



Research paper

Role of osmotic suction in volume change of clays in salt solution

Yongfu Xu^{a,b,*}, Guosheng Xiang^a, Hao Jiang^a, Tao Chen^a, Feifei Chu^b^a Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China^b Geotechnical Engineering Center, Wentian College of Hohai University, Ma'anshan 243000, China

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ABSTRACT

The volume change behaviour is usually expressed by different curves of $e-p$ when concentrated pore fluids are introduced to clays. Increase in effective stress from osmotic suction in salt solution and increase in inter-particle attraction from the pore-water salt concentration in salt-clay system. The void ratio is smaller in the salt solution with higher concentration under the same vertical overburden pressure, and it results the different curves of $e-p$ in salt solution with different concentration. This paper aims to express the $e-p$ relationship using a unique curve for clays in salt solution with different concentration. A conceptual model is proposed to explain the influence of osmotic suction on the volume change of clays in a quantitative way. A new formula for effective stress is proposed as $p^e = p + p_\pi$ incorporating with osmotic suction (π), and $p_\pi = (p/\pi)^D - 2\pi$. Experimental data for volume change of clays in NaCl solution with different concentration can be expressed by a unique curve using the proposed effective stress.

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1. Introduction

The influence of pore fluid composition on clay behaviour has been the subject of considerable interest in clay mineralogy (Low, 1980), soil physics (Barshad, 1952; Sposito, 1981), geotechnical engineering (Bolt, 1956; Mesri and Olson, 1971; Sridharan and Rao, 1973) and environmental engineering (Ye et al., 2014). As a matter of fact, clays, whose natural state pore fluid is generally a compound solution, may also come in contact with different aqueous solutions either deliberately or accidentally. The mechanical behaviour may be strongly influenced by physicochemical effects when salt concentrated pore fluids are introduced to clays (Studds et al., 1998; Di Maio et al., 2004; Rao and Thyagaraj, 2007; Tripathy et al., 2013).

A great number of experimental studies dealing with the chemical effects on the swelling behaviour of clays are available in literature (Barbour and Fredlund, 1989; Studds et al., 1998; Calvello et al., 2005; Ye et al., 2014). Barbour and Fredlund (1989) studied the effect of a chemical agent (NaCl in aqueous solution) of different concentration (0.01 mol/l up to 5 mol/l) on sand-bentonite mixtures, and proposed a constitutive model based on the effective stress and the osmotic pressure as state parameters. Chen et al. (2000) concluded the effects of pore fluids on the kaolinite compressibility can be attributed mainly to van der Waals attractive forces. The effect of van der Waals attractive forces clearly diminishes with an increase in vertical overburden stress. Malusis and Shackelford (2002) presented extensive theoretical and

experimental work on osmotic effects, and specifically focused on determination of the osmotic efficiency as a function of concentration. Di Maio et al. (2004) and Calvello et al. (2005) presented results of experimental studies on the impact of pore fluid composition on compressibility of Ponza bentonite and Bisaccia clay. A strong volume change occurs as a result of osmotic consolidation during the clay samples were exposed to the solutions, and the effect of the NaCl solution shows to be reversible by exposing the sample to distilled water. Increase in pore-water salt concentration weakens the diffuse double layer repulsion forces that reduce the compressibility and swell potentials of the clay specimens (Calvello et al., 2005). Thus, the relationships between volume change and vertical overburden pressure are different curves for clays in salt solution with different concentration (Mesri and Olson, 1971; Studds et al., 1998; Di Maio et al., 2004; Calvello et al., 2005).

Barbour and Fredlund (1989) and Di Maio (1996) have shown that on exposure to concentrated salt solutions, volume changes of saturated clays also occur from fluid flow out of clays in response to chemical concentration gradients. According to Barbour and Fredlund (1989), osmotic flow out of the specimen decreases the pore-water pressure, leading to an increase in effective stress and subsequent volume decrease. Variations in initial pore-water salt concentration impact the pore-fluid osmotic suction of clays as it relates to the dissolved salt content in pore water (Rao and Shivananda, 2005). The increase in osmotic suction in pore water acts as an additional total stress component that favours the reduction in swell potential of the compacted clay specimens at a total vertical pressure to swell pressure ratio of less than unity (Rao and Thyagaraj, 2007). The volume change behaviour of clays is controlled by the effective stress, in which the osmotic suction should be incorporated (Barbour and Fredlund, 1989). Rao and Thyagaraj (2007) proposed that the total net vertical stress (p)

* Corresponding author at: Room A 419, Mulan Building, No. 800, Dong Chuan Road, Min Hang District, Shnanghai 200240, P. R. China.
E-mail address: yongfuxu@sjtu.edu.cn (Y. Xu).

experienced by compacted clay specimens exposed to an increase in pore fluid osmotic suction, and represented as follow

$$p = (\sigma - u_w) + p_\pi \quad (1)$$

where σ is normal stress, u_w is pore water pressure, p_π is the pore fluid osmotic suction component, $p_\pi = \alpha\pi$, here π is osmotic suction, α is a empirical constant, and $0 < \alpha < 1.0$. However, Rao and Thyagaraj (2007) did not give the method to determine the value of α . Because part of the effective stress in clay is derived from net inter-particle repulsive forces seated in diffuse double layers around clay aggregations, the applicability of the concept of effective stress has at this stage been restricted to conditions of constant volume, constant chemistry, and constant temperature (Graham et al., 1992).

Existing studies on volume changes in clays from changes in pore-water salinity have not examined the influence of variations in pore-water salt concentration on pore-fluid osmotic suction. The role of pore-fluid osmotic suction in the volume change behaviour of clays is not well understood. Up to the present, a comprehensive theoretical description of the combined influence of osmotic suction on the volume change behaviour of clays has been lacking. In this paper, on the basis of the fractal model for the clay surface, effective stress is proposed by incorporating with the osmotic suction. The volume change behaviour of clays is expressed by a unique curve using the proposed effective stress for clays in salt solution with different concentration. The comparing results of experimental data in literature show the proposed effective stress offers good approach to express the volume change of clays by a unique curve.

2. Theory

2.1. Fractal model for clay surface

The surface fractal dimension serves to characterize its surface roughness or irregularities. The magnitude of the surface fractal dimension is relevant to many important physico-chemical processes namely adsorption, surface diffusion and catalysis. Avnir and Jaroniec (1989) proposed a convenient method to determine the surface fractal dimension from the nitrogen adsorption. Similarly with the adsorption isotherm equation, the correlation of the water volume absorbed by clays to the vapour pressure is given by

$$\frac{V_w}{V_c} = k \left[\ln \left(\frac{P}{P_0} \right) \right]^{D-3} \quad (2)$$

where D is the surface fractal dimension, V_w is the water volume absorbed by clays, V_c is the volume of clays, P is the partial water vapour pressure in equilibrium with clays at some water content w and temperature T and P_0 is the equilibrium water vapour pressure of pure water at temperature T .

The adsorption isotherm allows the calculation of swelling pressure of clays as a function of the water content (Kahr et al., 1990). Satisfactory agreement is found between the calculated and the experimental data for water content bigger than 10% (Kahr et al., 1990).

$$p_s = \frac{RT}{M_w \bar{v}_w} \left[\ln \left(\frac{P}{P_0} \right) \right] \quad (3)$$

where p_s is the swelling pressure, R is the molar gas constant (8.31 J/mol/K), T is the Kelvin temperature, M_w is the molecular mass of water (18.016 kg/kmol) and \bar{v}_w is the partial specific volume of water.

According to Eqs. (2) and (3), the relationship between the normalized water volume by the volume of clays and swelling pressure is written as

$$\frac{V_w}{V_c} = \beta p_s^{D-3} \quad (4)$$

where $\beta = k(M_w \bar{v}_w / RT)^{D-3}$. From the thermodynamic viewpoint, Xu et al. (2003) deduced the same relationship as Eq. (4) on the basis of a balance between the decrease in free energy of water and the increment in the work of swelling pressure.

The swelling pressure of Tsukinuno bentonite was measured using an odometer and measuring by a steel ring. The typical profiles of Tsukinuno bentonite used in this study are listed in Table 1. The compacted specimen was set up on the test apparatus. Silicone grease was also applied to the inner wall of the ring to reduce friction between the specimen and inner wall. While distilled water was supplied to the specimen from its bottom, swelling pressure increased under the condition of the sample height keeping constant. The apparatus used to measure the swelling pressure is shown in Fig. 1. In Fig. 1, the reading of the displacement transducer represents the change in the specimen height. The reading of the displacement transducer was kept zero through the rise or descend of the specimen bottom by using the displacement regulator. Further stress is necessary to supply the specimen through a steel ring to compress the specimen to its original height. Typical measuring process of swelling pressure is shown in Fig. 2 (Xu et al., 2003). Swelling pressure increased with the swell of specimen at the beginning of the water supply (from point I to point II in Fig. 2). Then, the specimen was nearly compressed to its original height through the rise of the specimen bottom (from point II to point III in Fig. 2), and swelling pressure increased rapidly with the compression of specimen. Finally, swelling pressure was defined as the pressure value of the point (point IV in Fig. 2) at which the heave-settlement curve intersected the axis of swelling pressure.

Relationship between the normalized water volume (V_w/V_c) and swelling pressure is shown in Fig. 3, V_w is the water volume, V_c is the clay volume, C_b is the content of bentonite in bentonite-sand mixtures. It is seen from Fig. 3 that the relationship between the void ratio of clay and swelling pressure can be described by a linear function in a log-log

Table 1
Physical properties of bentonites.

Physical index	Tsukinuno (Xu et al., 2003)	Wyoming (Studds et al., 1998)	Ponza (Di Maio et al., 2004)	Bisaccia (Di Maio et al., 2004; Calvello et al., 2005)	GMZ01 (Ye et al., 2014)
Specific gravity G_s	2.79	2.75	2.77	2.78	2.66
Liquid limit w_L (%)	473.9	354	390	110	276
Plastic limit w_p (%)	26.6	27			37
Plasticity index I_p	447.3	327			239
Montmorillonite content C_m (%)	48		70–80	30	75.4
Specific surface area S_e (m ² /g)	810	780	500	190	570
Cation exchange capacity M_e (mEq/g)	0.732	0.95	0.40	0.42	0.62
Smectite type	Na-smectite	Na-smectite	Na-smectite	Ca-smectite	Ca-smectite
Surface fractal dimension D	2.62	2.56	2.55	2.67	2.78

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