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Stability of retaining wall on subsidence soils

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Abstract. The paper presents the results of survey and calculation of stability of retaining walls along motorways located at the slope of the slope. The results of numerical solution in modelling of slope and retaining wall interaction are analyzed, showing that the most dangerous are the zones of development of maximum horizontal deformations at retaining walls caused by shear deformations. The shear deformation propagation zone covers a large volume of slope soils. Subsidence soils, subsiding from their own weight on the slope under water saturation, deteriorate the initial value of cohesion, angle of internal friction, modulus of deformation, changing the stress-strain state. The trajectories of movement of subsidence soil particles during the change of stress-strain state of the slope on the retaining wall show that the movement of soil particles occurs at the boundary of subsidence and non-subsidence loams. Numerical calculations using PLAXIS programme showed that in water-saturated state, the slope is landslide-prone. The retaining wall on the slope of the slope, composed of subsidence soils, is not stable and soil sliding occurs only in the layers of subsidence soils of the slope.

Keywords: *subsiding soil, clutch, shift, the angle of internal friction, microshear, deformation, deformation modulus*.

1. Introduction

Retaining structures are various kinds of underground structures combined with the ground environment, which provide stability of structures under the action of horizontal soil pressure [1]. One of the examples of such structures are retaining walls, which are built to strengthen soil slopes from collapse, fence excavations, prevent erosion of the coastal zone of rivers, seas, lakes, when building road embankments in confined conditions (on mountain slopes, in the city limits, etc.), as well as in the construction of buildings and structures near the slopes. Retaining walls experience significant horizontal pressure from the soil, are often subjected to dynamic, seismic and vibration effects from mobile transport, frost heave pressure, the action of filtration forces. Calculation and design of retaining walls begins with determining the value of horizontal soil pressure. There are two types of pressure on the retaining structure: active and passive. Active pressure is the lateral pressure from the soil in the ultimate stress state in the direction of displacement of the structure.

Passive pressure is the lateral pressure from the side of the soil, which is in the limit stress state, in the direction opposite to the displacement of the structure There are various methods for calculating the values of active and passive pressure on retaining structures according to Sorochan [1], according to Eurocode 7 [2]. At the same time, none of these methods considers the strength anisotropy of soils, which significantly reduces the accuracy of determining the internal forces in retaining wall structures and, as a consequence, leads to an increase in the cost of structural solutions adopted in the project.

Soil anisotropy is inhomogeneity of its properties in different directions. Numerous experimental studies have shown that most types of soils have filtration, deformation, strength anisotropy, manifested by changes in these properties when changing the direction of external influence.

The method of circular-cylindrical sliding surfaces is the most widely used in practice, as it allows to consider the complex nature of the slope surface, soil conditions, external loads and is based on reliable empirical data. At the same time, the calculation of slopes on structurally unstable soils raises problems that were not considered in calculations and that in some cases caused landslides. It is a question of base deformations that can radically change the stress-strain state and strength of slopes. Existing calculation methods, which do not reflect such processes, naturally cannot provide reliable results of slope stability calculation under such conditions, as an example, the stability of slopes underlain by subsidence loess loams and sandy loams. In the second type of subsidence, subsidence from its own weight exceeds 5 cm and can reach about 1 m, thus a subsidence funnel is formed, within which, in addition to vertical deformations, horizontal displacements to the center of the funnel with the formation of cracks in the soil are essentially developed [3,4].

The effects of such processes on the slope are, on the one hand, similar to the effects of slope erosion, which results in a reduction of the resistance forces. On the other hand, the geometry of the slope is changed, and horizontal deformations and the formation of cracks in the soil lead to a significant reduction in the influence of cohesion within the collapse prism. Since cohesion plays a decisive role in ensuring the strength of cohesive soils, the influence of these processes in the development of subsidence cannot be ignored in the calculation of slope stability.

The problem we have studied is an example of the occurrence of different types of soils in the same slope massif behind a retaining wall.

The site under consideration for the study of slope effect on retaining walls is located in Almaty region at the foot of the Alatau mountains. The available absolute ground surface elevations range from 916.0 to 985.835m, which is a difference of 69.835m. The geological and lithological structure includes Lower Quaternary aeolian deposits represented by loess-like subsidence loams (QI) and Upper Quaternary alluvial-proluvial deposits (apQIII) represented by gravelly soils overlain by loams and modern soil and vegetation layer (QIV). The loams (QI) are brownish-grey in colour, up to the depth of 21.0 m they are subsiding, below they are non-subsiding. The loams (QI) were penetrated to a depth of 40.0 m. Pebble-nick soils with sandy aggregate were discovered in the northern part of the site and are characterised by the following content of fractions: boulders 10-15%, pebbles 50-55%, gravel 10-15%, aggregate 15-20%.

1.1. Subsection

In subsidence loess soils there are problems of slope slope mass collapse at full or partial water saturation of soils due to significant deterioration of design parameters (cohesion, angle of internal friction and modulus of deformation). The objective of the research was to analyse the stress-strain state of the slope of the slope composed of subsidence soils and to assess the stability and strength of the retaining wall structure to ensure safety during the operation of the motorway.

2. Materials and methods

As a result of instrumental inspection of slopes and retaining walls made of monolithic reinforced concrete and drainage systems, numerous defects have been identified in the design process, which endanger the safe operation of the motorway and the structure. Monolithic reinforced concrete retaining walls with natural stone facing with a height of 4.0-20.0 m and a width of 0.6 m are supported on slabs with dimensions of 1.2 x 2.40 meters.

They are rigidly pinned with pile foundations. The slope is exposed to atmospheric and flood waters during the year. The identified defects indicate inadmissible cracks and slope of the retaining walls along the motorway (Figure 1).

A retaining wall made of any material must have a foundation, the wall body itself and drainage. The depth of the foundation depends on the height of the structure, but in any case, its width should be greater than the width of the wall body by about 20 cm to ensure the required strength and stability, in addition, it is necessary to provide drainage for water drainage, which is not done with this retaining wall.

Figure 1. Defective retaining wall design

The study of limit state parameters of loess soils is connected with the peculiarity of this special group of clayey soils. Low-moisture loess soils under consolidated in natural state can have significant structural strength due to rigid crystallization bonds. Moistening of loess promotes the transition of crystallization bonds into water-colloidal ones, which in turn leads to a decrease in structural strength. For the same physical properties ((density, mineralogical composition, etc.), a change in moisture content alone leads to a significant difference in strength parameters. Since moistening reduces the structural strength of loess soils, the value of the structural strength Pstr, is a determining factor that must be considered when determining the strength properties of loess [4]. The structural strength of loess soils of different moisture content was estimated by the method developed in MSCU by V.F. Sidorchuk and V.F. Shahi Biswa [5] according to the compression dependence of lateral and vertical pressures: σb= f (σv).

Compression tests were carried out on a PKP-10 type device on loess soils of undisturbed structure. Vertical loading was carried out in steps of 0.025 and 0.050 MPa. The dwell time at each stage was 10 minutes. Figure 2 shows the graphs of dependence σb= f (σv) of loess soils of different moisture content, confirming the results of research and it is established that the graph of dependence of lateral and vertical pressures is characterized by two linear sections with a break point depending on the soil moisture content. So, for loess soil with humidity 0.02 the vertical pressure determining structural strength is 0.276 MPa, for humidity 0.12-0.140 MPa and at humidity 0.18, P-0.640MPa. There is a significant decrease in the structural strength as the soil moisture increases. The intensity of lateral pressure at the first plot of the dependence is always less than at the second plot (beyond Pstr). In addition, the moisture content of loess soil also affects the lateral pressure coefficient. For low-moisture soil, the values of Co are almost twice less than the similar Co (on the first and second plots) for soil with moisture content of 0.18, while the difference in the lateral pressure coefficient of samples with moisture content of 0.12 and 0.18 is less significant.

To determine the value of the design resistance R, as stated earlier, knowledge of the strength properties of the loess soil φ (angle of internal friction) and cohesion C. The tests were carried out on twin specimens of soils of the same physical condition on which the previous series of compression experiments had been performed. The vertical static load was assigned considering the structural strength of the soils. The displacement was performed using the shear force step loading technique. Shear forces were applied at a rate of 10 min, after which the magnitude of the specified displacements was recorded.

The first group of tests of loess loam with moisture content of 0.02 were conducted at vertical loads of 0.10 and 0.20 MPa (σv≤Pstr). Figure 3 shows the shear diagrams τ = f (σv), the angle of internal friction φ was 33º, and the cohesion was 0.34 MPa. The second group of experiments was performed at loads of greater structural strength (σv ≥ Pstr).

The test results show that in the second case there is an increase in the angle of internal friction up to 44º and a decrease in adhesion up to 0.27 MPa (vertical load was 0.30;0.40;0.50 MPa). In addition, from the shear diagram it can be seen that the point of intersection of the dependencies τ = f (σv), at loads before and after Pstr is close (on the abscissa axis Pstr) to the value of structural compressive strength. Studies of strength properties of soils of higher moisture content have shown that this regularity regarding the change of strength properties depending on the vertical pressure σv is also observed in these cases. Similar tests were carried out for loess loams with humidity 0.12 and 0.18, at loads depending on the value of Pstr. Shear was performed at loads 0.025; 0.050; 0.075 MPa (less than Pstr) and at pressures 0.15; 0.200; 0.300 MPa (more structural strength). The shear diagrams are shown in Figure 3. Numerical values are given in Table 2.

Table 2. Numerical values

Humidity	When σv≤Pstr		When σv ≥ Rstr	
W	*φ* degree	*C* (MPa)	*φ* degree	*C* (MPa)
0.02	33	0.34	44	0.270
0.12	15	0.165	37.5	0.139
0.18	13	0.077	30	0.061

Wetting of loess soils promotes the transition of crystallization bonds to water-colloidal bonds, which leads to a decrease in structural strength. Since moistening reduces structural strength, this value is a determining parameter in determining all deformation and strength characteristics of loess.

The stress-strain state of the slope under the impact on retaining walls was assessed considering the behavior of subsidence soils. The slope soils are characterized by: variability of physical and mechanical properties (reduction of porosity, deformation modulus, cohesion, angle of internal friction); change of stress state due to their redistribution after soaking; change of strain tensor components, which is associated with the development of elastic-plastic and viscoplastic deformations [7,8,9].

In the simplest elastic-plastic models, the strength characteristics of soils are added to the calculation. These models allow to consider the non-linear character of foundation deformation with increasing load. The limit state criterion in this case looks like some surface in the space of principal stresses, limiting the area of possible stresses for a given material. In soil mechanics, the limit surface defined by the Coulomb-Mohr criterion is most often used.

The advantage of such a model is the use of traditional parameters (modulus of deformation, specific cohesion and angle of internal friction) obtained in standard engineering-geological surveys. The disadvantages include ignoring the nonlinear relationship between stresses and strains in compression under compression conditions, as well as the assumption of equality of strain moduli at the loading and unloading stages.

In the classical Cam-Clay strengthening model, as described in K. H. Roscoe and J. B. Borland [5]. H. Roscoe and J. B. Borland [5], an elliptical surface is assumed as the loading surface, which is justified energetically and defined by a rather simple equation. According to the concept of critical state, the loading surface in the coordinates of principal stresses corresponds to the same volumetric plastic deformations of the soil at different combinations of stresses acting on the element of the medium.

The disadvantage of the classical Cam- Clay model is the lack of consideration of cohesion for clayey soils due to previous compaction. The simplest modification of the model to take this factor into account is to move the elastic work area of the soil by the value c · ctgφ. Such an approach, for example, is used in the well-known geotechnical programme PLAXIS.

In clayey soils, shear resistance depends on the strength of water-colloid bonds and the number of contacts of particles (with their water-colloid shells) with each other, but not on the amount of friction at these contacts. The number of contacts is obviously related to the density (porosity) of the soil, which for fully water-saturated soils in undrained conditions does not change practically with increasing or decreasing total volumetric stresses.

The inconsistency of the Cam-Clay model behavior with experience under deviatoric loading can adversely affect the modelling of real geotechnical situations. The absence of nonlinear shear deformations in a part of the loading trajectory can lead to a general underestimation of the magnitude of deformations within the whole calculation scheme. This is especially significant in the calculation of clayey soils with low filtration coefficients, in which volumetric deformations will occur over a long period of time. Shear deformations play the main role in the behavior of such soils during construction and operation. To eliminate the described contradictions, we have developed a modification of the hardening elastic-plastic soil model that more correctly reflects the behavior of weak clayey soils. The model under consideration can be called 'Coulomb-Prandtl medium' or 'elastic-ideal-plastic medium with Coulomb plasticity criterion'. It is universal enough and allows modelling various types of soils and rocks. The deformation model should establish in mathematical form the relationship between deformations and stresses in the element of the medium. The deformation model of an elastic medium is Hooke's law, which establishes a linear relationship between stresses and strains for plane deformation conditions. Stresses σ1 and σ3 are coaxial with corresponding deformations ε1 and ε3. This important statement, as well as the unambiguous relationship between stresses and strains in elastic-plastic medium is valid only in unidirectional process of deformation, the absolute majority of real geotechnical problems satisfy this condition: the change in the stress state under the foundation of the erected building, in the slope of the deepening pit, around the passable excavation has a unidirectional character. Thus, the relationship between stresses and deformations in the zone of plastic flow has been established.

Under water saturation in subsidence soils, a stress state appears, which differs significantly from the initial one. We consider a plane problem in elastic-plastic formulation using the Coulomb-Prandtl model, which assumes elastic behavior of the medium at stresses below the yield stress and equal-volume (with zero dilatancy) plastic flow at stresses at the yield stress. The yield stresses are described by the equation [10,11,12]

$$\sigma max== S + \lambda \sigma min$$

Where λ=ctg^2$(\pi/4 - \phi/2)$ - coefficient of passive soil pressure; $S=2C$ctg$(\pi/4 - \phi/2)$ - uniaxial compression strength; σ_{max}, σ_{min} - maximal and minimal principal stresses. In the area of tension the yield (rupture) criterion has the form:

$$\sigma_{min\,=}\,-T$$

where T is the tensile strength, taken in the programme as C/5.

After rupture occurs at stress σ =- C/5, in further analyses the tensile strength of the element is assumed to be zero (T=0).

3. Results and discussion

The model of elastic-plastic solution is realised by the finite element method and is achieved by the well-known method of 'initial stresses' using the iterative Newton-Raphson procedure [13,14] with a constant stiffness matrix but with a variable vector of loads replenished during the iterative process by 'initial forces' in plastic elements [15. 16.17] Newton's method, also called the Newton-Raphson method, is a simple and efficient algorithm for approximate finding the roots of real-valued functions, i.e. solving equations of the form: f(x)=0. The soft creeping soil model is an improved version of the soft soil model, including modelling of the second stage of creep. The error as a result of the FEM calculation consisted of the discretization error due to the replacement of a body possessing an infinite number of degrees of freedom by a model with a finite number of degrees of freedom, and the error of rounding of numbers when performing computational operations on a computer [18.19]. As a result of the numerical analysis of the set problem using the calculation scheme (Figure 2) and the deformation mechanism (Figure 3), the following results were obtained:

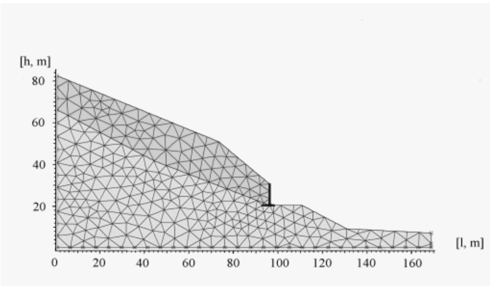

Figure 2. Calculation diagram

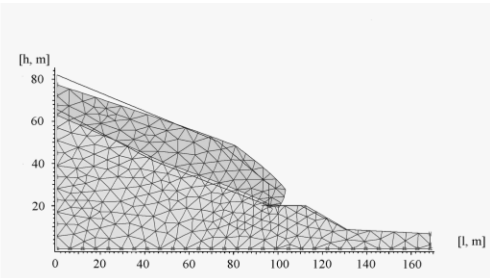

Figure 3. Deformation mechanism

Distortion of the finite element mesh (Figure 4), horizontal and total deformations of the slope at change of design characteristics of subsidence soils (Figures 5 and 6), as well as the isoline of maximum horizontal (shear) stresses (Figure 7) and trajectory of movement of subsidence soil particles (Figure 8) at change of stress-strain state of the slope to the retaining wall.

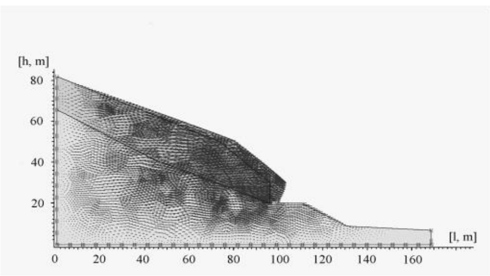

Figure 4. Horizontal deformations

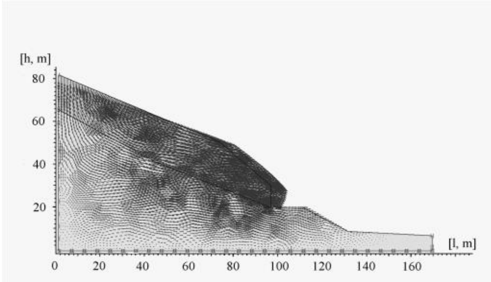

Figure 5. General deformations

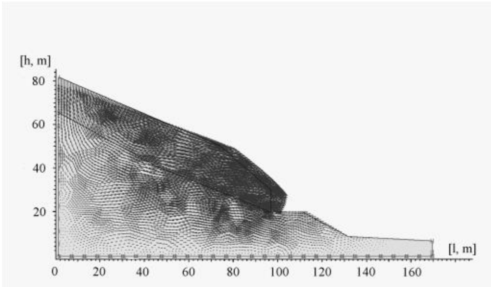

Figure 6. Horizontal stresses

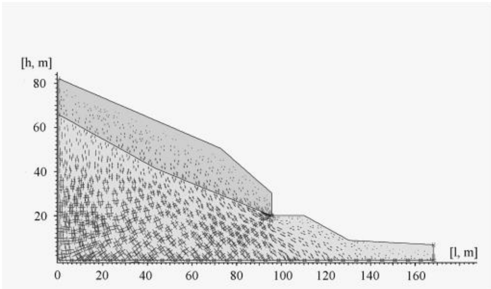

Figure 7. Ground motion trajectories

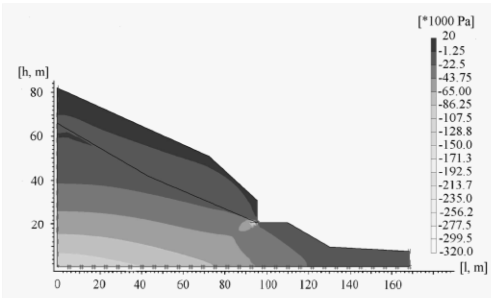

Figure 8. Isolines of maximum shear stresses

4. Conclusions

The calculation scheme for determining the stability of a slope on subsidence soils should consider:

- subsidence - vertical displacements of the slope base within the limits of the subsidence funnel based on the most disadvantageous location of the soakage centre at the base of the soil mass;
- horizontal displacements of the soil mass within the subsidence funnel;
- formation of cracks in the slope surface;
- changes in soil characteristics during wetting

As a result of accumulation of melt water in the gully at the base of the landslide, soaking and subsidence of the loess base occurred, which led to violation of the slope stability and destruction of residential houses. Calculation of slope stability without considering the processes associated with subsidence confirms its stability. At the same time, the calculation performed considering the processes occurring during soaking of loess base gives the value of stability coefficient less than one.

Analysis of the results of numerical solution in modelling the interaction between slope and retaining wall shows that the most dangerous are the zones of development of maximum horizontal deformations at retaining walls due to shear deformations. The zone of shear deformations spreading covers a large volume of slope soils. Subsidence soils subsiding from their own weight on the slope under water saturation worsen the initial value of cohesion, angle of internal friction, modulus of deformation, changing the stress-strain state. The trajectories of movement of subsidence soil particles 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 subsidence and non-subsidence loams. Numerical calculations have established that the retaining wall on the slope of the slope composed of subsidence soils is not stable and the soil sliding occurs only in the layers of subsidence soils of the slope.

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

According to the results of compression tests, loams occurring up to the depth of 15.5-21.0 m show subsidence properties when soaking. The initial subsidence pressure varies from 0.028 to 0.361 MPa. Calculations show that the value of total subsidence is 8.8-73.51cm. According to the results of numerical solution when modelling the mutual interaction of the slope and retaining wall, it is established that the most dangerous are the zones of development of maximum horizontal deformations at retaining walls, caused by shear deformations of the slope.

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Шөгінді топырақтағы тіреу қабырғасының тұрақтылығы

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Аңдатпа. Мақалада еңіс баурайында орналасқан автомобиль жолдарының бойындағы тіреу қабырғаларының тұрақтылығын зерттеу және есептеу нәтижелері келтірілген. Көлбеу мен тіреу қабырғасының өзара әсерін модельдеу кезінде сандық шешімнің нәтижелері талданды, бұл ең қауіптівигысу деформацияларынан туындаған тіреу қабырғаларында максималды көлденең деформациялардың даму аймақтары екенін көрсетті. Жылжымалы деформацияның таралу аймағы көлбеу топырақтың үлкен көлемін қамтиды. Суға қаныққан кезде беткейде өз салмағынан шөгетін шөгінді топырақтар адгезияның бастапқы мәнін, ішкі үйкеліс бұрышын, деформация модулін нашарлатады, кернеулі деформацияланған күйді өзгертеді. Шөгінді топырақ бөлшектерінің қозғалыс траекториялары тірек қабырғаға еңістің кернеулі-деформацияланған күйі өзгерген кезде топырақ бөлшектерінің қозғалысы шөгінді және шөгінді емес саздақтардың шекарасында жүретіндігін көрсетеді. PLAXIS бағдарламасы бойынша жүргізілген сандық әдіспен есептеулер су қаныққан жағдайда еңіс көшкін болатынын көрсетті. Шөгінді топырақтармен бүктелген көлбеу беткейдегі тіреу қабырғасы тұрақты емес және топырақтың сырғуы тек көлбеу шөгінді Топырақтардың қабаттарында болады.

Негізгі сөздер: *шөгінді топырақ, ілінісу, сдысу, ішкі үйкеліс бұрышы, микродысу, деформация, деформация модулі*.

Устойчивость подпорной стены на просадочных грунтах

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Аннотация. В статье приведены результаты обследования и расчёта устойчивости подпорных стен вдоль автомобильных дорог, расположенных у склона откоса. Проанализированы результаты численного решения при моделировании взаимодействия откоса и подпорной стены показывавшие, что наиболее опасными являются зоны развития максимальных горизонтальных деформаций у подпорных стен, вызванные сдвиговыми деформациями. Зона распространения сдвиговых деформации охватывает большой объём грунтов откоса. Просадочные грунты, проседая от собственного веса на склоне при водонасыщении, ухудшают первоначальное значение сцепления, угла внутреннего трения, модуля деформации, изменяя напряженно-деформированное состояние. Траектории движения частиц просадочных грунтов при изменении напряженно-деформированного состояния откоса на подпорную стену показывают, что движение частиц грунта происходит на границе просадочных и непросадочных суглинков. Расчеты численным методом, проведенные по программе PLAXIS, показали, что в водонасыщенном состоянии, откос является оползневым. Подпорная стена на склоне откоса, сложенного просадочными грунтами, является не устойчивой и скольжение грунта происходит только в слоях просадочных грунтов склона.

Ключевые слова: *просадочный грунт, сцепление, сдвиг, угол внутреннего трения, микросдвиг, деформация, модуль деформации.*

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