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Method for Assessing the Reliability of Earth Dams in Irrigation Systems

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Abstract:

Irrigation systems for irrigated agriculture begin with reservoirs and basins. The latter are formed with earth dams and levees. The reliability and stability of earth dams under static and especially dynamic loading is of paramount importance. Destruction of dam structures, reservoirs, can lead to disastrous environmental and economic losses. The methods and ways to ensure the reliability of earth dams are different. Under static (own weight, water pressure) and dynamic (vibrations, explosions, earthquakes) loads, the strength and stability of earth dams are calculated at the stages of their design. In this case, it is necessary to determine the failure surfaces (surfaces of possible collapse) of the dam slopes. The circular cylindrical method for finding the failure surface (surfaces of collapse) of slopes of a homogeneous earth dam under static (own weight) loading is considered in the paper. It is shown that when the value of the total stability coefficient is greater than unity, there are local sections of the slip line where stability is violated. This circumstance creates the possibility for a fracture line development under seismic loads. It is proposed to take into account seismic stresses in the soil mass based on the solution of basic equations of continuum mechanics. The numerical solution of wave equations for the soil mass is presented by the finite difference method with known boundary conditions and zero initial conditions. The dynamic stress-strain state of earth dam is determined taking into account its moisture content and elastic, viscous, and plastic properties of soil. The ways of considering dynamic stress state when calculating the reliability and stability of earth dams are shown.

1 Introduction

In the complex of irrigation systems, reservoirs occupy a special place. The main structures of the reservoirs are the dams. The dam of the irrigation system, as a rule, is constructed from earth and rock mass. The strength and stability of earth dams under seismic impacts is primarily the key to the smooth operation of the entire irrigation system in agriculture.

The problem of earthquake resistance of earth dams is a classic problem of hydro-technical engineering. The attention of the prominent researchers and specialists all over the world in the fields of irrigation and hydro-technical engineering, soil mechanics, strength of deformable bodies, continuum mechanics, structural mechanics, fluid mechanics, etc., is riveted to the solution of this problem.

Despite the success achieved in the development of various methods for determining, evaluating, and predicting the earthquake resistance of earth dams, research is being intensively and successfully carried out in this direction. One of the latest new publications is presented in [1]. In [1], the seismic reliability of slopes of earth dams during an earthquake was studied, taking into account the variability of strain characteristics of soils and rocks. The seismic effect in [1] was generated by stochastic ground motions based on the time-frequency complete non-stationary model. The great interest in this study indicates the significant urgency of the problem of earthquake resistance of earth dams at present [2-5].

In the last decade, various researches have been carried out in this sphere [6-20]. In addition to the earthquake, a significant danger to earth dams is caused by the erosion of soil particles under the influence of water - the water erosion. The study in [6] was devoted to this problem. The problem of water erosion of earth dams and levees can be complex and dangerous given the internal communications in earth dams, such as culverts [6]. In [6], the mechanisms of gradual destruction of interphase erosion at the boundary were studied by taking into account the influence of the degree of compaction and clay content in the dam body. A study of the reliability and stability of earth dams and levees, taking into account simultaneously two dangerous factors - water erosion and earthquakes, is yet to be done. These two issues are currently addressed separately.

The response of a homogeneous earth dam to a seismic load was analyzed by the finite element method in [7]. There, the general laws of dam behavior were analyzed from the point of view of displacements and fields of stresses, strains, and accelerations [7]. The nonlinear seismic response of the “dam-reservoir” system using the finite element method was studied in [8]. A probabilistic analysis of the seismic hazard of the Sefidrud earth dam near the city of Rudbar (Iran) was conducted in [9]. There, the seismic hazard of the earth dam was estimated taking into account the equation for predicting the ground motion during earthquakes [9].

In [10], an earth dam was considered as homogeneous horizontal layers, considering soil moisture-content. A numerical procedure has been developed to determine the two-phase elastic-plastic seismic response of earth dams [10]. An elastic-plastic nonlinear analysis of the Cope earth dam using a three-dimensional boundary finite element with a scaled polyhedron was carried out in [11]. In [12], the stability of slopes (inclinations) was analyzed by the finite element method taking into account large strains in soil. It was shown there that failure surfaces in the soil mass have developed gradually, and could not be modeled using the traditional method of limit equilibrium [12].

A simplified method for constructing a slip curve of a slope strain was proposed in [13]. The analysis of seismic strain of the slope was carried out taking into account the peak and residual shear strain of soil. The effect of soil mechanical characteristics on the value of slip displacement using the methods of continuum mechanics was shown in [13]. A calculation method for analyzing the time-history of the dynamic stability of a three-dimensional slope was developed in [14]. The use of spectral-random functions, with a decrease in size in combination with a random process of soil motion, provides seismic reliability of complex nonlinear three-dimensional slopes as the authors of [14] have shown by stochastic analysis.

Changes in mechanical characteristics of soil in the dam space and their influence on seismic response of earth-fill dam were studied in [15]. A nonlinear analysis was performed based on several earthquake records, with a stochastic representation of mechanical characteristics of soil in space [15]. In [16], seismic stability of a dam 300m high was considered and solved, taking into account the sliding and relaxation of soil strain by the finite element method under impulse motions. The dynamic stability parameters of a dam with internal inhomogeneity were determined in [16].

In [17], an empirical technique was proposed for estimating the shear wave velocity in a dam core and an empirical relationship between the average effective stress determined by the finite element method and the shear wave velocity in a dam core. In [18], the general effect of ruptures in the earth dam body on its safety was discussed.

Experiments on the safety of earth dams have been the subject of studies in [19-20]. In [19], the seismic safety of a rock-fill dam was estimated by the method of dynamic modeling in a centrifuge. The influence of the time variation of the stone material on the seismic response of the dam was determined. In [20], experimental studies of a rock-fill high-rise dam were carried out on a large-scale model. A series of tests of the dam model under various types of seismic excitation with different magnitudes were carried out. The zones of maximum accelerations and residual strains in the soil mass of the dam were experimentally determined. Dynamic characteristics of the dam were determined under different simulations of a seismic load [20].

Thus, the reliability and stability of earth dams, levees, slopes, and inclinations are determined and evaluated mainly by three methods:

1. by experimental ways that require huge material and financial costs. Therefore, the studies devoted to experimental research of dynamic behavior of earth dams are few. However, to assess the reliability of theoretical results on seismic resistance of dams, levees, the results of experiments are of great value;
2. by engineering methods. The seismic resistance of earth dams in most cases is estimated by simple and practical engineering methods that do not require large amounts of computation. A review of engineering methods and their advantages and disadvantages are given in detail in [21]. The main

problem of engineering methods is the correct determination of the failure surface in the dam body. This issue was also investigated in [21] and a new method for its determination was recommended;
3. by the methods of continuum mechanics. This method is based on the determination of the stress-strain state of the soil mass using complex equations of state of soils, taking into account their rheological properties [22-25] and nonlinear structural changes [26-29] under strain. The problems considered there are usually solved by numerical methods. A review of numerical methods for solving the problems of earthquake resistance of earth dams and their advantages and disadvantages are given in [30];
4. This work aims to develop the method for determining and assessing the seismic reliability of earth dams using the advantages of the latter two ways of studying the earthquake resistance of earth structures.

2 Methods

2.1 Circular cylinder method for determining the safety of earth dams

One of the main issues related to assessing the safety of earth dams, as well as determining the dimensions of a possible sliding triangle, is the construction of the most probable failure surface. It is generally accepted that the value of the safety factor *K* of the dam slope is defined as the ratio of the sums of restraining and shear factors acting along the most probable failure surface, which, by name, should be determined so that the value of *K* has a minimum value. In the general case, the value of *K* is defined as the ratio of two curvilinear integrals along the failure (slip) line. The criterion for soil destruction in the form of the Coulomb-Mohr law is adopted along the entire failure surface. At the limit stressed state of the soil mass, the formula representing the stability coefficient has the form:

$$K = \frac{\Psi_u}{\Psi_s},$$

where Ψ_u, Ψ_s are the restraining and shear factors acting along the most probable failure surface.

The forces acting along a possible failure surface, or in the case of a circular cylindrical failure surface, for homogeneous earth dams, according to the Terzaghi method of moment forces relative to the central axis of the cylinder, can serve as these factors. If L is the arc coordinate of the slip line (2.1), the shape and position of which are known, then the curvilinear integrals can be replaced by determined ones and the value of the safety factor *K* can be found by the formula:

$$K = \frac{M_u}{M_s} \text{ или } K = \frac{F_u}{F_s}.$$

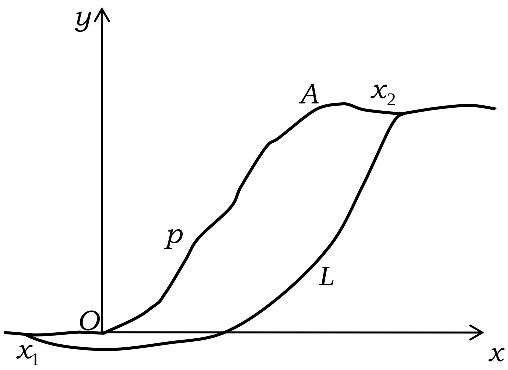

Figure 2.1 – Calculation scheme of earth dam slope

In the case of an inhomogeneous and arbitrary profile of the dam slope, the formula for determining the stability coefficient has the form, as in [1]:

$$K = \frac{\int_L \tau_u dL}{\int_L \tau_s dL} = \frac{\int_L [f\sigma_N + c] dL}{\int_L \tau_N dL} \quad (2.1)$$

or

$$K=\frac{\int_{x_1}^{x_2}\left[f_\gamma\left(y_1-p\right)\cos\alpha+\frac{c}{\cos\alpha}\right]dx}{\int_{x_1}^{x_2}\gamma\left(y_1-p\right)\sin\alpha dx}, \qquad (2.2)$$

where τ_u is the restraining stress and τ_s is the shear tangential stress; γ is the specific gravity of soil; c and f - are the cohesion and coefficient of the angle of internal friction of soil $f=\mathrm{tg}\varphi$; α is the angle between the tangent lines of the sliding surface and the vertical line; p is the function that describes the surface profile of the dam slope; y_1 is the function expressing the failure surface: x_1 and x_2 are the abscissas of the boundaries of the failure surface (2.1).

It should be noted that due to the inhomogeneity and geological features of the soil slope, the specific gravity, cohesion, and the coefficient of the angle of internal friction depend on *x, y* coordinates, and the functions p and y_1 are the arbitrary functions of x.

A function that describes the profile of a flat slope surface (2.2) has the form

$$p=\begin{cases}0 & x<0,\\ x/m & 0\le x\le x_A,\\ h & x\ge x_A,\end{cases}$$

where $h=y_A$ is the slope height, $m=x_A y_A^{-1}=x_A h^{-1}$ is the slope ratio coefficient. In the case of a circular cylindrical sliding surface, the function describing the profile of the failure surface, according to the circular cylindrical surface (circular arc), has the form $y=y_C-\left(R^2-\left(x-x_C\right)^2\right)^{-1/2}$, where $\left(x_C, y_C\right)$ and R are the coordinates of the center and the radius of the circle, the arc of which describes the profile of the proposed failure surface.

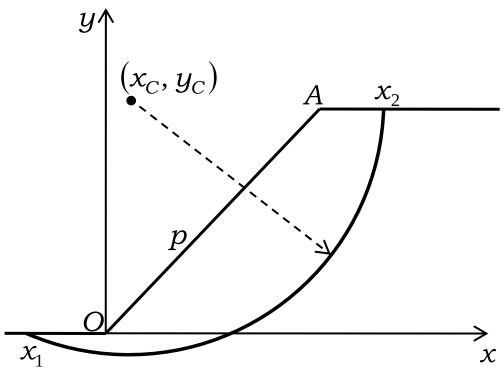

Figure 2.2 – Calculation scheme for a circular cylindrical sliding surface

This shows that the function y is continuous and continuously differentiable, and the function p is continuously piecewise differentiable. When calculating the safety of dam slopes by this method, the problem is to find a circular cylindrical surface where the stability coefficient has a minimum value, or for function (2.2) there is a point $\left(x_C, y_C\right)$ and radius R at which it has a minimum value.

2.2 The implementation of the method for determining the circular cylindrical sliding surface

From an analysis of publications presented in the introduction, the methods for calculating slope stability and strength of earth dams, it follows that there is no single approach to determine the proposed center and radius of a circular cylindrical sliding surface.

In this section, we propose one of the methods for determining the center and radius of a circular cylindrical sliding surface and for calculating the slope stability coefficient, i.e. stability and reliability of earth dams. For this, an algorithm has been created and a program has been drawn up to calculate the slope stability of earth dams. In addition to the mechanical and strength characteristics of the dam, the geometrical data of the near-slope zone of the dam are also set as the initial ones (2.3). The origin is attached at the slope intersection with the base (point O). The search area of the point (x_C, y_C) - the center of the circular cylindrical surface includes (the shaded area in 2.3): the coordinates of the slope top (x_A, y_A) (point A), the coordinates of point B (x_B≈(5÷10)·x_A) and the ordinate of the upper point D (y_D≈(5÷10)·y_A), and the abscissa of the point *a* x_a≈(5÷10)·x_A.

The region of the assumed center of the circular cylindrical sliding surface (shaded area in 2.3) is divided into N_x and N_y subdomains (grids). For each node of this grid, varying the values of the radius of the circular cylindrical sliding surface from the values aR to the least one (equal to the distance of the perpendicular from the center to the dam slope), the stability coefficient is calculated by formula (2.2) and the radius is fixed, which causes the least value of the stability coefficient of the circular cylindrical surface. Further, from the totality of results of stability coefficients and radii, for all nodes, a center of the circular cylindrical sliding surface is selected corresponding to the minimum value of the stability coefficient. Such a procedure for finding the center of a cylindrical surface requires a huge amount of computation. However, it defines the center more reliably. Another variant of finding this center was proposed in [20]. For analysis, the program prints ten such centers (the coordinates of the centers) and the corresponding radii of the circular cylindrical sliding surface and the values of the stability coefficients.

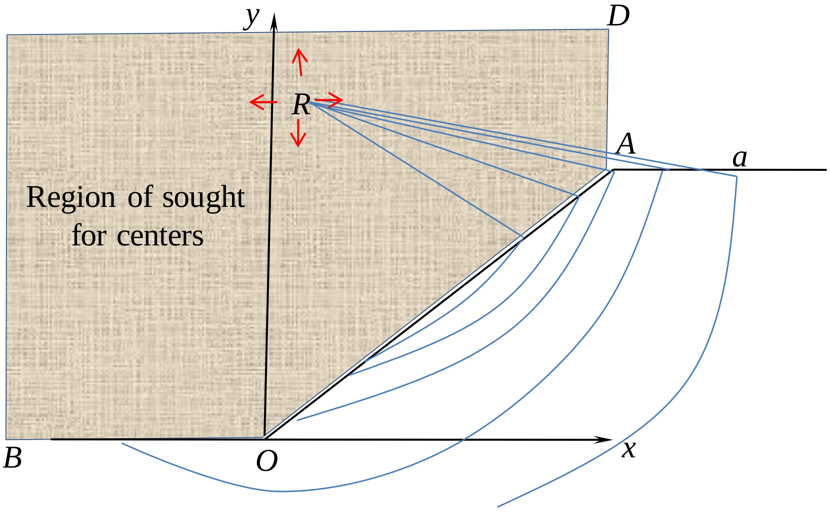

Figure 2.3 – Design scheme for setting the initial geometrical data

It should be noted that assuming sufficiently large values of N_x and N_y, it is possible to determine with the necessary accuracy the sought for center and radius of the circular cylindrical sliding surface. The calculation program was modified to sequentially determine the center of the circular cylindrical sliding surface. Based on the 10 values of the centers found, a new region of the sought for centers is automatically compiled containing these centers and its circle. Then, the finding of the next new centers and radii of the circular cylindrical sliding surface are repeated.

The calculations showed that for an optimal determination of the center and radius, 2-3 stages of such approximations are sufficient.

Note that the program is designed in such a way that it is possible to set different slope profiles (two, three, or multi-stage, in the form of a curved function, as shown in 2.1) and to account the inhomogeneity of the soil mass.

3 Calculations results and their analysis

Consider the slope of a homogeneous earth dam of low height ($h = 20$ m) and an angle of incidence $\alpha = 45°$ at the following physical and mechanical characteristics: density $\rho = 2000$ kg·m^{-3}; specific weight $\gamma = 18.5$ kN·m^{-3}; specific cohesion $c = 30$ kPa; angle of internal friction $\varphi = 30°$. 3.1 and 3.2 shows the obtained profile of a circular cylindrical sliding surface and a diagram of the restraining and tangential shear stresses along this surface. In 3.1 and 3.2, the dashed curve x_1x_2 corresponds to the most dangerous circular cylindrical sliding surface, and the curve ab corresponds to diagrams of shear stresses. The lines on the diagrams have a length $l = \tau(\rho g)^{-1}$ ($g = 9.81$ m/s²). The tangential stress values are $\tau = l\rho g$.

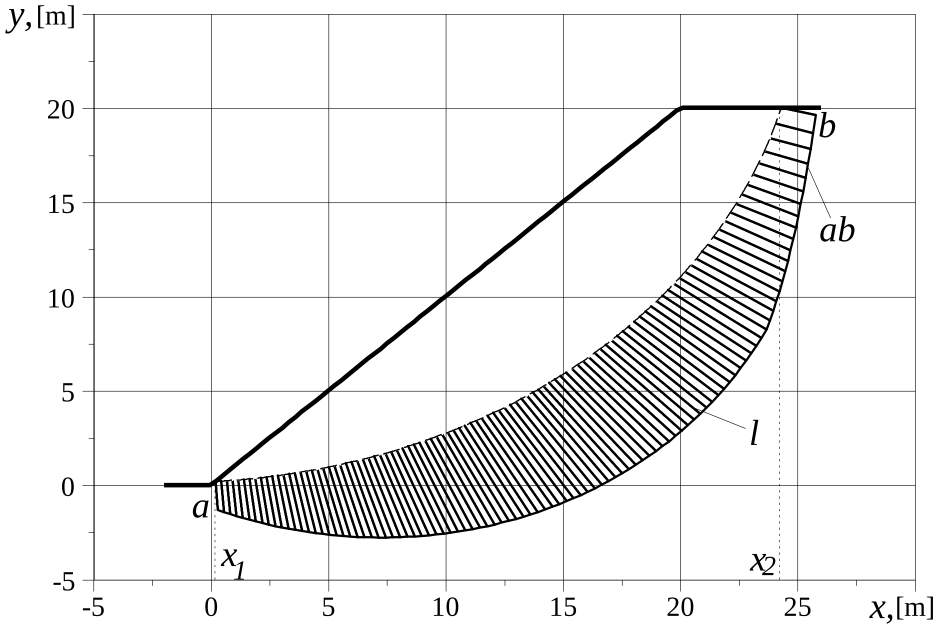

Figure 3.1 – The sliding surface and the diagram of the restraining tangential stresses along the surface

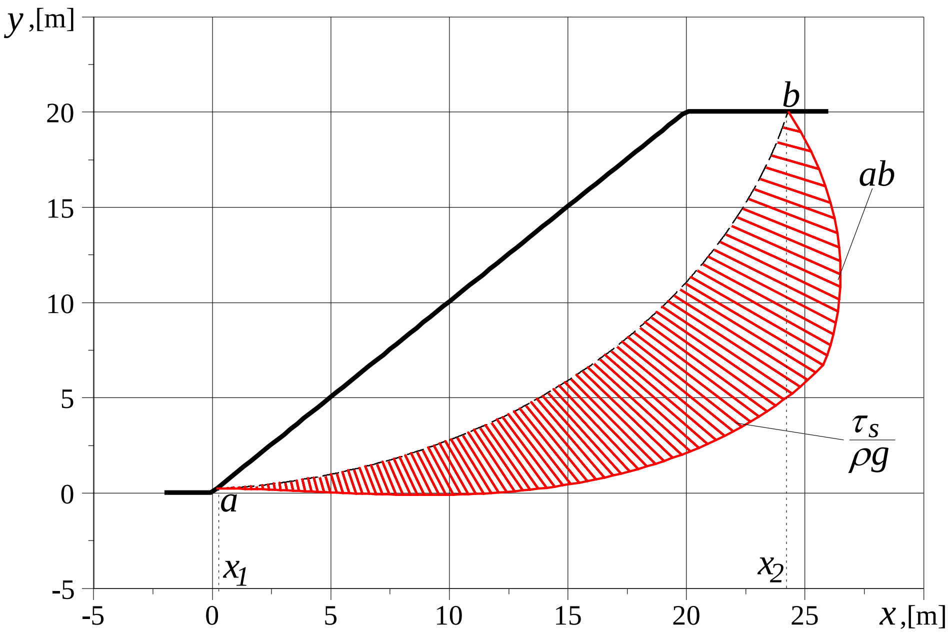

Figure 3.2 – The sliding surface and the diagram of tangential shear stresses along the surface

3.1 shows the obtained values of the stability coefficient determined from relation (2.2) and the parameters (radius, center coordinates, abscissas of the boundaries of the circular cylindrical sliding surface) for the ten most dangerous sliding surfaces.

Table 3.1 – Stability coefficient and sliding surface parameters

K	R, m	x_c, m	y_c, m	x_1, m	x_2, m
1.3654	26.7409	-1.5192	26.8856	0.2	24.32
1.3658	26.8235	-1.2990	26.9816	0.2	24.60
1.3660	26.6614	-1.7422	26.7906	0.2	24.04

1.3668	29.0468	-2.7042	29.1013	0.2	24.88
1.3669	26.9093	-1.0816	27.0788	0.2	24.88
1.3670	28.9448	-2.9177	28.9764	0.2	24.60
1.3674	29.1523	-2.4934	29.2277	0.2	25.16
1.3675	26.5853	-1.9680	26.6968	0.2	23.76
1.3680	28.8462	-3.1341	28.8529	0.2	24.32
1.3684	24.8986	-0.3322	25.0930	0.2	24.04

As can be seen from 3.1, the stability coefficient of the considered dam slope in all cases is greater than unity. The dam slope in this case is quite stable. However, 3.2 shows that tangential shear stresses, at heights from 5 m to 15 m, exceed the restraining stresses. The total ratio of the area of restraining and shear stresses diagrams gives a stability coefficient of 1.3654.

3.3 shows the diagrams of shear (curve 1) and restraining (curve 2) shear stresses for the case when tgφ=0.36. 3.3 shows that in the upper parts of the slope the shear forces significantly exceed the restraining forces, and in the lower parts, on the contrary, the restraining forces exceed the shear forces. The ratio of these diagrams is equal to the slope stability coefficient - 1.2579. These results show that the calculation of the stability and safety of earth dams under static, and especially dynamic impacts, must be carried out differentially, taking into account the above factors and the strain characteristics of the soil mass.

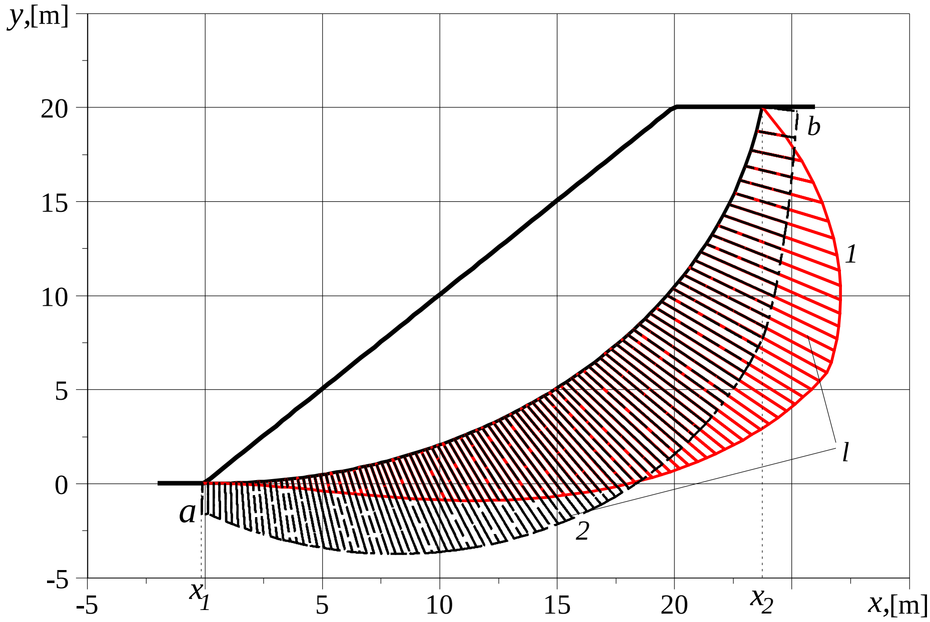

Figure 3.3 – The sliding surface and the diagram of shear (1) and restraining (2) stresses along the sliding surface

In cases of inhomogeneous dams, finding the sliding surface is more complicated. In this case, the sliding surface is not cylindrical and its location is found by the method described in [21].

In [31], the problem of determining the stress-strain state of earth dams was considered, taking into account the dam core and structural changes in soil, where the maximum stresses under seismic impact occur on stone fills, i.e. on the dam slopes. The values of horizontal stresses approximately two times exceed the vertical ones. Due to a decrease in the strength characteristics of the dam core, the stress state fluctuates within 0.05 MPa [31]. The stresses arising according to calculations [31] under the influence of the set seismic load are permissible for the operation of the dam under consideration.

4 Conclusions

As the results in [31] show, the stress-strain state of the earth dam slope in different parts of the soil mass is characterized by different stress states. In the general case, depending on the stresses arising, some areas of the soil mass may be in a limit or beyond-the-limit stress state, and some areas will not reach a limit state as in 3.1 and 3.3. In areas where the beyond-the-limit stress state of soil is possible, it will be displayed only by local instability. This does not mean a violation of slope stability as a whole. The stability of the soil mass is determined by the relation of the maximum permissible stresses for a given soil to the stresses actually occurring in the failure surfaces, according to the relations (2.1) or (2.2).

Hence, following [1], a method is proposed for assessing the stability of homogeneous soil slopes, combining two calculation approaches: the assumed sliding surface is considered to be circular cylindrical surface and in calculations by formula (2.1) or (2.2), the stress state is supposed to be determined from the solution of the two-dimensional problem of continuum mechanics as shown in [26]. In this case, the normal and shear stresses acting on the site, and forming an angle θ with the horizon (with the *x* axis), are calculated by the formula:

$$\sigma_{\mathrm{N}} = \sigma_{xx}\sin^2\theta + \sigma_{yy}\cos^2\theta - 2\tau_{xy}\sin\theta\cos\theta\ ,$$

$$\tau_{\mathrm{N}} = \tau_{xy}\left(\cos^2\theta - \sin^2\theta\right) - \left(\sigma_{xx} - \sigma_{yy}\right)\sin\theta\cos\theta\ ,$$

where σ_{xx}, σ_{yy} and τ_{xy} are the stress values obtained from the solution of the two-dimensional problem [26]. In the case of considering a dynamic non-stationary problem, the greatest value of stress is taken, that occurs during the considered time. Thus, using the normal and tangential stresses along the line of the sliding surface, it is possible to determine the stability coefficient of the earth dam. However, the whole difficulty lies in determining the estimated sliding surface corresponding to the least value of the stability coefficient. Therefore, the problem of assessing stability is a statically indeterminable problem. For the case of an arbitrary unknown sliding surface, the task becomes more complicated. The essence of the proposed method for assessing the stability of earth dams is to accurately find the most probable (dangerous) sliding surface using the stress-strain state of the earth dam.

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