Stability of dam slopes taking into account anisotropy

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Abstract. This paper presents the results of experimental studies on the deformation and strength anisotropy of gravel-pebble soils used in soil dams. During stabilometric tests, varying shear angles were obtained for stone at different orientations of soil particles in the working chamber, whether horizontal or vertical. As the hydrostatic pressure in the working chamber increased to 0.8 MPa, a reduction of shear angles of a stone by 8–12 degrees depending on the direction of layering of soil was observed. The authors compiled a calculation program called OTKOS_Ani (Delphi), which considers the strength anisotropy of pebble soils for calculating the stability of slopes of soil dams and slopes. The slope calculations were carried out for different design and height of stone and stone-soil dams, and correction factors for taking into account the strength anisotropy in slope stability calculations, \( k_{an} \), were obtained depending on the type, height, and density of gravel-pebble soil stacking in the dam body. The results showed that considering the anisotropy of strength properties in the calculations of slope stability of earth dams reduces the safety factors by 3–11%. This should be taken into account when selecting the design of earth dams with prisms of gravel-pebble soils.

Keywords: deformation anisotropy, strength anisotropy, passport of gravel-pebble soil, triaxial experiments, slope stability, stress-strain state of soil dams.

1 Introduction

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2 Methods

- Methods of determining the anisotropic properties of soils used in geomechanics have a long history of research by many scientists, including Lekhnitsky S.G. [4], Zenkevich O. [5], K. Wolf, L. Barden, Abelev M.Yu. [6], Boldyrev G.G. and Idrisov I.Kh. [7, 8], Goldstein M.N. and Lapkin V.B. [9], Nabokov I.M. [10], School [11], Ter-Martirosyan Z.G. [12, 13], Korobova O.A. [14], and others. Studies of slope stability, taking into account the anisotropic structure of soil and rock massifs, are presented in the works of Zerkal and Fomenko [15], Kremnev, Vishnyakov, and Sedun [16], and others.

- Most of these works consider rock massifs (slopes) with different angles of stratification of weaker in strength layers, lenses, along which different strength parameters of the material are set apart from the whole massif. The aim of the present investigation of anisotropic properties of gravel-pebble soils was to obtain differences in strength properties of bulk soil depending on its stress-strain state, in particular, depending on the position of the main stress area in the soil with respect to the direction of the layering axis of the gravel laid into the dam body.

To reveal the anisotropic properties of gravel-pebble soil, the experiments were carried out with horizontal and vertical orientation of particles by a larger diameter when putting them into the working chamber, thus simulating horizontal and vertical layering. The minimum size of oriented particles with an aspect ratio greater than 3 was 10 mm on the smaller dimension. In both the compression and triaxial experiments, the main stress $\sigma_y$ was directed vertically. Thus, the experiments determined the mechanical properties of the soil along and across the layering axis. Each experiment was performed five times. The obtained results of strain anisotropy tests for gravel-pebble soil in all experiments gave

Additional Note:

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higher strain moduli for vertically placed soil particles (along the stratification axis) than strain moduli for soil particles placed perpendicularly to the acting load. The anisotropy coefficient determined from the strain modulus ratio as $\eta = \frac{E_x}{E_y}$ (for the initial strain moduli) in the odometric tests varies in the range from 1.2 to 1.7 [17]. The anisotropy coefficient of gravel-pebble soil was tested using a vacuum stabilometer, which yielded results ranging from 1.7 to 1.9 [18]. Another test conducted using a large triaxial stabilometer at a compression range of 0.2 to 0.8 MPa showed that the anisotropy coefficient ranged from 1.2 to 1.4 [19, 20].

It is well-known that the shear strength of soils depends on the applied stresses, with the shear angle $\phi$ reaching its maximum value at low stresses $\sigma$ and decreasing as the stresses increase [21, 22]. Based on the triaxial test results, Mohr's circles were constructed from experimental data for two different layering orientations to determine the variation in soil shear angle $\phi$ with axial and normal pressures. The relationship between the shear angle $\phi$ and the principal stresses $\sigma_1$ and $\sigma_3$ is determined by the Coulomb-Mohr strength condition given by Equation (1):

$$\sin \phi = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3}$$

3 Results

Research conducted using uniaxial compression apparatus, full compression apparatus, and large triaxial stabilometer indicated that the deformation behavior of gravel-pebble soil in a dam is dependent on the orientation of layering. Mohr circles were constructed from experimental data for two different layering orientations to determine the variation in soil shear angle $\phi$ with axial and normal pressures. The relationship between the shear angle $\phi$ and the principal stresses $\sigma_1$ and $\sigma_3$ is determined by the Coulomb-Mohr strength condition given by Equation (1):

$$\sin \phi = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3}$$

![Fig. 1. Soil strength passport for horizontal layering.](image-url)
Using the obtained values of shear angles, approximate relationships were constructed for the two different layering orientations, which are presented in the form of Equations (2) and (3) below:

For horizontal layering (\(\varphi_\parallel\)):
\[
\varphi_{\text{max}} = 1.57\sigma^2 - 8.56\sigma + 52.86
\]

For vertical foliation (\(\varphi_\|\)):
\[
\varphi_{\text{min}} = 1.27\sigma^2 - 8.97\sigma + 50.78
\]

Here, \(\sigma\) is the normal stress applied on the shear pad, measured in MPa.

As can be seen, in contrast to the deformation properties, the value of shear angles for the gravel-pebble soil in the stratification direction \(\varphi_\|\) is lower than the values of shear angles in the direction across the stratification \(\varphi_\perp\) (\(\varphi_x < \varphi_y\)). The functions \(\varphi = f(\sigma)\) obtained in the experiments as a function of the normal pressure at the shear pad and the orientation of the foliation axis with respect to the direction of the main stress at the shear pad (Fig. 3) correlate with the experimental data presented in the works of Rasskazov L.N. [23] and Kagan A.A. [24].

Based on the graphs of the \(\varphi_{\text{max}} = f(\sigma)\) and \(\varphi_{\text{min}} = f(\sigma)\), the function of the ratio of soil shear angles depending on the normal stress \(\Psi = \varphi_{\text{min}} / \varphi_{\text{max}} = \varphi_x / \varphi_y = f(\sigma)\), which graph is shown in Fig. 4, can be obtained.
The difference in strength characteristics of gravel-pebble soil depending on the position of the stratification axis in relation to the principal stress area (PSA) at some point of the soil at the shear pad can be represented as a hodograph of shear angles changing according to the law of the ellipse. The values of shear angles of the material at the location of the main stress area along and perpendicular to the axis of soil layering are taken as the largest and smallest radius of the ellipse semi-axis. The direction of the layered material axis on the hodograph is assumed to be horizontal, along the x-axis. Thus, in experiments with a horizontal arrangement of particles, the principal stress vector (axial compression) is perpendicular to the stratification axis, and the main stress axis (MSA) is parallel to the stratification axis of the material. In this experiment, the shear angle takes the highest value: $\phi_{\text{max}} = b$, which is deposited on the large (vertical) semiaxis of the ellipse (Fig. 5).

In the experiment with vertical orientation of the particles in the working chamber, the shear angle is smaller: $\phi_{\text{min}} = a$, and it is plotted on the horizontal axis (Fig. 5), with the MSA perpendicular to the layering axis of the material.

For an arbitrary direction of the main stress in relation to the axis of layering of the material, which is taken at an angle $\alpha$, we can obtain an expression for the value of the shear angle based on the canonical equation of the ellipse, which in the Cartesian coordinate system is written in the form:

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1$$

where $a$ and $b$ are values of the major and minor semi-axes of the ellipse.

Fig. 4. Ratio of shear angles of gravel material $\frac{\phi_{\text{min}}}{\phi_{\text{max}}}$ as a function of the normal stress at the shear site.

Fig. 5. Calculation scheme for determining the values of $\phi = f(\alpha)$.
Any material point on the surface of the ellipse (p. M) defines the direction of the principal stress in the form of a vector connecting the origin of coordinates (intersection of the major axes of the ellipse) with the point itself, and the angle between the direction of the principal stress and the axis of layering is defined as the angle $\alpha$, where $0 \leq \alpha \leq \frac{\pi}{2}$.

For $p. M$ on the surface of the ellipse, the value of the shear angle is determined by the value of the radius vector $\varphi$. To determine $\varphi$ from the known angle $\alpha$, we can write the equation of the ellipse in parametric form:

$$
\begin{align*}
\varphi_x &= \varphi \cdot \cos \alpha \\
\varphi_y &= \varphi \cdot \sin \alpha
\end{align*}
$$

After substituting (5) into (4), we obtain the expression for $\varphi$:

$$
\varphi = \sqrt{\frac{a^2 \cdot b^2}{b^2 \cdot (\alpha + a)} + a \cdot \alpha}
$$

Thus, the value of the shear angle $\varphi$, taking into account anisotropy depending on the angle $\alpha$ can be determined by formula (6). The values of shear angles $a$ and $b$ included in expression (6) are determined by functional dependences (2) and (3), depending on normal stress at the shear area (Fig. 3).

To determine the trajectories of main stresses in design elements of dams and solve problems about stress-strain state of the dam, including those taking into account deformation anisotropy of soil, the angle $\alpha$ can be obtained at each point of the collapse surface.

The authors have developed mathematical models of changes in the strength properties of the material, i.e. depending on the angle $\alpha$, can be determined by formula (6). The program was tested by comparing the obtained results with the results of calculations by "Otkos" program, developed and used in the practice of calculations at the GIS department of Moscow State Building University for more than 30 years.

The series of calculation problems included structures of homogeneous dams, dams with a central core, concrete faced soil dams and dams with a diaphragm. Typical dam constructions were considered in different heights: 20m, 50m, 150m, 200m, 250m, 300m and different slope ratios, which was taken equal for upstream and downstream prisms.

1:1.6 and 1:2.4 slope ratios were considered.

The interface of the program complex with calculations is shown on pic. 6 for rock fill dam with 200m high diaphragm and 1:2,4 slope ratio.
Fig. 6. Calculation of stability of dams with and without strength anisotropy for 200-m high dam.

Nomograms for determination of correction factor $k_{an}$ for taking strength anisotropy into account in slope stability analysis of the groundwater dams were prepared by the results of calculations in Fig. 7 (for concrete faced soil dams) and in Fig. 8 (for dam with central impervious element):
Fig. 8. $k_{an}^H$ for considering of strength anisotropy of soil dams with central impervious element.

4 Discussions

$K_{an}^H = k_{an} \cdot K_n$

$k_{an} = 0.89$

5 Conclusions

$E_x > E_y$

$\eta = \frac{e_x}{e_y}$

$(\varphi_x < \varphi_y)$
depends on the type of dam (with screen, with diaphragm, with core), height and density of soil stacking in the dam buttress prisms. According to obtained diagrams on Fig. 9÷12, coefficient values change in the range of 0.89 - 0.97, which gives a reduction of slope stability coefficient by 3-11%.

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References


