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Making unsaturated soil mechanics accessible for engineers: Preliminary hydraulic–mechanical characterisation & stability assessment

Alessandro Tarantino *, Gráinne El Mountassir

Department of Civil and Environmental Engineering, University of Strathclyde, UK

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ABSTRACT

The paper presents an accessible approach for preliminary hydraulic and mechanical characterisation of unsaturated soils and stability analysis of geo-structures under unsaturated conditions. The approach is 'accessible' in the sense that the laboratory investigation and geotechnical analyses can be completed in a relatively short time and at a reasonable cost. The overall philosophy behind this approach is that laboratory testing should not be eliminated but kept to a minimum and that any simplification introduced should be conservative. The paper illustrates that shear strength can be characterised conservatively by performing constant water content tests with no facilities to control/monitor suction and that water retention behaviour can be predicted successfully by performing a single water retention measurement. The paper also demonstrates that stability analyses can be carried out within the classical framework of limit analysis. We show that a preliminary analysis of the influence of infiltrating rainwater on suction can be carried out using a simple and conservative method that makes use of solutions available in 'saturated' geotechnical textbooks. Such an approach may be used to assess when it is worthwhile or necessary to conduct further time consuming and costly unsaturated experimental testing, field monitoring and numerical analyses when considering the stability of geostructures.

1. Introduction

Geotechnical structures like embankments, cuttings, earth dams, retaining structures, slopes, and foundations are very often located above the groundwater table and their response therefore involves layers with negative pore-water pressures, which are generally unsaturated. The effect of negative pore-water pressure is very often neglected in engineering practice because either i) the ground water table is assumed conservatively to be at the ground surface or at the surface of the retained material (e.g. shallow and deep foundations, retaining structures) or ii) the soil above the water table/phreatic surface is assumed to be dry in the sense that pore-pressure is set to zero in the analyses (e.g. back-analysis of failures, embankments).

Assuming that the ground water table is at the ground surface can result in significant over-design of engineering structures, and cost savings could be possible if a proper assessment of the unsaturated behaviour and hydraulic boundary conditions (e.g. rainfall) was made. In many cases, cost savings would also be accompanied by a reduction in the energy and carbon 'embodied' in the geotechnical structure.

On the other hand, the design of remediation and upgrade measures for geotechnical structures is often based on the back-analysis of existing geotechnical structures, which can be misleading if the influence of suction above the water table is ignored. For example, steep artificial and natural slopes, including vertical and near-vertical cuts, are often stable because of the suction generated by partial saturation. If this effect is not understood and quantified, an effective cohesion can misleadingly be assigned to the soil.

Overall, neglecting the unsaturated aspects of behaviour can lead to problems associated with ground–atmosphere interactions being overlooked, which may be costly to remedy at a later stage. These include foundation subsidence associated with shrinkage after prolonged periods of dry weather, heave in swelling soils, volumetric collapse of meta-stable open soils, and instability of natural and artificial slopes triggered by rainfall.

To implement unsaturated soil concepts into current geotechnical practice, simple tools need to be developed for 'preliminary' assessment of the effect of suction on the response of geostructures. As a first step in this direction, this paper focuses on the pre-assessment of stability of 'routine' geotechnical structures in unsaturated soils based on simple analytical procedures using a very limited set of laboratory data. This approach is 'accessible' in the sense that the laboratory investigation and geotechnical analyses can be completed in a relatively short time and at a reasonable cost. The overall philosophy is that laboratory

* Corresponding author at: Department of Civil Engineering, University of Strathclyde, 107 Rottenrow, G4 0NG Glasgow, Scotland, UK. Tel.: +44 141 548 3539; fax: +44 141 553 2066.

E-mail address: alessandro.tarantino@strath.ac.uk (A. Tarantino).

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testing should not be eliminated but kept to a minimum and that any simplification introduced in data interpretation and analyses should be conservative. This approach is intended to be used to identify (and not replace) when a more accurate design based on appropriate laboratory testing, field monitoring, and numerical analysis is required.

2. An accessible and inexpensive approach to unsaturated shear strength characterisation

A shear strength equation is required to analyse the stability of geotechnical structures. There is no unanimous consensus concerning the relationship to model the effect of partial saturation on the shear strength of unsaturated soils. Two shear strength criteria are therefore identified and validated in this paper, which will serve as the basis to discuss an approach for a low-cost estimation of unsaturated shear strength.

For the sake of simplicity, the paper will focus on the critical (ultimate) shear strength, which in general enables a conservative estimate of the factor of safety against instability to be made. It is assumed here that the parameters characterising the shear strength at the critical state are independent of void ratio, similar to saturated soils.

2.1. Ultimate (critical) shear strength criteria for unsaturated soils

Shear strength criteria for unsaturated geomaterials proposed in the literature generally fall into two broad categories. The first approach assumes that the contribution of partial saturation to shear strength is only dependent on suction (Fredlund et al., 1978; Alonso et al., 1990; Khalili and Khabbaz, 1998). In this case, shear strength is expressed by Eq. (1)

$$\tau = \sigma \tan \phi' + \Delta\tau(s) \quad \text{or} \quad q = \mathrm{M}p + \Delta q(s) \tag{1}$$

where τ is the shear strength, σ is the total stress normal to the failure plane, ϕ' is the 'saturated' angle of shearing resistance, $\Delta\tau$ is the contribution of partial saturation to shear strength, s is the suction, q and p are the deviator and total mean stress at the ultimate state respectively, M is the slope of the 'saturated' critical state line, and Δq is the contribution of partial saturation to deviator stress at the ultimate state.

The second approach assumes that the contribution of partial saturation to shear strength is independently controlled by both suction and degree of saturation (Toll, 1990; Vanapalli et al., 1996; Öberg and Sällfors, 1997) according to Eq. (2)

$$\tau = \sigma \tan \phi' + \Delta\tau(s, S_r) \quad \text{or} \quad q = \mathrm{M}p + \Delta q(s, S_r) \tag{2}$$

where S_r is the degree of saturation.

Eq. (2) suggest that different degrees of saturation at given level of suction lead to different values of ultimate shear strength. Different degrees of saturation may occur at the same suction because of the effect of void ratio on the water retention curve (Romero and Vaunat, 2000; Karube and Kawai, 2001; Gallipoli et al., 2003) or hydraulic hysteresis. The variation in ultimate shear strength at a given suction associated with a change in the degree of saturation may be significant. Fig. 1 presents the contribution of partial saturation to ultimate shear strength for reconstituted BCN clayey silt samples (Boso, 2005). Three series of samples were tested in the direct shear box. Each series was obtained by consolidating samples from a slurry state to different vertical stresses, σ_{cons} (100, 300, and 500 kPa). Samples from each series were subjected to different values of suction by air-drying to target water contents; samples were subsequently sheared in a suction-monitored shear box. The three different initial pre-consolidation stresses generated different initial void ratios and, hence, three different water retention curves (Tarantino, 2009). As a result, samples from these three different series showed, at the same suction, different degrees of saturation at the ultimate state as shown in Fig. 1a. This resulted in significantly different critical state shear strength at a given suction. It is worth noticing that if shear strength data are plotted against the product of suction s times the degree of saturation S_r as shown in Fig. 1b, differences tend to disappear suggesting that suction and degree of saturation independently control shear strength according to Eq. (2).

The independent effect of suction and degree of saturation is also illustrated in Fig. 2a, where the contribution of partial saturation to the ultimate deviator stress Δq is plotted against suction for compacted kaolin samples dried from a saturated state or wetted after being dried to a given degree of saturation (Uchaipichat, 2010). At the same suction, the degree of saturation is higher along a drying path than on a wetting path (hydraulic hysteresis) and this results in a higher deviator stress contribution as shown in Fig. 2a. Again, if the contribution to deviator stress Δq is plotted against suction weighted by an 'effective' degree of saturation, differences between samples on the drying and wetting curve disappear (Fig. 2b).

The concept of effective degree of saturation has been discussed by Tarantino and Tombolato (2005) and Tarantino (2007). They observed that the shear strength of unsaturated compacted clay could be modelled using the following equation:

$$\tau = (\sigma + sS_{rM}) \tan \phi' \quad \text{or} \quad q = M(p + sS_{rM}) \tag{3}$$

where the contribution of partial saturation to shear strength is proportional to suction weighted by the degree of saturation of the macropores, S_{rM}. This is defined as:

$$S_{rM} = \frac{e_w - e_{wm}}{e - e_{wm}} \tag{4}$$

where e is the void ratio, e_w is the water ratio (i.e. e_w is the volume of water per volume of solids, $e_w = wG_s$), and e_{wm} is the microstructural water ratio, which is associated with the adsorbed water stored in the saturated aggregates (Eq. (4) is only valid for $e_w > e_{wm}$). The rationale behind this approach is that only capillary water in the macropores, i.e. the water in the pore space between the aggregates, contributes to shear strength. Tarantino and Tombolato (2005) determined the microstructural water ratio e_{wm} as a best-fit parameter using Eqs. (3) and (4) and found this value to be in very close agreement with the microstructural water ratio inferred from the measured pore size distribution (Tarantino and De Col 2008). A similar idea can be found in the Soil Science literature. Nearing (1995) analysed unconfined compression data on compacted 'aggregated' clay and also speculated that shear strength is only controlled by inter-aggregate water.

An approach based on an 'effective' degree of saturation was also presented by Vanapalli et al. (1996):

$$\tau = \left(\sigma + sS_r^k\right) \tan \phi' \quad \text{or} \quad q = \mathrm{M}\left(p + sS_r^k\right) \tag{5}$$

where the degree of saturation is scaled through the exponent k. Eqs. (3) and (5) suggest that only one parameter is sufficient to model unsaturated shear strength, in addition to the 'saturated' parameters and can therefore in principle be determined by performing a single shear test. To assess the capability of Eqs. (3) and (5) to model the shear strength of unsaturated soils, 18 datasets were examined in this paper. Reconstituted, compacted and natural soils were considered with grain size distributions ranging from clayey to sandy soils (Table 1). Parameters e_{wm} and k were obtained by best-fitting using the least square method and are also reported in Table 1. Ultimate (critical) state data were considered.

The validation of Eqs. (3) and (5) is presented in Figs. 3 and 4. It can be observed that the two models fit the experimental data in a very similar way and that both models perform quite well. These two models are indeed very similar at relatively high degrees of saturation as discussed by Alonso et al. (2010). It is interesting to note that when the clay fraction is negligible or absent and little or no aggregation is expected, data are fitted by $e_{wm} = 0$ and $k = 1$ (Fig. 4). This corroborates the