Effective stress concept for mechanical modeling of clays under different environmental conditions

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1 Introduction

Clays (especially if active) may exhibit different mechanical responses depending on their environmental conditions (e.g., Di Maio 1996; Manca et al. 2016). Due to this, advanced modeling of the mechanical behavior of clays must pay particular attention to the adopted: (i) stress variables, (ii) strain variables, and (iii) stress-strain relationships. In the context of continuum mechanics, a suitable effective stress framework can allow converting a representative elementary volume (REV) of real medium with m mixtures (solid substances and fluids) subject to n actions (total stress changes and environmental changes) into a mechanically equivalent continuum medium subject to a change in effective stress. In this study, a suitable effective stress concept for clays is presented, and the benefits of using it are demonstrated. For this purpose, first, based on recent physical-chemical studies of water-clay mineral interactions, the different types of ions and water in clays are recalled. Secondly, a thermodynamic-geochemical integrated approach is utilized to redefine the effective stress concept taking these findings into account. By analyzing experimental data taken from the literature, implications of using the proposed effective stress concept are finally explored. In this regard, among others, the uniqueness of the critical or residual failure envelope regardless of the chemical composition of the pore water or the saturation state is noteworthy.

2 Effective Stress Concept and Mechanical Modeling Implications

Figure 1 provides terminology for water and ions in the presence of clay particles (Tuttolomondo et al. 2020). Cations dissociated from the clay mineral surface are named non-movable ions; they can extend for more than 1 nm (Tournassat et al. 2009), up to 50 nm according to (Terzaghi et al. 1996). All other cations or anions are called movable ions. As a result of its structural peculiarities (Tuttolomondo et al. 2020), water within 1 nm from the mineral surface is classified as solid water; water beyond 1 nm is classified as liquid (pore) water. Thus, particular emphasis must be placed on recognizing the possible presence of movable and non-movable ions in liquid water. The diffuse layer and bulk water consist only of non-movable ions and movable ions, respectively.

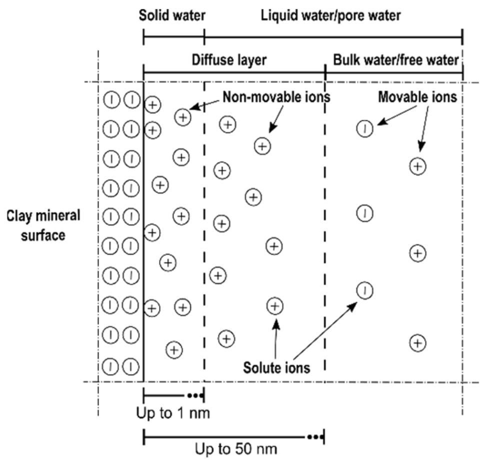

Fig. 1: Definition of water and ions in clays (redrafted from Tuttolomondo et al., 2021)

For unsaturated soils, the effective stress variable would take into account three different mixtures - solid mixture, liquid water, and gaseous solution (e.g., Nuth and Laloui (2008a)). By referring to unsaturated states and following a thermodynamic-geochemical integrated approach (like in Tuttolomondo et al. 2021), the effective stress variable for unsaturated clays can be expressed as follows:

$$\sigma'_{ij} = \sigma_{net,ij} + S_r(s_m - s_{s,e})\delta_{ij} \quad (1)$$

where $\sigma_{net,ij} = \sigma_{ij} - u_g\delta_{ij}$ is the net stress tensor (σ_{ij}: total stress tensor, u_g: gas pressure, δ_{ij} : Kronecker delta), $s_m\delta_{ij} = (u_g - u_w)\delta_{ij}$ is the matric suction stress tensor (u_w: measured, or externally imposed, water pressure), $s_{s,e}\delta_{ij}$ is the effective solute suction stress tensor, and S_r is the degree of saturation. The variable $s_{s,e}$ is the difference between solute suction in the pore water and

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bulk water. The former depends on both movable and non-movable ions, and an analitcal procedure for its determination is developed; the latter only on movable ions. Relationships describing the evolution of s_m and $s_{s,e}$ during the stress path of interest are essential in the newly developed framework.

Figure 2 shows the residual shear strength data of Ponza bentonite (plasticity index with distilled water equal to 320%, limit liquid with distilled water equal to 390%; Di Maio (1996) and Di Maio et al. (2004)), saturated with different solutions (Di Maio 1996), reinterpreted according to Terzaghi's effective stress (Fig.2a) and using the proposed definition (Fig. 2b) (Eq.1 for saturated states yields $\sigma'_{ij} = \sigma_{ij} - (u_w + s_{s,e})\delta_{ij}$) (cation exchange capacity equals 74 cmol/kg; fraction of non-movable cations within the pore water equals 0.15, (Tuttolomondo et al., 2021)). The latter framework enables better interpretation.

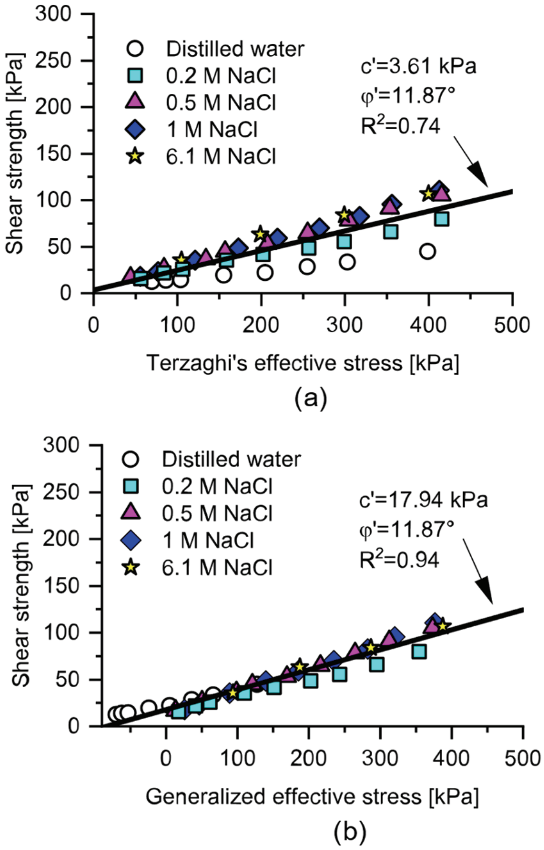

Fig. 2: Shear strength data with varying salt concentrations (experimental data from Di Maio, 1996) (redrafted from Tuttolomondo et al., 2021)

Figure 3 shows s_m and $s_{s,e}$ at varying S_r for compacted scaly clay from Sicily (liquid limit in the range of 60-64%, plastic limit in the range of 20-26%), at failure (Rosone et al. 2016). Soil water retention data are modeled according to Nuth and Laloui (2008b). Effective solute suction data are back-predicted based on shear strength and retention data. Using the developed analytical approach, back-predicted data are satisfactorily modeled.

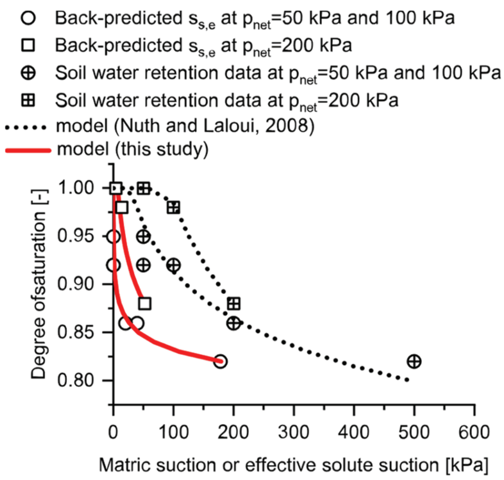

Fig. 3: Evolution of s_m and $s_{s,e}$ at varying S_r (experimental data from Rosone et al., 2016) (p_{net}: mean net stress)

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