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Variation with time of the factor of safety of slopes excavated in unsaturated soils

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ABSTRACT

While the evolution with time of the factor of safety against slope failure is well understood for excavations performed under fully saturated conditions, this evolution has not been extensively studied for excavations carried out in unsaturated soils. The objective of this paper is to investigate the relationship between the factor of safety and time for an excavation performed in an unsaturated silty soil, employing the finite element method. A hypothetical boundary value problem is considered and two types of analyses performed; in the first one, unsaturated soil behaviour is modelled through appropriate constitutive and soil–water retention curve models, whereas in the second one full saturation is assumed. The effect that the saturated soil permeability, its variation with suction, the increase of apparent cohesion due to suction, the depth of the groundwater table and the hydraulic hysteresis have on the results of the unsaturated analysis is examined in a parametric study. The analyses results demonstrate that for unsaturated soils the factor of safety may increase with time, in contrast to what is commonly accepted to be the case in fully saturated soils. Furthermore, it is not possible to know in advance which one of the two types of analysis performed (i.e. the saturated or the unsaturated) will produce conservative results. It is, therefore, advisable to perform unsaturated analysis in geotechnical practice, when dealing with excavations in such soils.

1. Introduction

Failure of excavated slopes constitutes an important geotechnical problem with various socio-economic implications. The presence of water within the soil pores is a key aspect in slope stability for two distinct reasons: (a) the effective stress and, consequently, the available soil strength is affected by the pore water pressure (pwp) and (b) the water phase has a central function in the consolidation/swelling process in soils of relatively low permeability. This is particularly applicable in the case of excavated slopes (e.g. for highway and railways systems). In a fully saturated soil the unloading imposed during the excavation generates negative excess pwp's. As these dissipate with time and negative load is transferred from the incompressible water phase to the compressible soil skeleton, the effective stresses are gradually reduced. As a result of this process (swelling), an excavated slope which was stable in the short-term might fail as the pwp's rise in the long-term.

As detailed by Bishop and Bjerrum [3] for fully saturated conditions, slope stability reduces with time since the mean effective stresses decrease with swelling and equilibration of the initially depressed pore water pressures. Leroueil [12] presented the degradation of the factor of safety with time, calculated by Chandler [4], for slopes excavated in fully saturated brown London clay (Fig. 1) and noted that the time necessary to reach pore pressure equilibration depends on the swelling properties of the soil, its hydraulic conductivity, the stratigraphy of the deposit and the geometry of the excavation.

Nonetheless, soils on significant areas of the earth's surface are unsaturated above the groundwater table (GWT) [8], exhibiting a significantly different behaviour in comparison to their saturated state below the GWT. Several constitutive models have been developed for unsaturated soils (e.g. [2,27,9,20,13,29,24]) which usually collapse into a model for saturated soils. Although this is automatically done in constitutive models developed in terms of Bishop's effective stress and suction (e.g. [27,20]) or Bishop's effective stress and degree of saturation (e.g. [29]), a switch to Terzaghi's effective stress is required in order to model the transition from unsaturated to saturated states in models developed in terms of net stress and suction (e.g. [2,9,24]) – see also Nuth and Laloui [15] and D'Onza et al. [5]. In this way, the same model can be used in an analysis both below and above the GWT, naturally accounting for the change in the soil behaviour caused by fluctuations of the GWT and the saturation front.

While the evolution with time of the factor of safety against slope failure is well understood when excavating under fully

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saturated conditions, the case of excavating in unsaturated soils has not been extensively investigated. This paper presents a numerical study of this evolution in an unsaturated silty soil and it is shown to be significantly different from the gradual degradation observed in fully saturated soils. The finite element (FE) method was employed and the Imperial College Finite Element Program (ICFEP – [17]) was used. A 10 m deep excavation was performed in a coupled consolidation analysis and the negative excess pwp's were allowed to dissipate with time until steady-state was reached. The factor of safety, F_s, was evaluated at selected times, each of which corresponded to a different pwp distribution, before reaching the steady-state, i.e. the clock was stopped when F_s was calculated (drained analysis). The same boundary value problem was approached in two distinct ways. In the first, a constitutive model appropriate for unsaturated soils [23,24] was employed, in combination with an appropriate soil–water retention curve model [23,25] and an algorithm describing the fluid flow within the unsaturated soil pores [21]. In the second, a version of the modified Cam-clay model [17] was used and a conventional algorithm for the flow of water within fully saturated soils was employed in the analysis. The former analysis is referred to as "unsaturated" and the latter as "saturated". As the two constitutive models are essentially the same under saturated conditions the difference between the two analyses is that in the former a realistic air-entry value of suction is assumed whereas in the latter the air-entry value is assumed to be infinite, thus preventing de-saturation.

The soil properties adopted in the study were based on the laboratory data published by Estabragh and Javadi [7] for an artificial silty clay tested at a high overconsolidation ratio (OCR was 5.5). A parametric study, regarding the effect on the numerical results of soil parameters and conditions which were uncertain, was performed. This included the effect of the saturated soil permeability, its variation with suction, the increase of apparent cohesion with suction, the position of the initial GWT and the hydraulic hysteresis often observed in unsaturated soils. The results lead to the conclusion that some aspects of the analysis, such as the value of saturated soil permeability and the depth of the initial GWT, have a significant effect on the numerical outcome, whereas others, such as the presence of hydraulic hysteresis, did not influence the results considerably. These results can be used as guidelines on which soil properties are of outmost importance to be accurately established. Furthermore, it is demonstrated that, contrary to current knowledge, short or intermediate-term slope stability may be critical in unsaturated soils.

2. Methodology

2.1. Constitutive model

The constitutive model of Tsiampousi et al. [24] was employed in the unsaturated analyses. This model follows a conventional approach for saturated states below the GWT (based on the effective stress principle) while the effect of de-saturation on the soil behaviour is modelled above the GWT employing two independent stress variable (Terzaghi's effective stress principle no longer applies). The model, which is a modification of the Georgiadis et al. [9] model, offers various options regarding the isotropic compression line in unsaturated states (linear; bi-linear; non-linear), the soil compressibility with suction (constant or degree of saturation, S_r, dependent) and the shape of the yield and plastic potential surfaces (as later explained). The version employed in the current study is similar to the Barcelona Basic Model (BBM) of Alonso et al. [2], apart from four significant differences:

(a) The two stress variables adopted in the formulation of the model are:

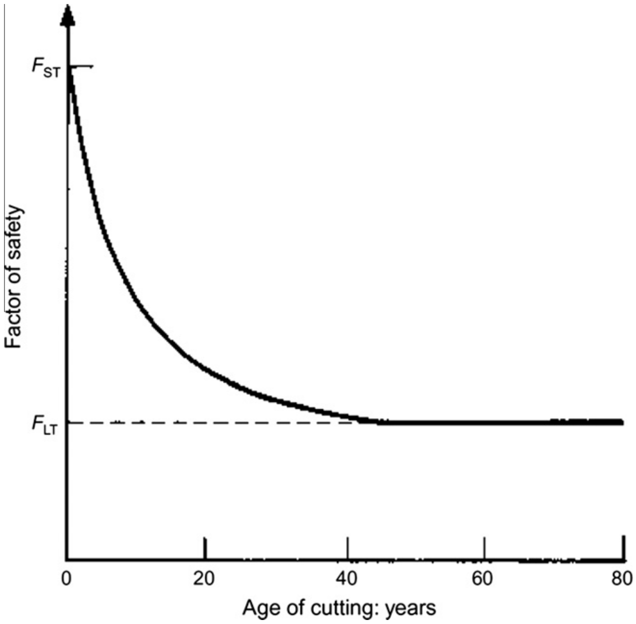

Fig. 1. Degradation of F_s with time for cuts in fully saturated brown London clay (after [12], from [4]); F_{ST} and F_{LT} refer to the short and long-term factors of safety, respectively.

a. The equivalent suction, s_{eq}, defined as the excess of the current suction, s, over the air-entry value of suction, s_{air}:

$$s_{eq} = s - s_{air} \tag{1}$$

b. And the equivalent net stress, σ, defined as the sum of the net stress $\sigma_{net} = \sigma_{total} - u_a$ (σ_{total} being the total stress and u_a being the air-pressure) and the air-entry value of suction, s_{air}:

$$\sigma = \sigma_{net} + s_{air} \tag{2}$$

In this way, the transition from saturated to unsaturated states is modelled at the air-entry value of suction. If, however, $s_{air} = 0$, as presently, the stress variables reduce to the matrix suction, s, and the net stress, σ_{net};

(b) The increase of apparent cohesion with suction is a function of the degree of saturation, S_r, i.e. the yield surface extends in the tensile region by an amount equal to $s_{eq} \cdot S_r$. The apparent cohesion can be calculated by multiplying the slope of the critical state line in the deviatoric stress, J – mean net stress, p, plane by $s_{eq} \cdot S_r$ (see also Fig. 2). Alternatively, the model allows a linear increase of apparent cohesion with suction

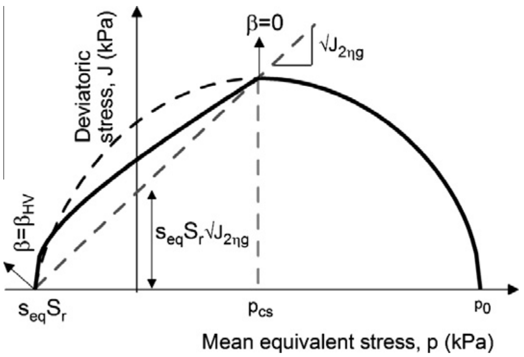

Fig. 2. Hvorslev surface on the dry side of the critical state.