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On the Definition of an Effective Stress for Shales

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Summary

Energy-related engineering applications involving shales pose ever-increasing challenges for the constitutive modelling of these geomaterials. The present work proposes a new definition of effective stress developed by using a thermodynamic approach associated with the concepts of continuum mechanics. The developed expression makes explicit the dependence of the effective stress on the chemical composition of the pore water. The paper shows that the proposed expression is able to improve the interpretation of unsaturated shear strength envelopes that would be achieved by using other formulations.

Introduction

The term "shale", in agreement with the definition given by Terzaghi *et al.* in 1996, identifies a category of geomaterials mainly composed by silt-size and clay-size particles, characterized by lamination planes and displaying fissility. Nowadays, the geomechanical behaviour of shales is of great interest for energy-related applications. In this context, physical processes which induce variations in temperature and chemical composition of pore water, in a range of even negative pore water pressures, need to be considered. These processes may have significant mechanical effects depending on the stress history, on the intrinsic (i.e. clay size fraction and mineralogy) and on the initial state characteristics (i.e. void ratio, water content) of the fine-grained geomaterial under examination (among others: Wong, 1998; Cekerevac and Laloui, 2004; Ferrari *et al.*, 2014; Favero *et al.*, 2016; Ferrari *et al.*, 2016; Minardi *et al.*, 2016; Favero, 2017).

In addition to the possibility of using the effective stress as a variable for the definition of strength criteria and for the interpretation of elastic processes, the effective stress can be used as the only mechanical variable within an elasto-plastic approach (Laloui and Nuth, 2009). These perspectives make greater the interest for a meaningful and efficient formulation of it. In the context of unsaturated geomechanics, expressions of effective stress which are widely used today are those function of the matric suction and in which the scaling factors of the pressure of the fluids are considered to be the degree of saturation (Nuth and Laloui, 2008) or the effective degree of saturation (Lu *et al.*, 2010; Alonso *et al*., 2010; Rosone *et al*., 2016) and their complements to one.

However, extensive experimental campaigns performed on fine-grained soils (among others: Di Maio and Fenelli, 1994; Witteveen *et al*., 2013; Manca *et al*., 2016) and on shales (among others: Wong, 1998; Wakim *et al*., 2009; Ewy, 2014, 2015; Favero, 2017) show a dependence of their shear strength and their volumetric behaviour on the solute suction of the aqueous solution used to test them. Some of the aforementioned works has led researchers of the past to define expressions of effective stress as a function of electrochemical stresses (a review is given in Hueckel, 1992); these expressions - being derived at the particle scale by imposing mechanical equilibrium and compatibility equations - should be more correctly called inter-particle stresses and, although used at the REV scale, remain of limited practical use.

This contribution proposes a new theoretical formulation for the effective stress of fine-grained soils and shales and shows its performance for the interpretation of shear strength results.

Framework development

Clay minerals are part of the inorganic solid constituents of fine-grained geomaterials and shales. These minerals are characterized by the so-called isomorphic substitution degree: the Silicon (Si^{4+}) and Aluminum (Al^{3+}) ions are "substituted", within the theoretical crystalline structure, with ions characterized by lower valence. In spite of that, the electroneutrality of the dry clay minerals is ensured by the presence of cations on their external surfaces. The presence of water molecules results in the partial or total dissociation of these cations (Bolt and Bruggenwert, 1976). Such cations may also be exchanged with other cations characterizing the aqueous solution of the geomaterial. A measure of the quantity of ions exchangeable per unit mass of geomaterial is provided by the cation exchange capacity (CEC).

The proposed approach considers the geomaterial as a thermodynamic system characterized by a solid phase (clay minerals and not), a liquid phase (aqueous solution with different salts) and a gaseous phase (air). A Representative Elementary Volume (REV) of this material is placed in contact with a matric suction measurement system. The following conditions are imposed on the systems in contact under examination: i) the electroneutrality in the aqueous system characterizing the measurement instrument; ii) the electroneutrality of the geomaterial, and iii) the thermodynamic equilibrium conditions applied to the geomaterial and the measurement system. Thus, the determination of the pore water pressure within the geomaterial allows obtaining the following expression of effective stress:

$$\sigma'_{ij} = \sigma_{net,ij} + S_r(s_m - s_{o,e})\delta_{ij}$$

in which $\sigma_{net,ij}$ is the net stress tensor computed as a difference between the total stress tensor σ_{ij} and the air pressure tensor $u_a\delta_{ij}$, S_r is the degree of saturation, s_m is the matric suction and $s_{o,e}$ is the effective solute suction. The latter is found to be a function of the chemical composition of the aqueous solution and of the intrinsic characteristic of the geomaterial. Based on theoretical considerations, a model for the variation of the effective solute suction with respect to the degree of saturation is proposed.

Results

The parametric analyses carried out make it possible to verify, under certain conditions, a significant dependence of the effective stress on the chemical composition of the pore water, with consequent mechanical implications consistent with the experimental evidence. An example of reinterpretation of results with the proposed effective stress substituted in the Mohr-Coulomb (MC) failure criterion is given in Figure 1 with reference to shear strength tests performed under different matric suction values. In particular, the shear strength data and the retention curve were used to determine the parameters of the model that describes the variation of the effective solute suction with the degree of saturation. The non-linearity of the shear strength envelope in the plane matric suction-shear strength (well known in literature, Escario and Sáez, 1986) is well captured when the proposed effective stress is used and not if the generalized effective stress (Nuth and Laloui, 2008) is considered.

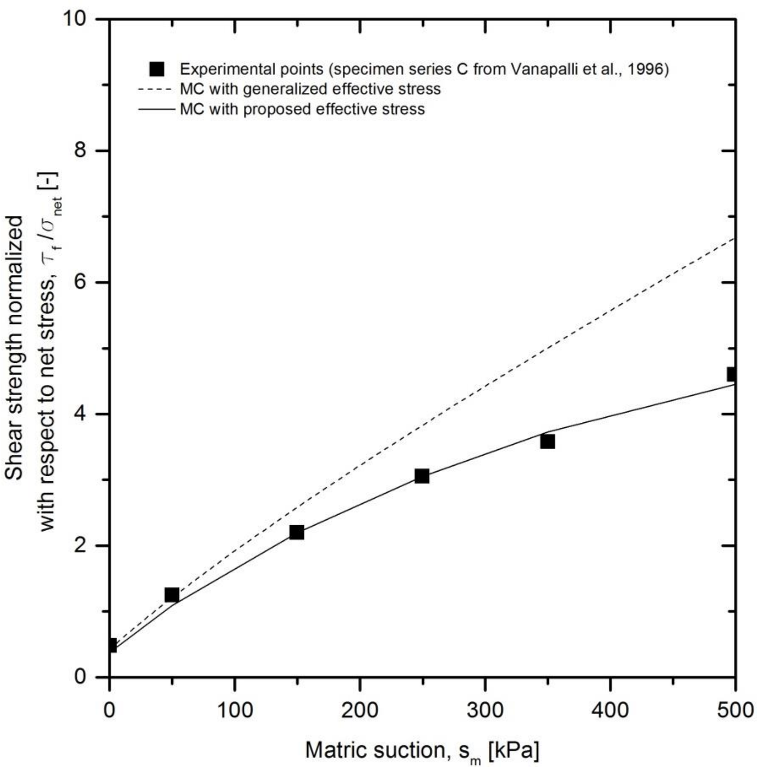

Figure 1 *Shear strength envelope of Canadian Glacial Till (test data from Vanapalli et al., 1996)*

Conclusions

The developed effective stress, replaced in the Mohr-Coulomb shear strength criterion, allows obtaining a better interpretation, compared to the one obtained with the generalized effective stress, of the results of shear strength tests under matric suction control. Furthermore, the proposed formulation makes it possible to explicitly consider the mechanical effects induced by a change in the chemical composition of the pore water. As a consequence, it has the potential to be used for interpreting comprehensively the results of tests on fine-grained geomaterials and shales subjected to variations in the pore water chemical composition, which otherwise, should be seen as results related to different geomaterials and used accordingly.

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