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A microstructural effective stress definition for compacted active clays

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HIGHLIGHTS

- A microstructural effective stress is defined based on chemical potentials difference.
- The micro effective stress is identified with the thermodynamic osmotic pressure.
- Introduction of the effect of total stress, water content and environmental salinity.

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ABSTRACT

The volumetric deformability of the microstructure of compacted active clays is linked to the water mass exchange with the macrostructural void space. Given that this exchange is determined by the difference in the chemical potential of water in these two structural levels, this work proposes to define a microstructural effective stress (understood as the magnitude controlling microstructural strains) from this difference in chemical potentials, identifying the microstructural effective stress with the thermodynamic swelling pressure. To assess the scope of this definition, an inspection exercise has been conducted, examining the important functional dependence on the microstructural void ratio for different loads, water content and environmental salinity conditions. For the compacted active clays analysed, the thermodynamic swelling pressure is a robust and consistent definition of the microstructural effective stress.

1. Introduction

In recent years, considerable effort has been made to improve the characterisation of the coupled thermo–hydro–chemo-mechanical (THCM) behaviour[1] of unsaturated soils,[2,3] with important contributions with regard to both flow and transport processes[4,5] and stress–strain modelling.[6,7] The effort has been specially intense in the analysis of the behaviour of active clays.[8] Significant advances were made to identify and characterise an "effective stress" (see for instance the reviews in Refs. 9–11, and the definition of the suction stress characteristic curve[12,13]), understood as the "function of the externally applied stresses and the internal fluid pressures which controls the mechanical effects of a change in stress".[14] Many of the proposals focus on the analysis of unsaturated single-porosity soils, although the definition of effective stress in double-porosity continua has also been analysed. When analysing compacted active clays, in accordance with Gens and Alonso,[15] the space among the particle aggregates is identified with the macrostructural porosity, and the microstructural porosity is identified with intra-aggregate spaces (inter- and intra-particle voids). Each structural level is assigned a different continuum level, although both media fill the same space.[16] This way, the internal complexity of microstructure is abstracted. Although at least two hierarchical levels of pores, interlamellar and interparticle voids, could be distinguished within it, only one macroscopic variable, the microstructural void ratio e_m (volume of intra-aggregate voids per volume of mineral), is used to describe the spatial arrangement of the microstructure. The spatial arrangement of the macrostructure is characterised with the macroscopic variable e_M, the macrostructural void ratio (volume of inter-aggregate voids per volume of mineral). For these kinds of materials, as pointed out by Mainka et al.,[17] some authors have proposed a Bishop-type effective stress, introducing the influence of the microstructure on soil deformability in Bishop's parameter. Other works propose a different approach, defining not a "global" effective stress but different constitutive stresses for macrostructure and microstructure.[8,18,19]

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Abbreviations: THCM, Thermo–hydro–chemo-mechanical; DI, deionised; SIS, Salinity increase steps

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Table 1
Dry densities and swelling pressures at equilibrium conditions after subsequent exposure to pure water and NaCl solutions of 0.1 M, 0.3 M ad 1.0 M.[23,24]

Id	Dry density (kg/m^3)	Swelling pressure (kPa)			
		0.0 M	0.1 M	0.3 M	1.0 M
Karnland et al.[23]					
S2–41	463	300	179	61	13
S2–42	795	598	363	160	50
S2–43	1321	2,946	2,709	2,312	1,554
S2–44	1529	9,321	9,170	8,775	7,302
S2–45	1634	15,280	15,103	147,53	13,447
S2–46	1851	32,825	32,849	32,417	31,122
S2–51	338	126			
S2–52	785	618	400	196	92
S2–53	1272	2,000	1,735	1,335	799
S2–54	1487	5,853	5,750	5,287	4,021
S2–55	1686	13,581	13,463	12,990	11,776
S2–56	1784	27,380	27,189	26,926	25,069
S2–61	535	216	82	41	13
S2–62	849	646	419	194	53
S2–63	1398	3,666	3,455	3,046	2,178
S2–64	1584	9,455	9,275	8,904	7,614
S2–65	1730	20,056	19,976	19,800	18,930
S2–66	2017	55,588	55,488	54,960	53,626
WyNa Karnland et al.[24]					
	458	232	115	70	44
	766	621	428	210	85
	1249	2,248	2,125	1,634	1,074
	1555	9,850	9,340	9,145	8,270
	1615	16,000	15,400	14,900	14,240
	1717	27,600	26,500	25,980	25,430

The present work follows the latter approach, and focuses on defining a microstructural effective stress that introduces the effect of total stress, water content, and environmental salinity in a thermodynamically consistent way. The definition proposed is founded on the analysis of the chemical potentials of macrostructural and microstructural water. Then, concepts linked to the particle-scale force analysis are not used, as opposed to the works of Hueckel,[20] Fam and Santamarina,[21] and Lu and Likos.[22] Consequently, the descriptive capacity of those works is lost. However, an up-scaled (macroscopic) definition of the microstructural effective stress is obtained without the need to introduce any hypothesis on the structure of particle interaction forces. After describing this definition, its scope and limitations are assessed by applying it to the analysis of several swelling pressure tests in which the salinity condition of an active clay varies with time.

The definition of the many variables used can be found in a notation Appendix at the end of the paper.

2. Material, methods and experimental data

This work analyses 18 swelling pressure tests conducted by Karnland et al.[23] (tests S2–41 to S2–66 in Table 1), which used a sodium-purified MX-80 bentonite with a cation exchange capacity *CEC* of 0.85 eq/kg and other 12 similar tests from Karnland et al.[24] (Table 1), which used a sodium-purified MX-80 with a *CEC* of 0.86 eq/kg (see other properties in Table 2). The samples of higher density were compacted using a special device, while those of lower density were compacted directly in the oedometric sample holders used later in the tests. In all cases, small samples were tested (1.6 cm,[3] Karnland et al.;[23] 4.8 cm,[3] Karnland et al.[24]) to minimise the time needed to reach equilibrium in the different testing steps. The oedometric holders prevented vertical displacements in addition to radial strains, to prevent the volumetric deformation of the sample.[23,24] For this reason, isochoric conditions were assumed as a working hypothesis when analysing the tests. After

Table 2
Properties of the tested material.[24,31]

Chemical composition (weight %)	
SiO_2	60.0
Al_2O_3	21.2
Fe_2O_3	3.7
Na_2O	2.5
MgO	2.4
CaO	0.1
K_2O	0.1
TiO_2	0.1
Mineralogical composition (weight %). Phases present only as traces are not shown	
Montmorillonite	83.5
Plagioclase	2.9
Quartz	2.8
Muscovite	2.8
Tridymite	1.9
Gypsum	0.9
Microcline	0.8
Illite	0.7
Lepidocrite	0.7
Orthoclase	0.7
Pyrite	0.6
Other properties	
$Na^+/K^+/Ca^{2+}/Mg^{2+}$ (eq/kg)	1.05/0.00/0.02/0.04
Specific surface area (BET, N_2) (m^2/g)	40
Liquid Limit	510
Plastic Limit	50
Plasticity Index	470

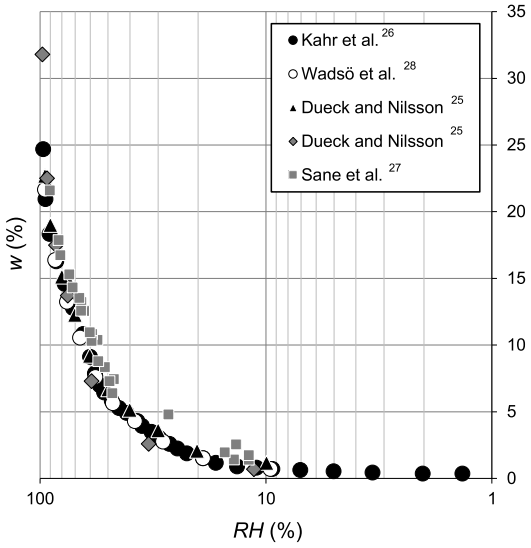

Fig. 1. Water retention data from Dueck and Nilsson,[25] Kahr et al.,[26] Sane et al.[27] and Wadsö et al.[30]

placing the samples in the holders, deionised water was slowly circulated intermittently through the bottom filter of the holder, letting the air out through the upper filter to avoid the formation of trapped air bubbles. After approximately one week, water was also circulated through the upper filter. Water was circulated until the swelling pressure, measured with a load cell, reached a constant value. In that equilibrium situation, saturation conditions were assumed.[23,24] Subsequently, the salinity increase steps (SIS) that will be analysed were started in the same sample holders. At each step, the salinity of the interstitial water was increased by contacting the sample top and bottom boundaries with a NaCl aqueous solution of controlled salinity. The salinity of the boundary solution was kept constant until a constant swelling pressure was