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Effective stresses for unsaturated states stemming from clay microstructure

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HIGHLIGHTS

- A microstructure conceptual model to interpret mercury intrusion porosimetries.
- Two effective stresses for unsaturated states stemming from clay microstructure.
- Compacted clay is modelled by considering reconstituted clay and dry powder.
- Microstructure conceptual model for volume behaviour of compacted clays.
- Microstructure conceptual model for shear strength behaviour of compacted clays.

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ABSTRACT

The paper first discusses a novel microstructure conceptual model for compacted clays based on the assumptions that compacted unsaturated clay is made of a water-saturated part (pores filled with water) and an air-saturated part (pores filled with air). The microstructure conceptual model is exploited to interpret a variety of MIP from the literature. The paper then shows the capability of the two effective stresses for unsaturated states stemming from this microstructure conceptual model to model volume change and shear strength behaviour of compacted clays. The model built around these two effective stresses is based on the assumption that the water saturated part behaves like reconstituted clay under saturated conditions and the air-saturated part behaves like clay compressed from dry powder under dry conditions. As a result, mechanical behaviour of compacted clay is modelled by only considering constitutive parameters from reconstituted clay and clay compressed from dry powder.

1. Introduction

The effective stress introduced by Terzaghi[1] for saturated/dry geomaterials was established on an experimental basis '*all measurable effects of a change of stress, such as compression, distortion and a change of shearing resistance are due exclusively to changes in effective stress*'. The liaison of the effective stress with 'measurable' effects makes this concept essentially an experimental result rather than a theory or a principle. Nonetheless, attempts have been made to justify this 'principle' based on simple micro-mechanical models. Bishop[2] considered an assemblage of inert and sub-rounded particles (granular material) and showed that the effective stress can be interpreted as the '*part of the local contact stress which is in excess of the fluid pressure*'. This micro-mechanical view of the effective stress was further developed and validated experimentally by Skempton.[3]

For the case of unsaturated geomaterials, an experimental evidence justifying the use of net stress and matric suction as effective stresses for unsaturated soils was provided by Fredlund and Morgenstern[4] and Tarantino et al.[5] Later on, a number of effective stress pairs have been proposed based on either thermodynamics considerations within the continuum mechanics framework (e.g. Ref. 6) or micro-scale considerations on the basis of the different states of water in an unsaturated granular material.[7,8]

However, none of these effective stress pairs have been validated experimentally (e.g. via null-type tests) or interpreted via micro-mechanical conceptual models similar to the one presented by Bishop.[2] In addition, these effective stresses are based on a micro-scale representation of soils that is essentially associated with granular materials. For example, effective stress pairs proposed by Buisson and Wheeler,[7] Gallipoli et al.[8] and Wheeler et al.[9] are based on the assumption that water in the pore space is present in the form of either bulk water or meniscus water. This concept is

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Notation list

σ'_W	Effective stress acting on the water-saturated fraction [kPa]
σ'_A	Effective stress acting on the air-saturated fraction [kPa]
σ'^{*}_W	Equivalent water-saturated pre-consolidation stress [kPa]
σ	Mean net stress [kPa]
$\Delta\sigma$	Change in total stress [kPa]
u	Pore water pressure [kPa]
Δu	Change in pore water pressure [kPa]
S_r	Degree of saturation [–]
ΔS_r	Change in degree of saturation [–]
w	Water content [–]
e	Void ratio [–]
e^W	Void ratio associated to the water-saturated pores
e^A	Void ratio associated to the air-saturated pores
Δe^W	Change in void ratio associated to the water-saturated pores
Δe^A	Change in void ratio associated to the air-saturated pores
Δe^{WW}	Change in void ratio of pores that are water-saturated before and after the change in effective stress σ'_W
Δe^{AA}	Change in void ratio of pores that are air-saturated before and after the change in effective stress σ'_A
Δe^{AW}	Change in void ratio of pores that experienced a fluid transition that are initially air-saturated and become water-saturated upon a positive change in degree of saturation, ΔS_r
Δe^{WA}	Change in pores that experienced a fluid transition that are initially water-saturated and become air-saturated upon a negative change in degree of saturation, ΔS_r
λ_W	Slope of the normal consolidation line (ncl) for clay reconstituted from slurry
κ_W	Slope of the unloading reloading line (url) for clay reconstituted from slurry
λ_A	Slope of the normal consolidation line (ncl) for clay prepared from dry powder
κ_A	Slope of the unloading reloading line (url) for clay prepared from dry powder
T	Shear force acting on the shear plane [kN]
T^W	Component of the shear force acting on the water-saturated fraction [kN]
T^A	Component of the shear force acting on the air-saturated fraction [kN]
τ	Average shear stress [kPa]
τ^W	Shear stress associated to the water-saturated fraction [kPa]
τ^A	Shear stress associated to the air-saturated fraction [kPa]
A	Area of the shear plan [m^2]
A^W	Water-saturated fraction of the area of the shear plan [m^2]
A^A	Air-saturated fraction of the area of the shear plan [m^2]

intuitive for granular materials (made of inert and sub-spherical particles) but not for clayey geomaterials. No attempts have been made to reconcile the 'granular' framework commonly used to justify the proposed pairs of effective stresses with the complex microstructure of compacted clays as recognised from Mercury Intrusion Porosimetry (MIP) and Scanning Electron Microscope (SEM) testing.

Pedrotti and Tarantino[10] have revisited the microstructure of clays encompassing both compacted and reconstituted clays. They formulated a conceptual microstructural model for unsaturated soil, alternative to the traditional 'aggregate-based' microstructural model, based on the assumption that macro-pores are filled with air and micro-pores are filled with water. In turn, this led to two microstructurally-based effective stresses, controlling the response of the air-saturated and water-saturated parts respectively. The practical advantage of these two effective stresses is that the modelling of complex hydro-mechanical paths in compacted unsaturated clays only requires constitutive parameters derived from clay reconstituted from slurry (and tested under saturated state) and clay formed from dry powder (and tested under dry conditions).

This paper further explores the conceptual microstructural model presented by Pedrotti and Tarantino[10] by showing its capability to interpret a variety of MIP from the literature. It then shows how the two pair of proposed effective stress and the model derived therefrom is capable of modelling volume change behaviour by considering additional hydro-mechanical paths from the literature different from those examined by Pedrotti and Tarantino.[10] In addition, it demonstrates that this pair of effective stresses is also capable of modelling shear strength behaviour of compacted unsaturated clays.

2. The microstructural model for compacted clays

Microstructure of compacted soils has been extensively studied by means of Mercury Intrusion Porosimetry (MIP) and Scanning Electron Microscope (SEM). Soils compacted on the dry side of optimum and at optimum water content typically show a bi-modal pore size distribution. This is generally taken as an indication of an aggregated structure.[11–13] Macro-pores are related to pores between aggregates (inter-aggregate porosity) and micro-pores are related to pores within the aggregates (intra-aggregate porosity) as shown in Fig. 1.[13–22]

This conceptual microstructural model has gained wider acceptance in the last two decades. The second generation of hydro-mechanical constitutive frameworks for partially saturated clays have been based on the assumption that clay particles form aggregates and the aggregates represent the elementary unit of the clay microstructure rather than individual particles. The literature is rich of contributions on the 'aggregate' nature of compacted unsaturated soils including.[12,15–17,20,23–25] This concept has also led to the formulation of successful macroscopic constitutive models, often incorporating microstructural parameters.[8,22,26]

Nonetheless, the 'aggregate' model still presents aspects that are contradictory or controversial if one inspects pore-size distributions at formation (compacted and reconstituted clays). Tarantino and Decol[24] observed that the characteristic pore size associated with micro- and macro-porosities in compacted kaolin remain the same from very low water contents (dry-side of optimum) up to the water content at optimum.

Pedrotti and Tarantino[10] carried out an experimental investigation to explore the microstructure of compacted kaolin clay and its interplay with the microstructure of clays reconstituted from slurry and compressed from dry powder. They showed that the PSD of kaolin reconstituted from slurry (formed water-saturated) and kaolin compressed from dry powder (formed air-saturated) overlap astonishingly with the modal sizes associated with the micro- and macro-pores of the compacted samples (Fig. 2a).

The straightforward conclusion drawn by Pedrotti and Tarantino[10] is that, in compacted samples, macro-pores are filled