

Analytical Prediction of Stability of Earthfill Dam

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Abstract - The sloping ground operation of hydraulic structures associated with the collision of landslide phenomena and shear deformations. The work presents the results of research of influence of variability of physical and mechanical soil properties on stress-strain state of an earth-filled dam. To increase the precision of the calculations and reduce the complexity of work to determine the main criterion of safety of dams – factor of stability, made the automation of calculations. Automation is achieved by modeling the stress-strain state of the bulk soil structures by methods of analytic geometry, development of algorithm analysis-energy calculation the stability of the dam, implemented in the computer program "Ustoychivaya nasyp". Established multi-factor regression dependencies of the geometric parameters of the dam from soil strength characteristics allow for the design stage under-collection of the soils for specified parameters of the dams or to set the geometrical sizes of structures based on the mechanical properties of local soils.

Keywords - prediction of stability; stress-strain state; groundwater dam; modeling; safety factor; regression

I. INTRODUCTION

The constant growth of minerals extraction rates leads to an increase in the volume of liquid industrial waste. One of the solutions to the problems of such wastes in order to limit their negative impact on the environment is building groundwater dams.

It is known that the exploitation of groundwater dams is associated with the risk of its destruction and the pollution of surface and groundwater, the surrounding land with toxic substances, the destruction of buildings and structures located downstream of the reservoirs [1].

The integral criterion of the reliability of dams is a factor of sustainability characterized by a minimum ratio limit of the generalized reactive forces of resistance to the active shear forces. Researches of the most part of scientists associated with the development of methods of stability assessment [2], studies of alluvial resistance [3,4] and bulk [5] dams, slope deformations [6], and also strengthening of the foundation [7, 8] are based on the definition of the arguments included in the function of the safety factor of stability. In general, the safety factor is a function of many variables: geometry, hydrostatic and hydrodynamic forces, physico-mechanical properties of soils, external load and impact. Assessment of the sustainability of dams is based on the mechanics of the granular medium [9], while not unambiguously solved the question concerning the choice of the strength characteristics of soils, as their variation even within the same facilities can

be significant. Thus, assessment of the impact of the variability of the soil properties on the safety factor is currently a significant objective.

II THE OBJECT OF RESEARCH

The object of the research is man-induced dispersed incoherent bulk clay soil of dams for storage of liquid wastes of industrial enterprises. The subject of the research is the influence of variability of physical and mechanical properties of soil on the stress-strain state.

As initial data, we used the materials of engineering-geological surveys for earth dams storage of liquid waste of the mining enterprises of Kuzbass. The survey materials were processed, samples of soils were selected: lessons of the same type drilling machine (URB-2A-2); tested on the same devices; a specific geological-genetic complex; above (in natural state) and below (saturated condition) depressionion curve. The results of the study of regularities of changes in the physico-mechanical properties of man-induced dispersed soil clay, bulk of structures, methods of mathematical statistics are presented in [10]. The random character of variations of the resistance properties of soils were identified characterized by the coefficient of variation, depth and area within the dikes, small (up to 4 %) dispersion in density ($1,77 \div 2,19$), a slightly larger (20 %) range of the angle of internal friction ($11 \div 35$) and very significant (up to 69 %) variation of values of adhesion ($0,009 \div 0,113$). In this regard the need arose to predict the stability of the dam considering the whole range of variability of soil properties.

Prediction of stability of sloping soil structures associated with calculations. To increase the accuracy of the calculations and reduce the complexity of work, it is required to determine the main criterion of safety of dams which is the factor of produced automation of calculations.

III. RESEARCH METHODS

Analytical method for prediction of stability with computer modeling of the stress-strain state.

IV. RESULTS AND DISCUSSION

Depending on the angle and the type of soil of the selected dams with the following grounds: horizontal rugged – rocky, sandy and semi-gravelly soils not having a clearly defined stratification, weak contact and weak interlayer; weak

horizontal natural or anthropogenic clay soils; sloping layered soils with a pronounced layering, weak contacts or interlayers.

The model of an earthfill dam is presented in the form of a flat profile with the following elements: the surface is grass-roots and top of the slopes, line of contact with the ground, the sliding surface. Graphically, these elements are defined by straight and curved lines. For modeling of the individual elements of the dam we used Cartesian coordinate system, the beginning of which is the lower edge of the downstream face, the x-axis coincides with the horizontal line, the y-axis reflects the elevation of the dam. The positions of the elements in the plane determined by the equations in coordinate form are given in (Table 1) [11].

TABLE 1. Equations elements of an earthfill dam

Item	Equation	Variables formulas
The lower slope	$y_i^{ho} = \frac{x_i}{m_1}$	m_1, m_2 – the odds of laying the grass-roots and top respectively of the slope; h_0 – the height of the bulk structure, m ; b – crest width, m ; α – the inclination angle of the base, grad.
Comb	$y_i^c = h_0$	
The upstream slope	$y_i^{so} = -\frac{x_i}{m_1} + \frac{m_2 h_0 + b}{m_1} + h_0$	
Base	$y_i = x_i \operatorname{tg} \alpha$	

The equation describing the position of the surface slip is inferred on the basis of research Institute of geometric constructions and the application of the methods of analytic geometry. Surface slip in the body of a dam on horizontal solid ground (Fig. 1) is represented by the curve under the form close to the tangential:

$$y_i = x_i \operatorname{tg} \left(\frac{\alpha_{1-5}}{x_5} x_i \right). \quad (1)$$

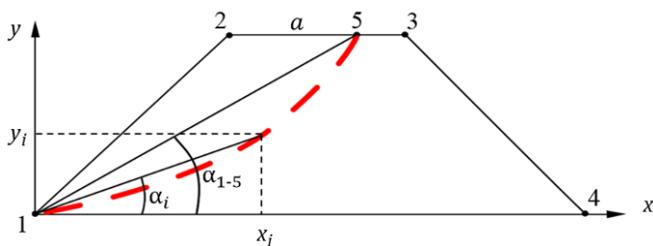


Fig. 1. The scheme of the sliding surfaces in the dam body on horizontal solid ground

In the case of horizontal weak base (Fig. 2) the sliding surface in the body of the dam has round shape described by the equation:

$$y_i = y_{O_1} - \sqrt{R^2 - (x_i - x_{O_1})^2} \quad (2)$$

at the base is close to the arc of a circle:

$$y_i = y_{O_2} - \sqrt{(l_{5-O_2} + \Delta_R [l_{7-5} - x_i + x_7])^2 - (x_i - x_{O_2})^2}, \quad (3)$$

where Δ_R the change of radius from l_{5-O_2} to l_{7-O_2} .

a)

b)

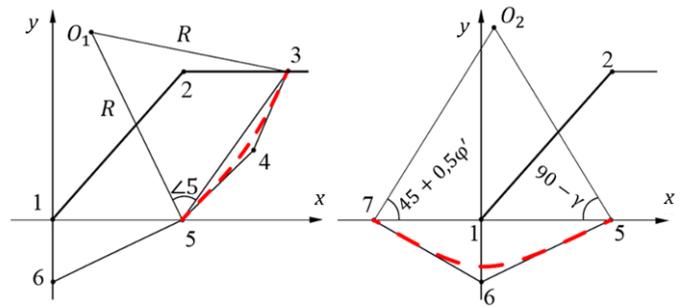


Fig. 2. The shape of the sliding surface for the horizontal dam on weak foundation: in the array (a) and weak base (b)

In the body of the dam with a sloping layered ground (Fig. 3) the sliding surface also has round forms:

$$y_i = y_{O_3} - \sqrt{R^2 - (x_i - x_{O_3})^2} \quad (4)$$

at the base coincides with the line of contact:

$$y_i = x_i \operatorname{tg} \alpha. \quad (5)$$

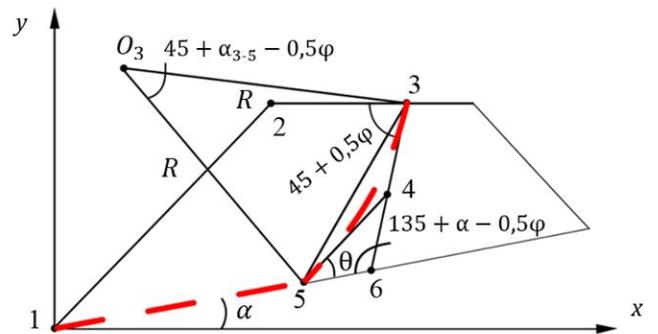


Fig. 3. Building a broken line in the body of the dams on sloping layered base

Checking of the calculations of equilibrium shift and the restraint forces means breaking of the body of the landslide into elementary blocks, three borders which are straight lines (side faces and the slope line), and the fourth curve (the sliding surface). At known coordinates of the corner points the geometrical parameters of the unit and forces operating on them are set (Table. 2).

The reliability of the dam is judged when the method is used of algebraic addition of forces by factor of (6); method vector, addition of forces – the magnitude of the residuals of the polygon of forces, calculated analytically using the coordinates of its corner-check into the conditional system of coordinates.

$$k_f = \frac{\operatorname{tg} \varphi \sum (P_i \cos \alpha_i) + C \sum l_i}{\sum (P_i \sin \alpha_i)}. \quad (6)$$

The algorithm of analytical calculation of factor of stability in the most intense sliding surface for levees on strong, weak and layered grounds is implemented in the computer program "Ustoychivaya nasyp" [12] and is given in the article of the authors [4].

TABLE 2. The parameters of elementary blocks and loads

Option	Equation	Variables formulas
Length of base l_i	$l_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$	$y_{i+1}^{e_n}, y_i^{e_n}$ – subsequent and previous ordinate of the go-containing lines (line no-gas slope or ridge); y_{i+1}, y_i – subsequent and previous ordinate of the sliding surface; ρ – density, t/m^3 и C – the grip of the soil, t/m^2
The inclination angle of the base α_i	$\alpha_i = \arctg \frac{y_{i+1} - y_i}{x_{i+1} - x_i}$	
The side length of $l_{i\text{бок}}$	$l_{i\text{бок}} = \sqrt{(x_i^{e_n} - x_i)^2 + (y_i^{e_n} - y_i)^2}$	
Weight P_i	$P_i = S_i \rho$	
Of adhesion on the grounds $C_{i\text{оч}}$	$C_{i\text{оч}} = Cl_{i\text{оч}}$	
on the side face $C_{i\text{бок}}$	$C_{i\text{бок}} = Cl_{i\text{бок}}$	
Area S_i	$S_i = 0,5 \left[(x_i^{e_n} - x_i)(y_i^{e_n} + y_i) + (x_i - x_{i+1})(y_i + y_{i+1}) + (x_{i+1} - x_{i+1}^{e_n})(y_{i+1} + y_{i+1}^{e_n}) + (x_{i+1}^{e_n} - x_i^{e_n})(y_{i+1}^{e_n} + y_i^{e_n}) \right]$	

Comparison of safety factor computed by different methods (Fellenius, Bishop, Janbu, Morgenstern-price, Spencer, etc.) using known software products (GeoStab, Geo5, Slope/W, Slide) and the programm " Ustoychivaya nasyp" [13 – 16] has shown good convergence of the results, allowing you to use the program for the solution of practical engineering problems (table 3).

TABLE 3. Comparison of results of calculation of safety factor for various programs

Method of calculation	The safety factor obtained for programs				
	GeoStab	Geo5	Slope/W	Slide	Ustoychivaya nasyp
Fellenius	1,76	1,75	-	1,70	-
Bishop	1,75	1,79	1,69	1,79	-
Janbu	1,60	-	1,57	1,63	-
The Morgenstern-Price	1,72	-	1,71	1,72	-
Spencer	-	1,79	1,71	1,75	-
Algebraic the addition of forces	-	-	-	-	1,77

In T. V. Mikhailova [17] it is proved that the physico-mechanical properties of soils have the most significant influence on the safety factor. To estimate the significance of individual properties, the graphical model of the dam was built (horizontal robust base, a height of 5, 10, 15 and 20 m, the coefficient of laying the top and bottom of slopes $m=2$, width along the ridge 5 m, water level of 1 m below the crest), created in "Sustainable mound".

According to the results of modeling of the stress-strain state of the dam, the correlation communications of the safety factor from the variability of the soil properties were built (Fig. 4). The analysis of the received dependences showed that for conditions of Kuzbass the stability of the dike 10 m high is provided with a minimum value of adhesion of primers and

average values of angle of internal friction and density of soil. For higher dams, with an average value of adhesion of soils for the entire range of variability of density and angle of internal friction change of the safety factor is respectively 10 and 30 %, its estimated value exceeds 1.5 at the standard of 1.1. However, the average values of the density [10], angle of internal friction and the grip is less than 0.03 MPa, the safety factor becomes below the standard, and at the minimum grip $C = 0,004$ MPa reaches the critical value of 1.0, indicating a greater probability of formation of the landslide slope. In variation of adhesion from the minimum to the maximum value, the change range of the safety factor reaches 70 %. The communication parameters and the results of the evaluation of its tightness are given in Table 4.

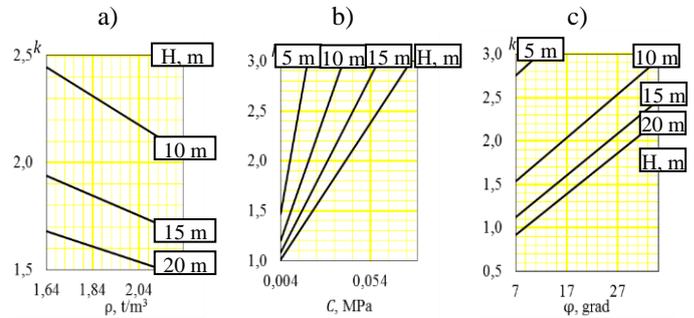


Fig. 4. The dependence of safety factor on the physico-mechanical properties of soil: density (a), adhesion (b) and angle of internal friction (c)

TABLE 4. The communication parameters of the safety factor of the physical and mechanical properties

The height of dam, m	C , MPa	φ , grad	ρ , t/m^3
5	$k_C = 101,67C + 0,99$	$k_\varphi = 0,05\varphi + 2,38$	$k_\rho = -1,29\rho + 6,03$
	0,90 / 0,01	0,87 / 0,01	0,85 / 0,01
10	$k_C = 51,49C + 0,98$	$k_\varphi = 0,05\varphi + 1,18$	$k_\rho = -0,67\rho + 3,55$
	0,89 / 0,02	0,86 / 0,03	0,91 / 0,04
15	$k_C = 35,19C + 0,94$	$k_\varphi = 0,05\varphi + 0,78$	$k_\rho = -0,46\rho + 2,70$
	0,87 / 0,01	0,84 / 0,02	0,83 / 0,02
20	$k_C = 27,42C + 0,90$	$k_\varphi = 0,05\varphi + 0,59$	$k_\rho = -0,35\rho + 2,26$
	0,91 / 0,03	0,85 / 0,01	0,92 / 0,01

The dependence of safety factor from the set of physico-mechanical properties of soil is described by the significant multiple regression equations presented in Table. 5. The resulting regression equation at the design phase allows us to select the characteristics of the soil in which the stability of the dam with specified parameters will be provided.

TABLE 5. The multiple regression equation for the factor of the aggregate physico-mechanical properties

The height of dam, m	The equation	R	Fisher	
			$F_{k\rho}$	F_φ
5	$k(C, \varphi, \rho) = 101,6C_i + 0,05\varphi_i - 1,2\rho_i + 2,4$	0,89	2,80	5231
10	$k(C, \varphi, \rho) = 51,4C_i + 0,05\varphi_i - 0,6\rho_i + 1,2$	0,85		5010
15	$k(C, \varphi, \rho) = 62,0C_i + 0,04\varphi_i - 0,4\rho_i + 0,8$	0,81		2013
20	$k(C, \varphi, \rho) = 27,2C_i + 0,04\varphi_i - 0,3\rho_i + 0,6$	0,85		4225

In the case of a limited variety of soils, it is possible to control the geometric parameters of the dam using the multiple regression equation (Table. 6) or nomograms (Fig. 5).

TABLE 6. The equation of the gradient of the slope groundwater dams of various heights

The height of dam, m	The equation	R	Fisher	
			F_{kp}	F_{ϕ}
5	$\beta(C, \varphi) = 35537C_i + 1,3\varphi_i - 6,4$	0,91	3,7	644
10	$\beta(C, \varphi) = 18824C_i + 1,3\varphi_i - 7,8$	0,85		1385
15	$\beta(C, \varphi) = 12340C_i + 1,3\varphi_i - 7,5$	0,84		2064
20	$\beta(C, \varphi) = 9470C_i + 1,3\varphi_i - 8,1$	0,80		2410

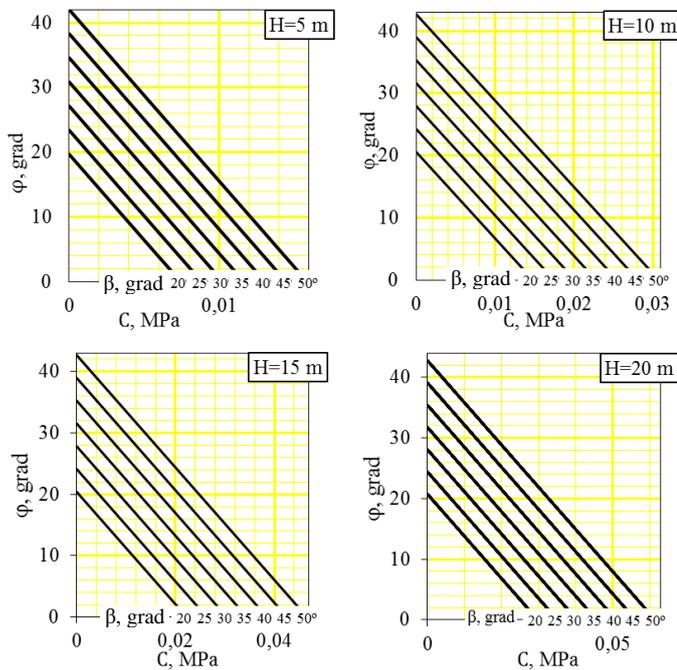


Fig. 5. Nomograms for determining the angle of repose for dams of various heights

V. CONCLUSION

1. Improving of the accuracy and reduction of the complexity of the prediction of stability of grounding of the dam under different types of bases (strong, weak, layered) is ensured by modeling of the sliding surface in the form of the equation of the curve expressed by the analytic geometry methods.

The estimated parameters of elementary blocks shifting and retaining forces acting on the potential sliding surface are expressed through the coordinates of their corner points formed at the intersection of the side faces of the blocks, the surfaces of actions, lines or downstream side of the ridge.

2. the developed analytical method for prediction of stability and the multiple regression equations established by the method of correlation analysis describing the relationship of the angle of slope from the mechanical properties of the soil allow to select at the design stage of the dam the following:

– characteristics of the soil, which will ensure the stability of the dam with specified parameters;

– the angle of the slope to ensure the stable position of the dam of the set height for the existing soil.

The summarized values of physico-mechanical properties of man-induced dispersed soil dams and the software package "Stable Dike" are used by the design institute OAO "Kuzbassgiproshakht" since 2015 in the calculations of the parameters of the designed dams, and also by KuzSTU in the performance of contractual work with industry on assessing the safety of hydraulic structures.

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