15].

2 Methods

The study of the influence of factors on the stress-strain state of gravity dams made of cement-sand and gravel (CSG) based on the theory of experiment planning allows reducing the amount of computational experiment and improving the design of dams at the stages of preliminary design [2 , 3].

To date, planning theory is a scientific field on its own and is used in many scientific experimental studies; it is an approach to research in which mathematical methods play a leading role [2]. In this paper, in the study of the stress-strain state of a gravity dam, taking into account the destruction of the concrete-rock contact seam, nonlinear deformation of dam and base materials, violations of the shear strength of interlayer construction joints, structural stability, a linear model of the full factor experiment (PFE) method was used. The form of the response function inside the factor space is given by the polynomial (1):

$$y(b,\mathrm{x}) = \mathrm{b}_0 + b_1x_1 + b_2x_2 + \ldots + b_nx_n + b_{12}x_1x_2 + b_{13}x_1x_3 + b_6x_2x_{13} + \ldots + b_{1n}x_1x_n + \ldots + b_{n-1}x_{n-1}x_n + b_{123}x_1x_2x_3 + \ldots + b_{mn}x_n^2 \tag{1}$$

In this situation, it seems natural to use the entire allowable range of variable changes when planning. In this case, the number of calculations is equal to N = 2^k.

Where N: is the number of experiments, K : is the number of variable factors; 2: is the number of levels of variation of factors.

The coefficients of the regression equation (1) are calculated by the least squares method (OLS), a matrix equation of the form (2) (3):

$$B = (X^T X)^{-1} X^T Y \quad (2)$$

$$b_0 = \frac{\sum_{j=1}^{n} y_j X_{0j}}{n} \quad b_1 = \frac{\sum_{j=1}^{n} y_j X_{1j}}{n} \quad b_2 = \frac{\sum_{j=1}^{n} y_j X_{2j}}{n} \quad (3)$$

After determining all the equations and functions, we determine the coefficients of the regression equation.

In this paper, the influence of three factors affecting the stress-strain state of gravity dams at design load was considered. The intervals of variation of factors are presented in Table 1. The matrix of planning a complete factor experiment is presented in Table 2.

Table 1. Test factors and levels.

Factor	Designation of factors	Levels of variation		
		Low level (-)	High level (+)	Variation intervals
Modulus of elasticity for dam (MPa)	X1	5000	15000	5000
Dam slope ratio (m)	X2	0,4	0,8	0,2
Dam height (m)	X3	60	100	20

Table 2. Table matrix of the complete factorial experiment of three factors $N=2^K$

Test number	Plan							
	X_0	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	$X_1X_2X_3$
1	+1	-1	-1	-1	+1	+1	+1	-1
2	+1	+1	-1	-1	-1	-1	+1	+1
3	+1	-1	+1	-1	-1	+1	-1	+1
4	+1	+1	+1	-1	+1	-1	-1	-1
5	+1	-1	-1	+1	+1	-1	-1	+1
6	+1	+1	-1	+1	-1	+1	-1	-1
7	+1	-1	+1	+1	-1	-1	+1	-1
8	+1	+1	+1	+1	+1	+1	+1	+1

The calculations were carried out in the "CRACK" software package, which implements the finite element method (FEM) in a strength formulation and allows you to explicitly model various continuity violations - seams, cracks, and contacts. The nonlinear model of contact interaction (physical model) implemented in the program allows taking into account the opening and closing (closing) of the contact between solid blocks, the elastic-plastic work of the contact during shear (taking into account possible softening), as well as the dilatation properties of cracks during shear deformations [12, 13].

We considered a gravity dam of a homogeneous symmetrical profile made of cemented sand and gravel (CSG) on a rock foundation with a height H = 60 (100) m, a normal water level (NPU) 58 (98) m. The width of the dam crest b = 10 m. The base area under the dam was modeled with dimensions of 2H x (4·H + B) m. The characteristics of the dam and the foundation are given in Table 3. Horizontal construction seams were clearly reproduced in the structure using contact elements (13 seams of 35 contact elements in a seam divided into two equal parts: "minus" - section and "plus" – section, i.e. 70 values of deformations and stresses in the seam) and a contact seam between the dam and the base. All seams in the body of the dam are the same in terms of shear characteristics. The values of the shear parameters of the seam and the contact seam between the dam and the base are selected according to studies on constructed dams made of rolled concrete, shown in Table 3.

Table 3. Basic physical and mechanical parameters of the dam body and foundation.

Physical and mechanical characteristics of the dam body						
The modulus of deformation of the dam E_{dam}. (MPa)	Ccompressive strength (MPa)	Tensile strength (MPa)	Poisson's ratio ν	Unit mass γ(KN/m^3)	Cohesion C (MPa)	Internal friction angle φ
5000	5	0,5	0,24	2,25	0,32	39
Modulus of elasticity for foundation E_{foun}.(MPa)	Physical and mechanical characteristics of the dam foundation					
6000	5	0,4	0,22	-	0,2	39

The grid of the finite element method of the dam–base system, with the location of the joints modeled by contact elements, was created using the "Mesh" program included in the software package, and contains 2852 nodal points and 2727 finite elements. A fragment of the FEM grid is shown in Figure 2. Taking into account the variation of the three factors studied at two levels, it is necessary to calculate 9 dam variants of different heights with maximum and minimum profile deposits, as well as cases when the factors have average values at the design load.

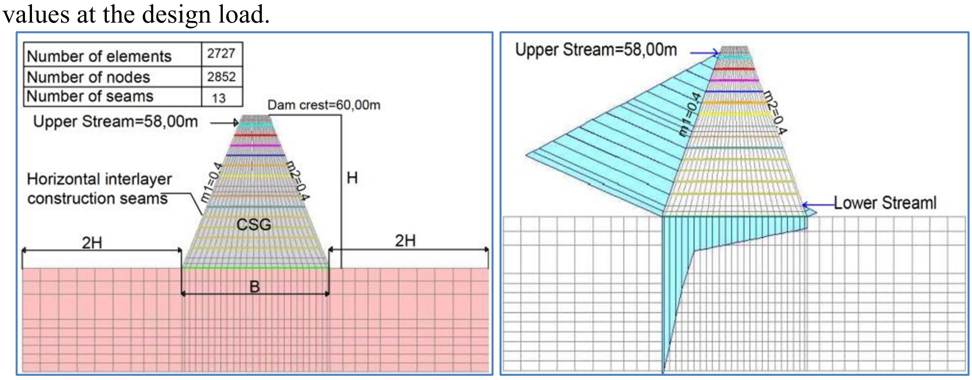

Fig. 2. A fragment of the FEM grid of the dam-foundation system and the location of the seams.

3 Results

The response functions were:

- Maximum horizontal movement $U_{max.;}$
- Opening depth of the contact seam L;
- Maximum compressive stresses in the dam on the upper and lower sides σ_2^u, σ_2^t;
- Maximum compressive stresses at the base of the bottom wedge σ_2;
- Coefficients of stability of concrete-rock contact Ks.

$$U_{max} = f(E,m,H); L = f(E,m,H); \sigma_{2dam(u)} = f(E,m,H);$$

$$\sigma_{2dam(t)} = f(E,m,H); \sigma_{2foundation} = f(E,m,H); Ks = f(E,m,H);$$

Having received the dependencies described below:

Where *E* is the modulus of deformation of the dam, *H* is the height of the dam and *m* is the slope ratio. We give these functions a symbol in the form of Y_1, Y_2, Y_3, Y_4, Y_5 and Y_6.

The results of the calculation of the main indicators characterizing dams for profile variants No. 1-9, and the coefficients of the regression equations are presented in Tables 4 and 5.

Table 4. The results of the calculation of the main indicators for dam's No. 1-9.

Test number	The values of the response functions obtained in the calculations					
	Maximum horizontal movement	Opening depth of the contact seam	Maximum principal stress (MPa)			
			Main compressive stresses upstream of the dam	Main compressive stresses downstream of the dam	Maximum compression at the base c	Coefficients of stability of the foundation
	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
	U_{max} (cm)	L (m)	σ_2^u (MPa)	σ_2^t (MPa)	σ_2 (MPa)	Ks
1	1.5	3	-0.57	-2.83	-1.87	2.79
2	1.1	0	-0.99	-4.17	-2.19	2.97
3	0.69	0.5	-0.68	-1.59	-1.22	5.09
4	0.55	0	-1.67	-2.66	-1.63	5.26
5	5.1	4.5	-0.96	-4.93	-3.93	2.3
6	3.5	0	-1.46	-6.91	-4.71	2.44
7	2.0	1	-1.14	-2.45	-2.31	4.27
8	1.5	0	-2.85	-3.91	-3.10	4.5
9	1.3	*0*	-1.34	-4.06	-2.58	3.57

• The minus sign in the table means compression

Table 5. Coefficients of regression equations.

Response function	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{123}
$Y_{1(Umax)}$	1.993	-0.330	-0.808	1.033	0.170	-0.195	-0.468	0.105
$Y_{2\ (L)}$	1.125	-1.125	-0.750	0.250	0.750	-0.250	-0.125	0.125
Y_{3} (σ2 Upper stream dam)	-1.290	-0.453	-0.295	-0.313	-0.223	-0.100	-0.098	-0.080
Y_4 (σ2 Lower stream dam)	-3.681	-0.731	1.029	-0.869	0.099	-0.129	0.341	0.031
Y_5 (σ2 the base of the bottom wedge)	-2.620	-0.288	0.555	-0.893	-0.013	-0.105	0.253	0.010
Ks (Coefficients of stability)	3.703	0.090	1.078	-0.325	0.010	0.003	-0.070	0.013

$$Y_{1(\mathrm{Umax})} = 1.993 - 0.33x_1 - 0.808x_2 + 1.033x_3 + 0.17x_1x_2 - 0.195x_1x_3 - 0.468x_2x_3 + 0.105x_1x_2x_3$$

$$Y_{2(\mathrm{L})} = 1.125 - 1.125x_1 - 0.75x_2 + 0.25x_3 + 0.75x_1x_2 - 0.25x_1x_3 - 0.125x_2x_3 + 0.125x_1x_2x_3$$

$$Y_{3(\sigma_{2\,\mathrm{Upper\ stream\ dam}})} = -1.29 - 0.453x_1 - 0.295x_2 + 0.313x_3 - 0.223x_1x_2 + 0.1x_1x_3 + 0.098x_2x_3 - 0.08x_1x_2x_3$$

$$Y_{4(\sigma_{2\ \mathrm{Lower\ stream\ dam}})} = -3.681 - 0.731x_1 + 1.029x_2 - 0.869x_3 + 0.099x_1x_2 - 0.129x_1x_3 + 0.341x_2x_3 + 0.031x_1x_2x_3$$

$$Y_{5(\sigma_{2\ \mathrm{the\ base\ of\ the\ bottom\ wedge}})} = 2.620 - 0.288x_1 + 0.555x_2 - 0.893x_3 - 0.013x_1x_2 - 0.15x_1x_3 + 0.253x_2x_3 + 0.01x_1x_2x_3$$

$$Y_{6(ks)} = 3.703 + 0.09x_1 + 1.078x_2 - 0.325x_3 + 0.01x_1x_2 + 0.003x_1x_3 - 0.07x_2x_3 + 0.013x_1x_2x_3$$

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In the formula:
Y_1 represents the horizontal movement response value;
Y_2 represents the depth of the opening of the contact seam;
Y_3 represents the stress response value of the upstream dam;
Y_4 represents the stress response value of the downstream dam;
Y_5 represents the stress response value of the base of the bottom wedge;
Y_6 represents the coefficient of stability of the base of the bottom wedge.

X_1 represents the Modulus of elasticity of the dam body, X_2 the slope ratio of the dam body, and X_3 represents the dam height.

4 Discussion

Analysis results of the regression equation of a homogeneous symmetric profile dam:

-the maximum horizontal and vertical movement is mainly strongly influenced by dam height and slope ratio shown in Figure 3;

-the depth of the opening of the contact seam is influenced by the modulus of deformation of the dam, and slope ratio;

-the results show that all the studied factors affect the maximum compressive stresses in the upstream dam shown in Figure 4;

-the maximum compressive stresses in the downstream dam are significantly affected by slope ratio, and less by dam height and the modulus of deformation of the dam shown in Figure 4;

-the maximum compressive stresses in the base of the bottom wedge are affected by the dam height and slope ratio shown in Figure 5;

- The coefficient of stability is affected by slope ratio, and dam height.

Figures 3-5 show the influence of the dam height on the amount of displacement and stress it is obvious that the amount of stress at the upstream dam and displacement increase with increasing dam height, but the amount of stress at the downstream dam and the base decreases with increasing slope ratio. The results of the stress-strain state and stability coefficients of the dam of a homogeneous profile No. 1, No. 3, No. 5, and No.7 are shown in Figures 6÷7.

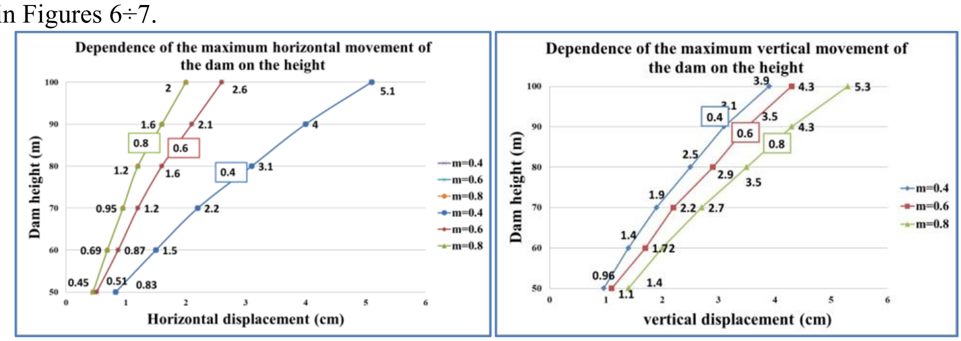

Fig. 3. Dependence of the maximum horizontal and vertical movements on the height at different slope ratio.

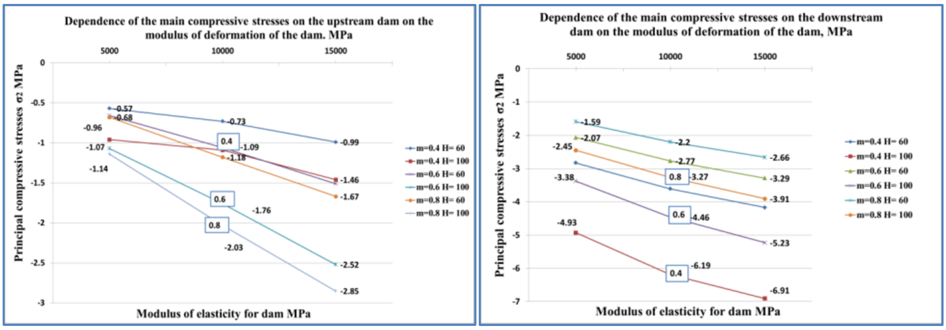

Fig. 4. The dependence of the main compressive stresses on the upstream and downstream dam on the modulus of deformation of the dam at different slope ratio.

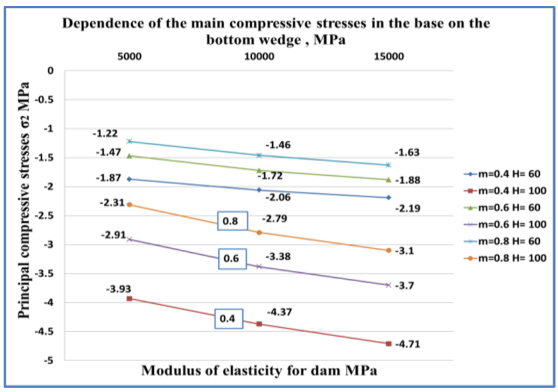

Fig. 5. Dependence of the main compressive stresses in the base of the bottom wedge on the modulus of deformation of the dam at different slope ratio.

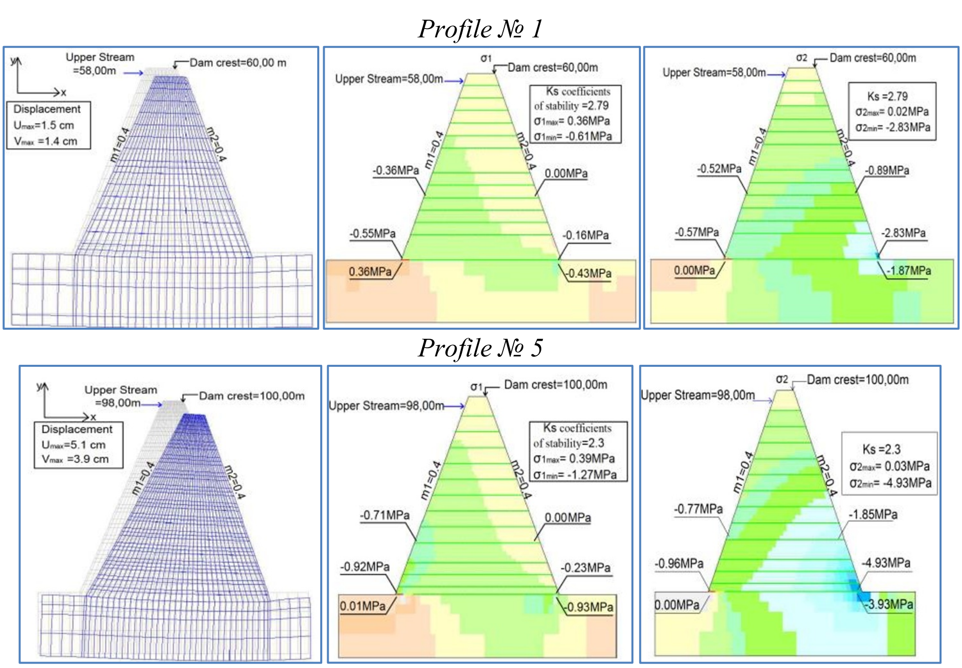

Fig.6 Stress-strain state and stability coefficients of the dam of homogeneous profiles No. 1, No. 5 in accordance with the experiment planning matrix.

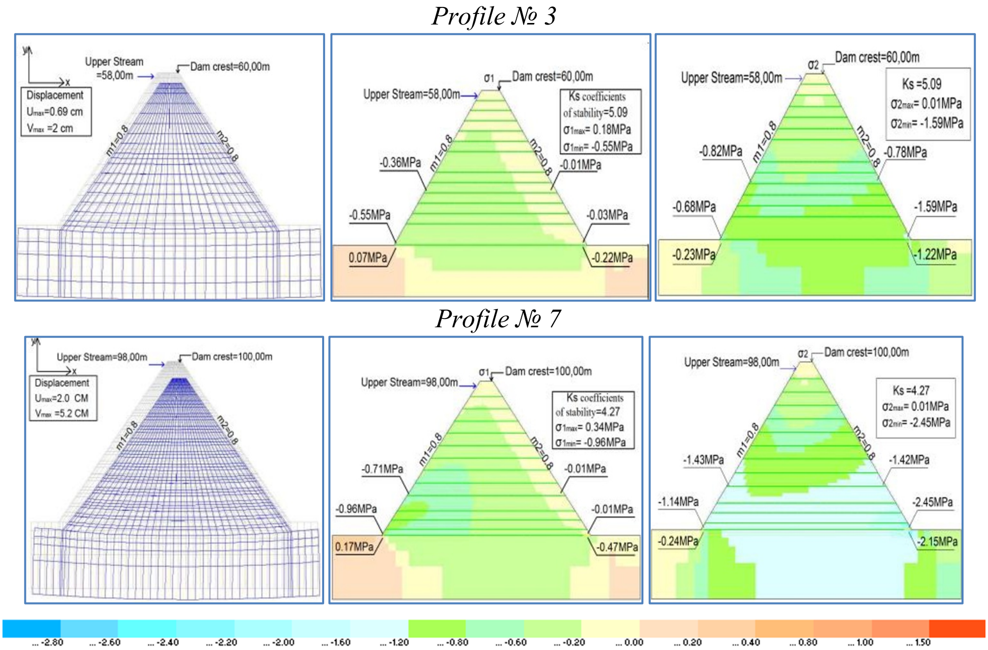

Fig.7. Stress-strain state and stability coefficients of the dam of homogeneous profiles No. 3, No. 7 in accordance with the experiment planning matrix.

5 Conclusions

The considered variants of the dam have high reserves of strength and stability.
The stability coefficients for horizontal construction seams are quite high, despite the low shear parameters, which range from 4.16 near the contact and are significantly higher at the crest of the dam (profile No. 1). It should be noted that at the design load, shear strength violations along the construction seams do not occur in all the profiles considered.

The level of compressive stresses in the dam profile for all the considered variants does not exceed the range of strength properties of the material from 5.0 to 7.0 MPa, depending on the composition (CSG).

The analysis of the obtained results, regression equations, and dam variants are presented below:

1. The maximum horizontal and vertical movement increases with increasing the dam height, and decreases with increasing slope ratio.

2. The depth of the opening of the contact seam is significantly influenced by the modulus of deformation of the dam, and the slope ratio, which are in the range from 0 to 4.5 m.

3. The main compressive stresses in the upstream dam edge are equally affected by all the factors considered, with their increase, the stress values increase, which are in the range from -0.57 to -2.85 MPa.

4. The main compressive stresses in the bottom wedge of the dam are in the range from -1.59 to -6.91MPa and the base from -1.22 to -4.71 MPa, and they increase with increasing modulus of deformation of the dam and the height dam and decrease with increasing slope ratio.

5. The stability coefficient of the concrete-rock contact is most influenced by the slope ratio, and its height, which ranges from k_s = 2.3 to 5.26 for profiles in accordance with the experiment planning matrix.

The obtained regression equations allow us to estimate the parameters of the stress-strain state of dams and solve problems related to the optimization of the dam profile (CSG) in a real project at the preliminary design stages.

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