Impact of the stress-strain state of the soil on the stability of the retaining wall

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Abstract. The results of the survey and calculation of the stability of retaining walls along highways located near the incline of the slope are presented. The analysis of the results of the numerical solution for modeling the interaction of the slope and the retaining wall shows that the most dangerous areas are the zones of development of maximum horizontal deformations at the retaining walls due to shear deformations. The zone, where shear deformations are spread, covers a large volume of slope soils. Collapsing soils, sinking from their own weight on the slope during water saturation, worsen the initial value of the adhesion, the angle of internal friction, the modulus of deformation, changing the stress-strain state. The trajectories of the movement of particles of collapsing soil when the stress-strain state of the slope on the retaining wall changes show that the movement of soil particles occurs at the boundary of collapsing and non-collapsing loams. Numerical calculations carried out under the PLAXIS program showed that in the water-saturated state, the slope is a landslide. The retaining wall on the incline of the slope, made of collapsing soils, is not stable and the sliding of the soil occurs only in the layers of collapsing soils of the slope.

1. Introduction

The site under consideration for studying the impact of the slope on the retaining walls is located in the Almaty region at the foot of the Alatau Mountains. The available absolute marks of the ground surface range from 916.0 to 985.835 m, which is a difference of 69.835 m. The geological and lithological structure includes lower quaternary Aeolian deposits, represented by loess-like collapsing loams (Q₁), as well as upper quaternary alluvial-alluvial fan deposits (apQ₃m), represented by pebble gravel overlain by loams and a modern soil-plant layer (Q₄V). Loams (Q₁) is brownish-gray in color, up to a depth of 21.0 m - collapsing, below non-collapsing. Loams (Q₁) were excavated to a depth of 40.0 m.

Pebble gravel with sand aggregate were excavated in the northern part of the site and are characterized by the following fraction content: boulders 10-15%, pebbles 50-55%, gravel 10-15%, aggregate 15-20%.

In collapsing loess soils, there are problems of collapse of the slope incline array with full or partial water saturation of the soil due to a significant deterioration in the design parameters (adhesion, internal friction angle and deformation modulus). The aim of the research was to analyze the stress-strain state of the incline of the slope formed by collapsing soils and to assess the stability and strength of the structure of the retaining walls to ensure safety during the operation of the highway.
2. Methods and materials

As a result of instrumental examination of slopes and retaining walls made of monolithic reinforced concrete and drainage systems, numerous defects were identified in the design process, which entail a threat to the safe operation of the highway and the structure. Monolithic reinforced concrete retaining walls with natural stone cladding with a height of 4.0-20.0 m, a width of 0.6 m are supported on slabs measuring 1.2 x 2.40 m.

They have a rigid pinching with pile foundations. The incline of the slope is exposed to atmospheric and flood waters throughout the year. The identified defects indicate unacceptable cracks and the slope of the retaining walls along the highway (Fig. 1).

![Figure 1. Defective design of the retaining wall.](image)

The assessment of the stress-strain state of the slope when exposed to retaining walls was carried out taking into account the behavior of collapsing soils. At the same time, the slope soils are characterized by: variability of physical and mechanical properties (a decrease in porosity, modulus of deformation, adhesion, angle of internal friction); a change in the stress state, due to their redistribution after soaking; a change in the components of the strain tensor, which is associated with the development of elastic-plastic and viscoplastic deformations [1, 2, 3] (table 1).

| Type of soil | Sampling depth (m) | Soil density (g/sm³) | Natural moisture (%) | Porosity (%) | Initial collapsing pressure (MPa) | Total subsidence (cm²) |
|--------------|--------------------|----------------------|----------------------|--------------|----------------------------------|-----------------------|
| Loess loam   | 15.5-21            | 1.51-1.75            | 12-16                | 30-42        | 0.028-0.361                      | 8.8-73.51             |

When water is saturated in collapsing soils, a stress state occurs, which is significantly different from the initial one. A plane problem in the elastic-plastic formulation is considered using the Coulomb-Prandtl model, which assumes elastic behavior of the environment at stresses below the yield point and equal-volume (with zero dilatancy) plastic flow at stresses at the yield point. The yield stress is described by the equation [4, 5, 6]

\[
\sigma_{\text{max}} = S + \lambda \sigma_{\text{min}}
\]

where \( \lambda = \text{ctg}^2\left(\frac{\pi}{4} - \frac{\theta}{2}\right) \) - passive ground pressure coefficient; \( S = 2C \text{ctg}\left(\frac{\pi}{4} - \frac{\theta}{2}\right) \) - uniaxial compressive strength; \( \sigma_{\text{max}}, \sigma_{\text{min}} \) - maximum and minimum main stresses. In the area of tension, the yield (break) criterion has the form:

\[
\sigma_{\text{min}} = T
\]

where \( T \) - the tensile strength accepted in the program is equal to \( C/5 \).

After the rupture occurs at a stress of \( \sigma = C/5 \), in further analysis, the tensile strength of the element is assumed to be zero (\( T=0 \)).
3. Results and discussion
The model of the elastic-plastic solution is implemented by the finite element method and is achieved by the well-known method of “initial stresses” using the iterative Newton-Raphson procedure [7,8] with a constant stiffness matrix, but with a variable load vector, supplemented during the iterative process by “initial forces” in the plastic elements[9,10,11] The error resulting from the calculation of the FEM consisted of the sampling error caused by the replacement of a body with an infinite number of degrees of freedom with a model with a finite number of degrees of freedom, and the error of rounding numbers when performing computational operations on a computer [12,13].

As a result of numerical analysis of the problem according to the design scheme (Figure 2) and the deformation mechanism (Figure 3), the following distortions of the finite element grid (Figure 4), horizontal and general slope deformations with changes in the calculated characteristics of collapsing soils (Figures 5 and 6), as well as the isolines of the maximum horizontal (shear) stresses (Figure 7) and the trajectory of the particles of collapsing soils (Figure 8) with changes in the stress-strain state of the slope on the retaining wall (Table 2) are obtained.

Figure 2. Calculation scheme.
Figure 3. Deformation mechanism.
Figure 4. Horizontal deformations.
Figure 5. General deformations.
Figure 6. Horizontal stresses.
Figure 7. Soil movement trajectories.
Table 2. Characteristics of the strength properties of loess soils at different W.

| Moisture | Adhesion (MPa) | Internal friction angle | Deformation modulus (MPa) | Structural strength (MPa) |
|----------|----------------|-------------------------|---------------------------|--------------------------|
| 0.12     | 0.061-0.065    | 35-37                   | 8-13                      | 0.14                     |
| 0.18     | 0.05-0.06      | 25-30                   | 6-9                       | 0.064                    |

Figure 8. Maximum shear stress isolines.

4. Summary
The analysis of the results of the numerical solution for modeling the interaction of the slope and the retaining wall shows that the most dangerous areas are the zones of development of maximum horizontal deformations at the retaining walls due to shear deformations. The zone, where shear deformations are spread, covers a large volume of slope soils. Collapsing soils, sinking from their own weight on the slope during water saturation, worsen the initial value of the adhesion, the angle of internal friction, the modulus of deformation, changing the stress-strain state. The trajectories of the movement of particles of collapsing soil when the stress-strain state of the slope changes on the retaining wall show that the movement of soil particles occurs at the boundary of collapsing and non-collapsing loams. Calculations by the numerical method established that the retaining wall on the incline of the slope, composed of collapsing soils, is not stable and the sliding of the soil occurs only in the layers of collapsing soils of the slope.

As a result of instrumental inspection of slopes and measurements of protective retaining walls made of monolithic reinforced concrete and drainage systems, numerous defects and damages made during the design and construction process were revealed, which entail a threat to the safe operation of the highway and the structure.

According to the results of compression tests, loams lying to a depth of 15.5-21.0 m show collapsing properties when soaked. The initial collapsing pressure varies from 0.028 to 0.361 MPa. Calculations show that the total subsidence is 8.8-73.51 cm. The numerical solution results in modeling the interaction of the slope and the retaining wall show that the most dangerous zones are the zones of development of maximum horizontal deformations at the retaining walls, caused by shear deformations of the incline of the slope.

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