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On modelling the compressibility of unsaturated fine-grained soils

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Abstract

An empirical expression linking the slope λ of the normal compression line (NCL) for unsaturated soils to the effective degree of saturation S_e is studied in this technical note. The parameters in this empirical expression are intrinsic soil parameter α, the slope of the normal compression line (NCL) at full saturation, $\lambda_{100\%}$, and the slope of the normal compression line at the driest state achievable by a soil, λ_d (a state at which only adsorbed water remains in the pores). The determination of λ at any other level of saturation usually requires a considerable amount of test data. This technical note explores the relationship between regression parameter α and the particle size, quantified by the D_{10} of the soil, based on test data for five different soils taken from the literature. A regression equation is developed that relates α to D_{10}. Based on the proposed regression equation, the slope of the normal compression line for unsaturated fine-grained soils at any degree of saturation can be estimated when the test data are limited.

Keywords: Unsaturated soil; Effective stress; Volume change behavior; Normal compression line (NCL); Particle size

1. Introduction

The principles of soil mechanics are well understood and widely accepted for saturated soils (Salgado, 2008; Terzaghi, 1943). However, those of unsaturated soils are not understood to the same degree. This technical note focuses on the response of the normal and isotropic compression of unsaturated soils. This response is expressed in saturated soil mechanics using the normal compression line (NCL), which is defined as a straight line in the plane of specific volume υ versus the natural logarithm of mean effective stress p'.

$$\upsilon = N - \lambda \ln \frac{p'}{p_r} \quad (1)$$

where p_r is a reference stress used for normalization (usually set to 1 kPa); N is the specific volume at the chosen reference stress; and λ is the slope of the normal compression line, observed to be a constant for a specific soil.

Ideally, in formulating an effective stress-based formulation for unsaturated soil mechanics, the NCL should be unique in the υ vs ln p' space, with p' defined in a way that takes into account the degree of saturation of the soil and the resulting suction (Sheng, 2011a). Lu and Likos (2006) have, in essence, separated the sources of the interparticle forces that can be determined (total stress, pore water pressure, and air pressure) from those that cannot be measured or separately determined (surface tension, double layer forces, and van der Waals forces). These forces should all satisfy the governing equations, starting

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with equilibrium in a static problem. They are interrelated, depending on the same intrinsic soil variables, and are enabled by each other. For example, surface tension only exists because of the coexistence of air and water; and thus, the difference between air and water pressures is directly related to it.

Since surface tension, double-layer, van der Waals, and any other electro-chemical forces cannot be measured, a definition of effective stress accounting for suction (the difference between air and water pressures enabled by these forces) that recovers the principle of effective stress for fully saturated and practically dry soil is desirable. This definition requires a parameter in order to reflect the complex interaction between these forces. To the degree that these interactions cannot be accurately captured, non-uniqueness in certain constitutive relationships may occur, including on the normal compression line (NCL) in space.

The main objectives of this technical note are to study the problem of volume change in unsaturated soils due to 1-D or isotropic compression and to assess how the slope λ of the normal compression line changes with the degree of saturation. Firstly, the proper selection of a stress variable (effective stress) is discussed as the use of *ad-hoc* stress variables can result in non-uniqueness for the normal compression line (NCL) in the $\upsilon - \ln p'$ space. Then, the expression proposed by Zhou et al. (2012a), used to model the λ of unsaturated soil as a function of the degree of saturation (in the form of the effective degree of saturation (Alonso et al., 2010)), is introduced. Subsequently, data available from the literature on the effect of the degree of saturation on λ are provided. Lastly, the effect of the particle size on λ is considered and a connection is made between an intrinsic parameter α (used to model the variation in λ with the degree of saturation) and the soil particle size distribution.

2. Stresses between soil particles

Considering a representative elementary volume (REV) of a soil–water–air mixture, as done by Lu and Godt (2013), and working with the assumption made by Houlsby (1997) that the areas on which pore-air and pore-water pressures act are proportional to their volume fraction, the following effective stress expression can be derived using the macroscopic stresses:

$$\sigma' = (\sigma_{\text{total}} - u_a) + S_e(u_a - u_w) \tag{2}$$

where σ' is the ratio of the summation of the soil-particle contact forces to the gross cross-sectional area of the soil; σ_{total} is the total external applied stress; u_a is the pore-air pressure; u_w is the pore-water pressure; and S_e is the effective degree of saturation, defined by Alonso et al. (2010) as

$$S_e = \frac{S_r - S_r^{\text{res}}}{1 - S_r^{\text{res}}} \tag{3}$$

where S_r is the degree of saturation and S_r^{res} is the residual degree of saturation at which the pore water in the soil only exists in micro-pores or in the adsorbed state.

Effective stress, as defined for use in Eq. (2), is the inter-particle force averaged over the gross surface area of the REV. The efficacy of the effective stress definition using S_e is affected by the type of soil considered, particularly the particle size. Surface tension and electrochemical forces are all affected by saturation and the particle size. Important for reflection in the present work, Lu and Godt (2013) showed that the electric double-layer repulsive forces, van der Waals forces, and surface tension forces all decrease with the increasing particle size and are weak in sand and gravel. As these forces are very low in sand, regardless of the degree of saturation, the compressibility of sand is not significantly influenced by the degree of saturation, an observation supported by Cho and Santamarina (2001) for spherical glass beads.

3. Normal compression line (NCL) of unsaturated soils

To extend Eq. (1) to the unsaturated state, two alternative assumptions have been proposed in the literature (Zhou et al., 2012a): (1) parameters N and/or λ are assumed to be functions of suction s and (2) parameters N and/or λ are assumed to be functions of the degree of saturation, as expressed by either S_r or S_e.

In most geotechnical tests, it is possible to control and measure suction s using the axis-translation technique (Hilf, 1956; Vanapalli et al., 2008; Zhang and Li, 2010; Tang et al., 2017). Therefore, researchers initially attempted to link N and/or λ to s. This approach was widely used in early work on the constitutive modelling of unsaturated soils. Sheng (2011a,b) and Zhou et al. (2012a) pointed out that there are some limitations to this approach. Further investigation into the limitations of this approach is beyond the scope of this technical note. To overcome these limitations, Al-Badran and Schanz (2010, 2014) proposed the concept of "S_r – lines", according to which N and λ both increase with a decrease in S_r. Other researchers suggested linking only λ to S_r (Sheng, 2011a) or S_e (Zhou et al., 2012a,b), as, conceptually, parameter N should be a constant because it corresponds to the state at which the soil has experienced no consolidation at all (since it is equal to the value of the specific volume at a very small effective stress).

The NCL in the υ vs $\ln p'$ space can be written with its slope as a function of the degree of saturation, as suggested by Zhou et al. (2012a).

$$\upsilon = N - \lambda(S_e) \ln \frac{p'}{p_r} \tag{4}$$

The value of λ varies from that at full saturation ($\lambda_{100\%}$) to that at the driest state (λ_d). Zhou et al. (2012a) suggested the following form for the expression of λ:

$$\lambda(S_e) = \lambda_{100\%} - (1 - S_e)^{\alpha}(\lambda_{100\%} - \lambda_d) \tag{5}$$

where α is a fitting parameter that controls the variation in λ with S_e. Zhou et al. (2012a) suggested that λ_d may be taken as the slope of the elastic compression line in the

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