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Stability of cut slopes in cohesive soils

Stabilité des talus taillés en sols cohérents

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ABSTRACT

Short-term stability in cohesive soils is defined by their undrained shear strength. However, after some time the stability decreases and experience shows that on the long run only those slopes are stable where the inclination is smaller than the soil's angle of internal friction. The short-term stability is due to the pore pressure change („suction") that emerges on soil removal. This negative excess pore pressure degrades over time due to a consolidation process, which results in a behaviour similar to granular soil. Numerical experiments were made to study the problem via the change of cohesion over time.

RÉSUMÉ

La stabilité en court temps pour les sols cohérents est définie par leur résistance au cisaillement non drainé. Quand même la stabilité peut décroître après quelques temps et les expériences montrent que seulement ces slopes sont stabiles dont l'inclinaison ne dépasse pas l'angle de frottement interne du sol. La stabilité de court temps est dirigée par les changements de la pressure de l'eau interstitielle (section) augmentée par les fouilles de sol. Cet excès négatif de la pression interstitielle est diminué dans le temps par les procès de consolidation, approché aux propriétés des sols granulaires. Des expérimentes numériques ont été exécutées pour étudier les problèmes par les changes de cohésion en temps.

Keywords : suction, slope stability, long term, clay

1 INTRODUCTION

It is well known in the international geotechnical practice that, for ensuring the short-term and long-term stability of cut slopes in cohesive soils, a different dimensioning method shall be used. Unfortunately, the use of dual planning does not form part of the practice in Hungary. In our study, it is dealt with the reasons for the different short-term and long-term behaviour of cohesive soils, as well as the importance and possibility of taking it into account.

2 SHEAR STRENGTH - WATER CONTENT RELATION

It is well known from the literature that the shear strength of cohesive soils (with the mud and materials of various plasticity also included) significantly depends on their water content (Carter and Bentley, 1991). We do not even intend to discuss the effect of water contents between the liquid limit and plastic limit in more details.

3 THE EFFECT OF NEGATIVE PORE WATER PRESSURE ON SHEAR STRENGTH

In case of water content below the plastic limit, the changes in shear strength of cohesive soils can be explained by capillary effects (www.up.ac.za) (see fig. 1).

The elastic capillary tube can be considered saturated with very small suction and large meniscus radius (a). This tube is saturated between two particles of a water layer in the clay (in this case, the meniscuses exist only at the boundaries of soil).

If the clay (tube) can dry up (b), the dewatering removes a small amount of water from the tube; thus, the suction is increased that reduces the length and diameter of tube (the clay particles are contracted together). The radiuses of meniscus are also reduced in order to compensate the suction. After all, the radius still remains less than that of the tube.

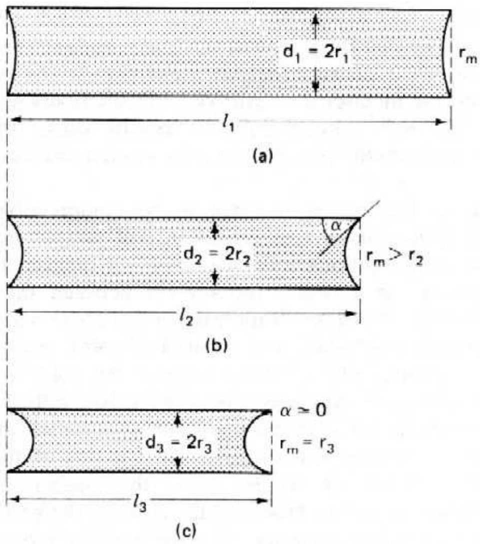

Figure 1. Capillary effects

With permanent drying, the meniscus radiuses and the dimension of tube will be reduced until the radiuses become equal to the radius of tube (c).This represents the maximum suction that can be maintained in the tube and it is at that point that the clay achieves its shrinking limit.

Should the drying continue even beyond this state, the meniscus is retracted into the tube while the suction remains constant. The clay fails to shrink any more; the saturation, however, is further reduced and the meniscus while retracting draws air into the soil. In case of porous media, it is called air entry value (AEV). This process is similar to the suction; in this way, however, the saturation of material is further reduced.

When drying the soils beyond the shrinking limit, the tensile stress prevailing in the water causes pressure between the

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particles that involves the increase in the shear strength (Kézdi, 1972). The existence and behaviour of the SSCC (suction stress curve) is supported by the unsaturated shear stress data found in the literature that relate to various kinds of soil types. The characteristics of the suction stress curve (Fig. 2.) and a method suitable to be used for its determination is shown by Ning Lu and Likos (2006). Based on the experimental evidences, it is stated that also the Mohr-Coulomb fraction and the critical state can be well described through the SSCC concept.

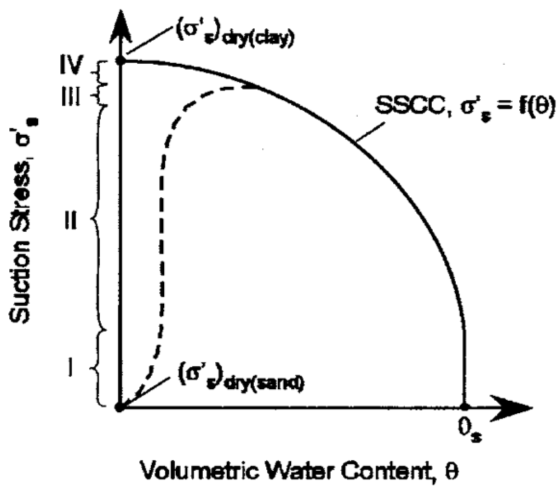

Figure 2. Suction Stress Curve

Depending on the possibility of water movement, the soils show different behaviour when get damaged/sheared (Kézdi, 1972):

In case of closed system, the excess pore water cannot be evacuated from the initially unloaded soil during the application of normal- and shear stresses. If the soil is saturated with water, the value of deviatoric stress causing failure is independent of the value of hydrostatic pressure prevailing in the soil. In this case, the volume of soil changes only to an insignificant extent; the soil acts like the ideally plastic bodies, that is, the value of shear strength is constant and independent of the value of full normal stress.

In an open system, the excess void water can always evacuated from the soil layer; thus, pore water pressure does not appear. In case of clay, the system can be considered open only if the load is developed very slowly and the consolidation is able to follow the changes in the stresses. In this case the cohesion of normally consolidated clay is zero; if, however, the soil is over-consolidated, a cohesion depending of its value appears.

By means of an appropriate experiment (breaking a specimen each normally consolidated and overconsolidated) the true (residual) friction angle and the value of cohesion can be determined.

The efficient and residual (true) friction angles of soils depend on their plasticity (clay mineral content): (Carter and Bentley, 1991), Fig. 3.

As a matter of fact, the cohesion of cohesive soils is the result of the suction that appears in the pore water during the shearing deformation (when the soil is kneaded thoroughly) and under its effect (Schofield, 1988).

In case of undrained shear and in critical state, the effective stress is constant and the strength of soil also remains constant; in fact, the value of friction angle of the soil being in critical state does not change in liquid state. In a thoroughly kneaded soft soil, the small clay particles and chemical bonds cause suction. Due to the equilibrium of stresses, the suction in pores is equal to the positive effective stress between the particles, therefore, in the thoroughly kneaded plastic clay, the

(virtual cohesion) = (suction) * (friction).

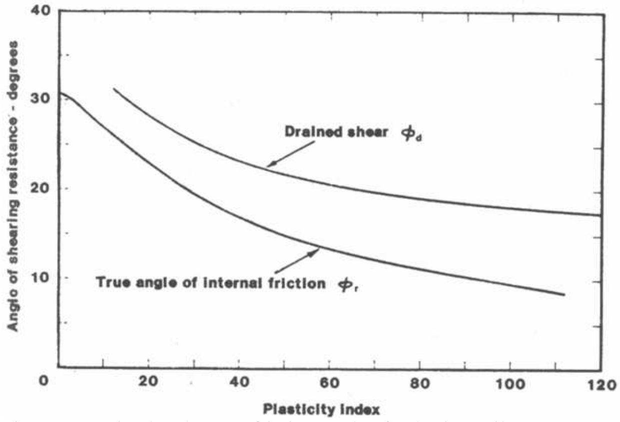

Figure 3. Drained and "true" friction angle of cohesive soils

4 STABILITY – TIME RELATION

Thus, as shown in the previous chapter, the behaviour of cohesive soils differs significantly depending on the fact that they form a closed or an open system in respect of their water content. Unfortunately, this dual calculation method is not used in the Hungarian design practice that would be especially very important in the calculation of cuts (Skempton, 1964).

When a cut is made in clay, the pore water pressure in any point depends on the ground water level, on the one hand and, to a significant extent, on the changes in stresses as well that take place inside of the clay during excavation, on the other hand. Nevertheless, these pore water pressures become equalized through the clay in course of time until they gradually get in hydrostatic balance with the ground water at all points. It is that state that is known as a long-term behaviour as opposed to the short-term state or the state at the time of building-completion.

Every natural slope is in the state of long-term stability; in case of cuts, however, several months or years are necessary to reach this state. The time required to this depends mainly on the permeability of clay.

It is remarkable that, during shearing the overconsolidated materials are susceptible to be expanded, especially after they have reached the peak value of shear strength.

In other countries, significantly more stress is laid on the durability, e.g. (Geotechnical Design Manual, 2005).

The overconsolidated cohesive soils are very hard and consist of silt and clay of variable plasticity. These soils are stable even in nearly vertical walls for a limited time; the reduction of horizontal stresses, however, results in cracks and may cause slumps within short time. In these soils, the slopes should be planned according to their internal residual friction angles and implemented with an inclination of 1:4 to 1:6. The shear strength parameters of cohesive soils can be determined from undisturbed soil samples by means of consolidated undrained triaxial experiment, using pore water pressure measurement, provided that the soil of the planned slope is saturated or might become saturated in the future. It is these effective shear strength parameters obtained from these tests that shall be used to plan the cuts and examine their long-term stability. Unconsolidated, undrained (UU) triaxial tests or direct shear tests can be used to obtain parameters for the analysis of short-term stability or if the planning based on the total stresses is sufficient. The necessary tests can be performed according to the expected stress condition and the estimated failure surfaces. One must know that the shear strength parameters obtained from unsaturated tests are independent of the water content at which the tests were performed. If the water content of the soil in question increases in the future, especially if it becomes saturated, its shear strength can be significantly reduced. Repeated direct shears can be performed in order to determine the value of remaining shear strength parameters in slumped areas. Residual strength parameters are required for planning cuts in case of very much overconsolidated soils; in fact, removal of part of earth releases the stresses included and makes it possible that the clay suffers significant deformation.

External effects (vegetation, rainfall, dynamic effects, and earthquakes) can significantly modify the in-time development of stability.

Reduction of suction is a significant destabilizing factor and the resulting unstable mass was the source of several very serious landslides (Lacerda, 2007). The vegetation increases the shear strength of the soil surface that, as a result of root-reinforcing, can be taken into account as cohesion. Where the ground water level is deep seated, the slopes are essentially stable. Nevertheless, the infiltration of rainwater can bring this superficial layer into a nearly saturated state. If the limit of saturation reaches certain depth below this root zone, the loss from the virtual cohesion may cause the sliding of the slope.

Stability against landslide and rainfall: it is possible that the rainfall influences the stability against landslide by stopping the suction (negative pore water pressure), and the increasing positive pore water pressure accelerates the loss of stability (Lan et al., 2003). The effect of rainfall on the resistance against landslide is in close relationship with the permeability and height of the slope.

The earthquakes of estimated frequency between thirty and fifty years accelerate this deformation (Picarelli et al., 2006). Especially, it is the strongest ones that are responsible for the landslides following the earthquakes as a result of equalization in the pore water pressure caused by vibrations.

5 FINITE ELEMENT ANALYSIS OF CUT SLOPE IN HOMOGENOUS CLAY

In the numeric model experiment, we examined the consequences of taking the closed system and open system pore water into consideration. For a few cases, we determined (by using the Plaxis V8.6 program) the relationship between the true friction angle that converts the effect of suction appearing in the pores into shear load bearing capacity and the equivalent cohesion that can be allocated to the quick examination.

The characteristics of the model:

- Geometry:
  - o Slope height: $h = 5$ m
  - o Slope inclination: 1:4 (14.04°)
- Soil parameters:
  - o Unit weight: $\gamma = \gamma_{sat} = 21$ kN/m^3
  - o Permeability: $k = 10^{-9}$ m/s = 8,64 10^{-5} m/day
  - o Poisson ratio: $\upsilon = 0.35$
  - o Oedometric modulus: $E_{oed} = 8$ MPa

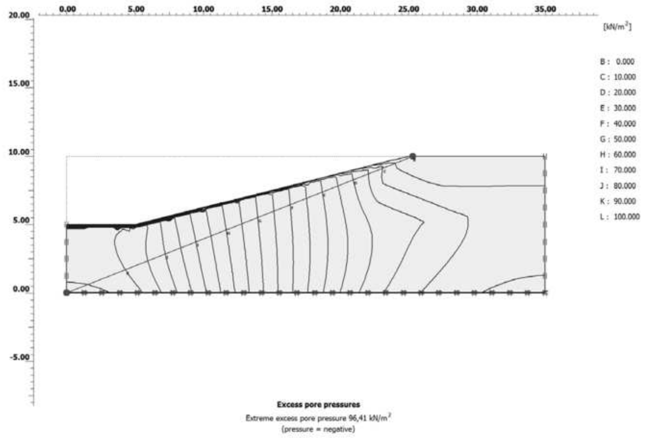

Figure 4. Pore water pressure due to soil excavation

The short-term safety of soil was determined for true friction angles of 15, 17.5, 20, 22.5 and 25 degrees (closed system, undrained model). With the same values, we also calculated the long-term stability (open system, drained model and calculation of consolidation), and determined the value of virtual cohesion (undrained, quick shearing strength) that gives the same safety in short term (complete stresses, drained model). Suction (negative pore water pressure) under the effect of soil excavation, the potential failure mechanism (closed system, undrained model, φ=20°) and the relationship of the virtual cohesion and the true friction angle are shown in Figs. 4 to 6. The relationship between the tangent φ and c is linear.

Table 1. Results in homogenous clay

Friction angle φ [°]	Cohesion c [kPa]	Soil behaviour	Factor of safety
15	0.1	undrained	1.91
15	0.1	drained	1.22
0	29.8	drained	1.91
17.5	0.1	undrained	2.25
17.5	0.1	drained	1.41
0	35.1	drained	2.25
20	0.1	undrained	2.60
20	0.1	drained	1.60
0	40.5	drained	2.60
22.5	0.1	undrained	2.95
22.5	0.1	drained	1.78
0	46.1	drained	2.95
25	0.1	undrained	3.31
25	0.1	drained	2.01
0	51.7	drained	3.31

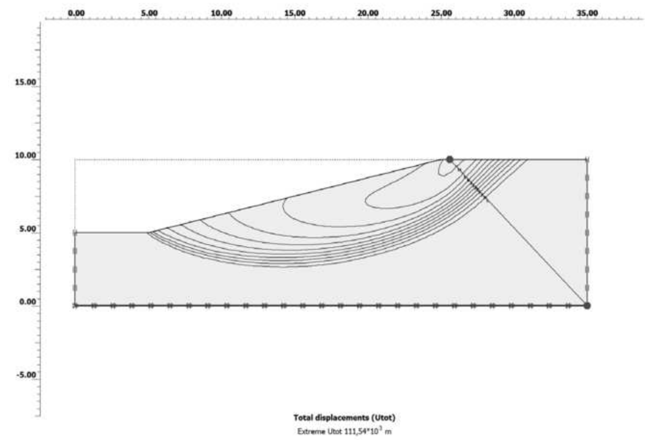

Figure 5. Potential failure mechanism

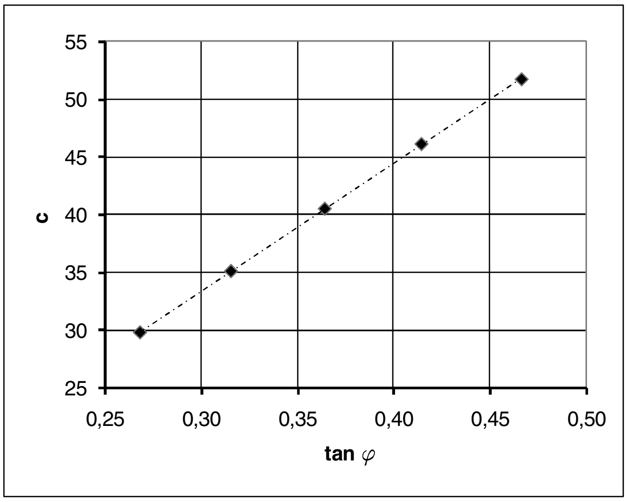

Figure 6. True friction angle vs. virtual cohesion

6 ANALYSIS OF BLOCK SLIDE

We also examined the case that a grained soil of high friction angle is situated over a clay layer. The finite element model is shown Fig. 9.

- Geometric data:
  - Depth of cut: h=10 m.
  - Slope inclination: 1:1.5 (33.7°).
  - Dip of clay layer: 5°.
- Soil characteristics
  - Clay
    - True friction angle: φ=20°
  - Grained layer:
    - Friction angle: φ=40°
    - Unit weight: $\gamma = \gamma_{sat}$ =18 kN/m3
    - Oedometric modulus: E_{oed} =40 MPa

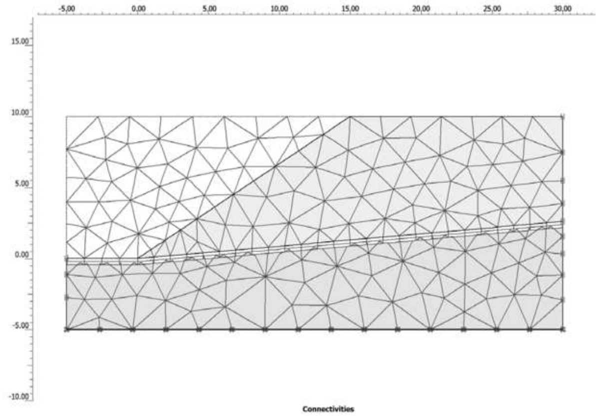

Figure 7. Finite element model of block slide

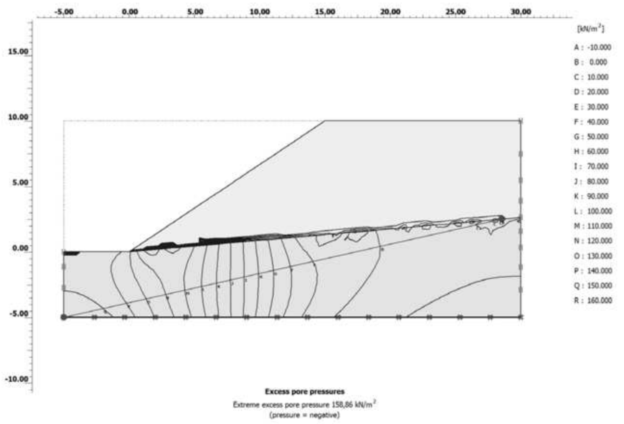

Figure 8. Pore water pressure

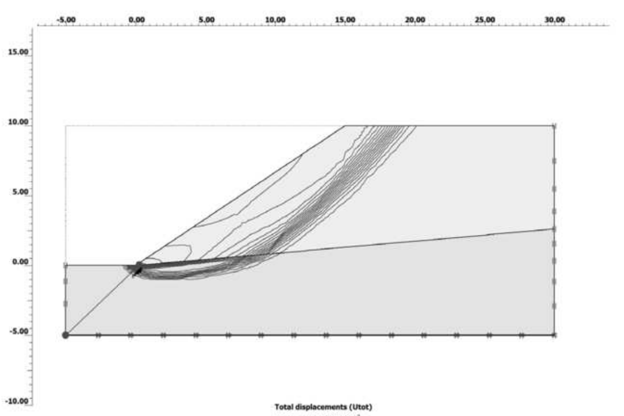

Figure 9. Failure mechanism

The negative pore water pressure under the effect of excavation and the potential long-term failure mechanism are shown in Fig. 8. and Fig. 9.

The obtained factors of safety are:
Immediate: n=1.48
Long-term: n=1.17
The equivalent virtual cohesion: c=48.4 kPa.

7 SUMMARY

In case of cuts made in cohesive soil, it would be very important to perform the stability analysis for short term and long term as well; in fact, in this latter case, the safety factor may be significantly lower. The examination of long term stability is also required in case of possible block sliding on the surface of clay layers. Doing only a short term analysis may result in serious damage within a few months/years following the implementation of cut.

For these calculations, the true friction angle of cohesive soils shall also be determined which is not included in the current laboratory processing practice. The true (residual) angle of friction and the suction (negative pore water pressure) originating from pre-loading (that can result from overconsolidation and the effect of excavation) ensure the virtual cohesion of soil and its unconsolidated quick shear strength. This shear strength can be increased by the effect of root system; however, it can be cut back by the thorough soaking or dynamic effects within very short time.

In overconsolidated clays of low water content (below shrinkage limit) the virtual cohesion can remain for significantly longer time; in fact, as a result of saturation, the suction is cut back more slowly. Nevertheless, the fact that the natural slopes are fairly flat proves the correctness of the above.

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