Deformation stability of a dam of tilt anisotropic structure

Baimakhan A.R.\textsuperscript{i)}, Salgarayeva G.I.\textsuperscript{ii)}, Rysbayeva A.R.\textsuperscript{iii)}, Seinasinova A.A.\textsuperscript{iv)} and Baimakhan R.B.\textsuperscript{v)}

\textsuperscript{i)} PhD student, Kazakh National University. Almaty, Kazakhstan.
\textsuperscript{ii)} Candidate of Tech. sciences, Kazakh State Women's Pedagogical University. Almaty, Kazakhstan.
\textsuperscript{iii)} Candidate of Tech. sciences, Kazakh State Women's Pedagogical University. Almaty, Kazakhstan
\textsuperscript{iv)} Candidate of Tech. sciences, Kazakh State Women's Pedagogical University. Almaty, Kazakhstan
\textsuperscript{v)} Doctor of Tech. sciences, Kazakh State Women's Pedagogical University. Almaty, Kazakhstan.

ABSTRACT

The work presents the results of studies of the deformed state of the dam of a new construction, with a slope of layered anisotropic structure, which consists from local geomaterials and geogrids filled with local soils and geotextiles.

Keywords: soil, dam, anisotropy, stress, strain

1 INTRODUCTION

In the Republic of Kazakhstan around 6 million people live in the area of the possible impact of mudflows. This is one third of the population of the Republic, and around 40\% of industrial enterprises are located in that area. Over the past 5 years, from 2010 onwards, almost all areas of Kazakhstan have been the element of water with large loss of life. Most landslide and mudflow areas are the northern region of the Tien Shan Mountains, the northern slopes of Zailiskiy Alatau and the foot of the Altay-Tarbagatay mountain systems. Just around the Southern capital of Republic of Kazakhstan – Almaty, in the mountains gorges 17 dams hanging on the numerous mountain lakes can be observed. The city is under real threat of the breakthroughs of these outdated dams. During the last three years of them have been damaged. Just this year the mudflow flooded 450 houses on 40 streets of Almaty. And in the last 5 years in the Almaty region, unable to withstand the power of the stone mudflow, 5 dams were destroyed, entailing 45 victims.

The paper proposes the new construction of the dam, which is being built by heterogeneous layers. It describes a technique for the construction of layers and method of laying geogrid filled with various soils. The geomaterials used for the construction of the dam consist of local hard sand, gravel, small stone, hard clay and boulders. Each layer within its thickness is uniform anisotropic. Between the inclined layers high strength waterproof geotextiles are laid. Layers of geogrids and geotextiles are interconnected by rigid coupling. Various deformed conditions of the dam for different angles of inclination of the dam layers are investigated by finite element method.

2. NEW CONSTRUCTION OF ANTIMUD SLIDE PROTECTION DYKE

The paper proposes the construction technology of antimud slide protection embankment dam to be built by inclined layers of geosynthetic materials. The layers consist of geogrids filled with local soils of different composition and structure. Black dots show the layers of geogrid and geotextile.

Fig. 1. The construction of the dam of antimud slide protection, consisting of: 1 - waterproofing geotextiles; 2 - geogrids, filled with stones from the ground; 3 - geogrids, filled with small stones and soil.
Further by exploring different strain states, the optimal angle of laying the sloping layers φ is determined.

The proposed construction is shown in Figure 1 in the form of horizontal layers investigated by finite element method. Using the analysis of the results, the paper establishes the most stable angle of laying inclined layers. The boundary conditions of the problem: the ground surface of the computational domain are free of loads, and they are given by the normal components of stress components and \( \sigma_n \) and \( \tau_n \) (figure 2).

Fig 2. Geomechanical and finite element model of the dam with a base

Lateral boundaries of the base can not move in the direction of the horizontal axis of the Cartesian coordinates. The shift along the vertical component is allowed. The base of the computational domain is rigidly fixed. The thick lines show the screen by hitting debris flow and plate on the crust of the dam. Sizing base lengths \( L \) and height \( h \) has called for the implementation of numerical experiments on the hypothesis Dinnik (Yerzhanov et al, 1971).

4. GEOMECHANICAL MODEL OF DAM.

For the simulation of the proposed construction of the dam, the obliquely layered anisotropic array model should be applied / 1 /, (EAMB model) / 2 /.

\[
\begin{align*}
\sigma_x &= c_1 \varepsilon_x + c_{12} \varepsilon_z + c_{13} \gamma_{xz}, \\
\sigma_z &= c_{31} \varepsilon_x + c_{33} \varepsilon_z + c_{35} \gamma_{xz}, \\
\tau_{xz} &= c_{53} \varepsilon_x + c_{55} \varepsilon_z + c_{55} \gamma_{xz}.
\end{align*}
\]

(1)

Which contains horizontal layering of 5 independent coefficients.

\[
\begin{align*}
n &= E_t / E_z, \\
c_0 &= (1 + \nu_l)(n(l - \nu_l) - 2\nu^2), \\
c_{11} &= (E_t(n - \nu_l^2)) / c_0, \\
c_{12} &= (E_t(\nu_l^2 + n \nu_l)) / c_0,
\end{align*}
\]

3. THE BOUNDARY CONDITIONS.

\[
\begin{align*}
c_{13} &= (\nu_z E_t) / (n(l - \nu_l) - 2\nu^2), \\
c_{33} &= ((1 - \nu_l)E_t) / (n(l - \nu_l) - 2\nu^2), \\
c_{44} &= G_z.
\end{align*}
\]

The coefficients of Hooke's law for dam pan-layered structure, with \( \phi \neq 0 \) are calculated using the angle of the plane of isotropy \( \phi \) by the use of the following expressions:

\[
\begin{align*}
c_1 &= \cos^2 \phi, & c_2 &= \sin^2 \phi, & c_3 &= \cos^4 \phi, \\
c_4 &= \sin^4 \phi, & c_5 &= \sin \phi \cos \phi, \\
c_6 &= \sin \phi \cos^2 \phi, \\
c_0 &= (1 + \nu_l)(n(l - \nu_l) - 2\nu^2), \\
c_{11} &= c_{22} = (E_t(n - \nu_l^2))/c_0, \\
c_{13} &= (\nu_z E_t) / (n(l - \nu_l) - 2\nu^2), \\
c_{33} &= ((1 - \nu_l)E_t) / (n(l - \nu_l) - 2\nu^2), \\
c_{55} &= G_z.
\end{align*}
\]

5. ALGORITHM OF SOLUTION AND BACKGROUND

The main steps of application of FEM for solving static elasticity problem consist of the following steps. The state of static equilibrium of the body of the dam is described by the following system of algebraic equations (Baimakhan, 2002; Zenkevich, 1975):

\[
[R] \{U\} = \{F\},
\]

(4)

where \([K]\) – is the system of stiffness matrix; \(\{U\}\) – displacement vector of nodal points; \(\{F\}\) – vector loads, which weights are generated based on the finite element finding their depth \(H\), m.

Then the components of the strain tensor and the stress is calculated within each isoparametric element in the Gaussian integration points \(i, j\) using the following expressions.

\[
\begin{align*}
\{\varepsilon_{ij}\} &= [B]\{U_{ij}\}, \\
\{\sigma_{ij}\} &= [D]\{\varepsilon_{ij}\},
\end{align*}
\]

(5)

where vectors \(\{\varepsilon_{ij}\}^T = \{\varepsilon_x, \varepsilon_z, \gamma_{xz}\}\),
\(\{U_{ij}\}^T = \{u_y, g_{ij}, \ldots\}\), \(\{\sigma_{ij}\}^T = \{\sigma_x, \sigma_z, \tau_{xz}\}\) – are the components of the vector strain, displacement and stress. \([B]\) –is gradient matrix and \([D]\) – is a matrix of elastic characteristics, which elements are calculated by the expressions (Salgarareva, 2004) and (Zenkevich, 1975).

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Experimental data on the options of anisotropic properties of soil structure is very small. The Table 1 below shows such data on physical-mechanical options for some very common types of soils of anisotropic structure in nature.

Table 1. Physical-mechanical options of soils of anisotropic structure

<table>
<thead>
<tr>
<th>№</th>
<th>Soils</th>
<th>𝜈₁, kN/m</th>
<th>𝐸₁, Mna</th>
<th>𝐸₂, Mna</th>
<th>𝐺₁, Mna</th>
<th>𝜈₂</th>
<th>𝜈₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rich loam</td>
<td>20.0</td>
<td>30.0</td>
<td>15.0</td>
<td>7.6</td>
<td>0.36</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>Ground</td>
<td>19.0</td>
<td>10.0</td>
<td>20.0</td>
<td>7.4</td>
<td>0.30</td>
<td>0.40</td>
</tr>
<tr>
<td>3</td>
<td>Loam</td>
<td>9.4</td>
<td>12.0</td>
<td>8.0</td>
<td>3.4</td>
<td>0.39</td>
<td>0.35</td>
</tr>
<tr>
<td>4</td>
<td>Sandy loam</td>
<td>19.8</td>
<td>19.6</td>
<td>18.4</td>
<td>7.1</td>
<td>0.31</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>Fine sand</td>
<td>21.1</td>
<td>81.3</td>
<td>85.0</td>
<td>32.7</td>
<td>0.28</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Angle of the plane of isotropy horizontally varies from zero (𝜑 = 0) to the vertical stratification (𝜑 = 90°), with increments of 𝜑 = 0, 15°. The geometrical dimensions: height of the dam-50m, width at the crest -20m, the width at the base-100m. The height and the height of the rocky foundation are 500m and 160m respectively. Given to the anisotropy of physical and mechanical properties of the material of the dam - fine-layered sandstone: Young's modulus- 𝐸₁ = 1.074 · 10⁴MPa, shear modulus- 𝐺₂ = 0.12 · 10⁴MPa, Poisson's ratios: 𝜈₁ = 0.413, 𝜈₂ = 0.198, volumetric weight- 𝑔 = 2.3 · 10²Mn/m³. Properties of geotextiles - epoxy acrylate: Young's modulus- 0.494 · 10⁴MPa, Poisson's ratio - 𝜈 = 0.34, volume weight - 𝑔 = 1.6510²Mn/m³. Compressive strength - 58.4 MPa, tensile strength - 14.5 MPa.

The area is divided into 29256 isoparametric finite elements. The total number of units is 30003. The number of solutions of the system of algebraic equations net fixed boundary nodes is 58861.

6. RESEARCH RESULTS AND ANALYSIS.

Some of the results of calculations carried out by the algorithms (1) and (6) in the definition of deformed states are shown below in Figure 3 under three characteristic angles to the plane of isotropy: 𝜑 = 0, 𝜑 = 30, 𝜑 = 45, 𝜑 = 60 and 𝜑 = 90°. The magnitudes of deformation in the components of displacements 𝑢, 𝑣 for other values of angles of the plane of isotropy for the extreme points of the ridge are shown in Table 2.

When horizontal layering 𝜑 = 0, the dam together with an elastic deformation of rock foundations is deformed down symmetrically (Figure 3a). The top ridge takes the maximum value of 𝑉 = −2.98m.

The magnitude of deformation of the base of the dam, resting on a rock half-plane is 𝑉 = −2.71 m.

When 𝜑 = 30°, firstly, with respect to the vertical axis of rotation, the phenomenon of deformation of the dam and the ground surface is observed (Fig. 3b). Effect of asymmetric deformation of the base is as follows: the right side of the dam deforms more, and vice versa, the deformation of the right base part is less than the deformation of the left part. Weight of the dam is slightly deformed to the right.

When 𝜑 = 45° (Fig. 3c), the right corner ridge is maximally shifted: 𝑉 = −0.25 m, 𝑈 = +0.28 m. The effect of rotation about a vertical axis of the dam with the offset to the right is observed. But the amount of deformation is significantly reduced compared to the previous embodiment. In this embodiment, for the first time, the crest value of the horizontal displacement component 𝑈 prevails a vertical component 𝑉 (Table 1).

When 𝜑 = 60° (Fig. 3d), the right corner ridge is maximally shifted: 𝑉 = −0.11 m, 𝑈 = +0.14 m. The amount of deformation is reduced. The left side of the base, being far away from the angle of laying remains undeformed. In this embodiment, the crest value of the horizontal displacement component prevails a vertical component.
Fig. 3. Epures of the elastic deformation of the dam: a – horizontal with \( \varphi = 0 \), b – inclined with \( \varphi = 45^\circ \) and c – vertical with \( \varphi = 90^\circ \) lamination.

In vertical layering (\( \varphi = 90^\circ \)) the dam along with the base deforms downwards symmetrically with respect to the central vertical axis. But the values of the displacement components are greatly reduced compared to the previous version of the calculation.

### Table 2. The values of the displacement components \( u, v \) of dam crest obliquely layered structure for different values of the angle of the plane of isotropy \( \varphi \).

<table>
<thead>
<tr>
<th>№ point</th>
<th>Angles ( \varphi ), the slopes of plane isotropy</th>
<th>Displacement components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left corner of the dam crest</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( u, m )</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>15(^\circ)</td>
<td>0.20</td>
</tr>
<tr>
<td>3</td>
<td>30(^\circ)</td>
<td>0.42</td>
</tr>
<tr>
<td>4</td>
<td>45(^\circ)</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>60(^\circ)</td>
<td>0.14</td>
</tr>
<tr>
<td>6</td>
<td>75(^\circ)</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>90(^\circ)</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### 7. CONCLUSION

The analysis of deformation of obliquely layered construction of the dam shows that with increasing angles of plane isotropy, the magnitude displacements \( u \) and \( v \) are greatly reduced. As it is seen from the table, the largest subsidence deformation of the whole body of the dam is observed in the horizontal stratification, with \( \varphi = 0 \). With each increase in the angle of inclination of the plane of isotropy \( \varphi \), the value of vertical deformation is twice reduced. In all embodiments, the amount of horizontal displacement components \( u \) is significantly less than the vertical component. This pattern is broken at \( \varphi = 45^\circ \). In this case, the horizontal and vertical components of motion are equal.

Thus, if the erect dam with inclined strata, and the larger the angle of inclination of the plane of isotropy, it becomes the smaller the amount of deformation of the dam with a base. Therefore, the most optimal in terms of deformation rainfall is erecting a dam by vertical layers.

### REFERENCES