Applied Clay Science 166 (2018) 299–306

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Research paper

Pore water salinity effect on the intrinsic compression behaviour of artificial soft soils

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ARTICLE INFO

Keywords:
Artificial soft clay
Pore water salinity effect
Intrinsic compression behaviour
Particle flocculation

ABSTRACT

The framework of the intrinsic compression behaviour of normally consolidated soft clay proposed by Burland (1990) is widely adopted in engineering practices. However, further investigations should be conducted on its validity in the coastal and offshore environments to verify the effect of pore water salinity. In the present work, oedometer tests were performed on remoulded artificial soft clays (mixtures of kaolin and bentonite with 0%, 5%, 10%, and 20% of bentonite by mass). The artificial clays were salinized with sodium chloride solutions at concentrations 0 mol/L (distilled water), 0.17 mol/L, 0.51 mol/L, 0.86 mol/L, and 1.70 mol/L at water contents equal to 1.0–1.5 times of the liquid limits. The results showed that the 'intrinsic' properties of clays, including the compression index C_c*(100–1000 kPa), void ratio e_{100}*, and compression line based on the void index I_v, changed with the pore water salinity. Following the empirical correlation proposed by previous researchers, the decrease in C_c* caused by pore water salinity could be generally characterised by the liquid limit and void ratio at the liquid limit (e_L). The dispersed correlation between the predicted e_{100}* and the experimental results in this study were caused by the significant changes in e_0/e_L controlled by pore water salinity. The relationships between void index I_v and vertical stress σ_v' deviated from the intrinsic compression line (*ICL*) under the saline environment. For the artificial clay rich in smectite, the slopes of I_v–log σ_v' before yielding increased with pore water salinity at the initial water content. Pore water salinity affected the intrinsic compression behaviour of soft clays primarily composed of kaolinite to a lesser extent.

1. Introduction

Burland (1990) introduced the concept of 'intrinsic properties' to describe the compression behaviour of remoulded soft clay. An intrinsic compression line (*ICL*) was defined by the void index I_v *versus* log σ_v' (the effective vertical stress) for clay remoulded at an initial water content equal to approximately 1.0–1.5 times its liquid limit (*LL*). This framework is widely used to predict the compression curve of normally consolidated soft clay. He also reported that 'ideally the water chemistry should be similar to that of the pore water in this clay in its natural state' during sample preparation. This implied that the change in pore water chemistry was not considered to evaluate the 'intrinsic properties'. However, owing primarily to the movements of seawater, surface water, and underground fresh water, the inevitable changes in pore water salinity may influence the compression behaviour of normally consolidated marine clays. Deng et al. (2014) reported that the compression index, swelling index, and secondary consolidation coefficient of Lianyungang marine clay became larger after percolation with deionised water. Subsequently, the change in pore water chemistry may result in potential hazards such as settlement beyond the allowable designed value of geo-infrastructures. Therefore, it is necessary to understand the pore water salinity effect on the 'intrinsic compression behaviour' of soft clays.

Many researchers collaborated to improve this framework (Cerato and Lutenegger, 2004; Tiwari and Ajmera, 2012; Horpibulsuk et al., 2011; Zeng et al., 2015 and Zeng et al., 2017). Cerato and Lutenegger

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https://doi.org/10.1016/j.clay.2018.09.027
Received 6 January 2018; Received in revised form 25 September 2018; Accepted 27 September 2018

(2004) reported that the 'intrinsic variable' I_v, which was based on the constant of intrinsic compressibility e_{100}* (void ratio corresponding to effective vertical stress $\sigma_v' = 100$ kPa), may in fact not be a true intrinsic parameter of the soil, but dependent on the initial water content. To account for the effects of clay mineral, Horpibulsuk et al. (2011) introduced a modified void index $I_{v'}$, defined as $(e\text{-}e_{50})/\ (e_{50}\text{-}e_{1000})$, where e_{50} was the void ratio at a vertical consolidation pressure of 50 kPa. Tiwari and Ajmera (2012) conducted oedometer tests on 55 different soils prepared with various proportions of smectite, illite, kaolinite, and quartz at initial moisture contents equal to the *LL*. Based on the test results, two equations were proposed to estimate the compression index of remoulded clays at the *LL*. A simple empirical approach for determining the intrinsic compression line was also proposed by Zeng et al. (2015) using the density of soil particles, initial water content, and *LL*. Zeng et al. (2017) improved the prediction of the compression curves of dredged clays by dividing these curves into pre-yielding and post-yielding zones. Nevertheless, the intrinsic properties of soft clay under changing pore water chemistry were rarely analysed until recently.

Previous studies revealed that changing the pore water chemistry (such as cation concentration, cation valence, and dielectric constant) significantly affected the physical and mechanical behaviours of clay dispersions or compacted swelling clays such as commercial MX-80, FEBEX, and GMZ bentonite (Bolt, 1956; Abdullah et al., 1997; Di Maio et al., 2004; Gajo and Maines, 2007; Lloret and Villar, 2007; Castellanos et al., 2008; Zhu et al., 2013; Zhu et al., 2015; Ye et al., 2014; Ye et al., 2015; Zhang et al., 2016; Chen et al., 2015; Chen et al., 2016). Clay particles generally carry a negative charge; consequently, a 'diffuse double layer', which refers to two parallel layers of charge surrounding the clay particle, is formed. The distance between two clay particles in an equilibrium clay–water system decreases with an increase in the electrolyte concentration of the pore fluid. Bolt (1956) first stated that the compressibility of pure clay dispersions could be accounted well by considering the interaction between diffuse double layers around clay particles. Chen and Anandarajah (1998), Sridharan and Prakash (1999) and Kaya et al. (2006) also studied the relevance of the sedimentation behaviour of clays and the properties of fluid, including the ion valence, ionic concentration, pH value, and dielectric constant. Di Maio et al. (2004) presented that an increase in the pore solution concentration may cause a reduction in the compressibility of compacted bentonite. Gajo and Maines (2007) investigated the mechanical behaviour of active clays affected by pore fluid acidity and alkalinity. Lloret and Villar (2007), Gómez-Espina and Villar (2010) indicated the influence of temperature and water salinity on the thermo-hydro-mechanical behaviour of highly compacted FEBEX and MX-80 bentonite. Castellanos et al. (2008) discussed the chemical effects of salt solution on the swelling capacity of FEBEX bentonite, and their results showed that the swelling pressure decreased as the solution salinity or concentration increased. Karnland et al. (2011) found that highly compacted sodium bentonite developed higher or comparable swelling pressures than calcium bentonite during Na/Ca ion exchange. Zhu et al. (2013, 2015), Ye et al. (2014, 2015), He et al. (2016), Zhang et al. (2016), and Chen et al. (2015, 2016) systematically investigated the influences of infiltrating solutions on the volume behaviour, hydraulic conductivity, consolidation coefficient, pre-yielding stresses, and water retention properties of highly compacted GMZ bentonite. The investigations above focused on the pore water chemistry effects on the hydro-mechanical behaviour of clay dispersions and highly compacted bentonite. Recently, Yan and Chang (2015) identified that the K_0 coefficient and friction angle of normally consolidated kaolin were not affected by the pore fluid salinity. However, as the salinity increased, the K_0 coefficient of bentonite decreased significantly and the friction angle increased noticeably. Song et al. (2017) illustrated that the salt leaching led to an increase in the compressibility of the illite-dominant remoulded marine clays.

Lianyungang marine clay in Jiangsu Province, China, was deposited under the sea trans/regression and is characterised by the high salinity of the pore water. From previous investigations on the distribution of clay minerals in this area, the mass contents of smectite encompass a range of 5% to 22%, and this proportion decreases from the north to south along the coastline (Zhao, 1983; Chen et al., 1985; Liu, 1987; Yi et al., 1988; Zhao, 1990; Deng et al., 2014). This paper focuses on the pore water salinity effect on the intrinsic compression behaviour of four soils with the smectite proportions (approximately 5% to 20%) at high initial water contents (1.0–1.5 times of *LL*). To simulate this variety of mineral composition and pore water salinity, a mixture of commercial kaolin, bentonite, and NaCl solution was employed in this investigation. The salinity effect on the intrinsic compression parameters C_c*, e_{100}* and intrinsic compression curve based on void index I_v was re-examined. A reasonable mechanism of salinity effect on the intrinsic compression behaviour was discussed.

2. Experimental program

2.1. Materials

To prepare the specimens in the laboratory, commercial kaolin and bentonite from Jiangsu Province in China were mixed at different proportions based on the dry weight ratio. For example, 5% bentonite represents that the mass ratio of dry bentonite to dry mixture is 5%. The mixture composition was selected based on the typical marine clay deposited in the Lianyungang area in Jiangsu Province. The basic physical properties of the materials are shown in Table 1. Sridharan and Prakash (2000) reported that a greater accuracy of *LL* determination can be achieved using the percussion method for bentonite, and the cone method for kaolin. Therefore, the *LL* of kaolin was determined with the cone method and that of bentonite with the percussion method, and their plastic limits (*PLs*) were determined using the thread-rolling method according to the British Standard BS1377 (1990). Three replicated tests for each soil type were performed, and results beyond the standard deviation were discarded. Additionally, the specific surface area (*SSA*) was determined using the ethylene glycol monoethyl ether method (EGME), in reference to Cerato and Lutenegger (2002) and Fan et al. (2014). The mineral compositions determined by X-ray diffraction analysis are listed in Table 2; the results suggested that the dominant clay minerals of the kaolin and bentonite were kaolinite (68.2%) and smectite (90.5%), respectively. The particle size distributions of the two soils were determined using the hydrometer method according to ASTM-D422 (1998), and the laser method with the laser particle analyser Mastersizer 2000 (Malvern Instruments Ltd., UK). As shown in Table 3, a clay fraction (< 0.002 mm) of 22% for kaolin, and of 43% for bentonite, were identified by the hydrometer method. The clay fraction of bentonite was underestimated by the laser method, which was attributed to the measurement limitation of the laser analyser (0.3 μm as the minimum particle diameter).

2.2. Specimen preparation

The air-dried powder of the pure kaolin or mixed clays were mixed with distilled water or sodium chloride solutions at a mass concentration of 1%, 3%, 5%, and 10% (equal to 0.17 mol/L, 0.51 mol/L, 0.86 mol/L, and 1.7 mol/L, respectively), referring to the *in-situ* salinity

Table 1
Physical properties of kaolinite and bentonite.

Soil types	specific gravity G_s	*LL* (%)	*PL* (%)	*PI* (%)	SSA (m^2/g)
Commercial Kaolinite	2.66	33.0	16.0	17.0	46.0
Commercial Bentonite	2.73	301.0	95.0	206.0	378.5