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Evaluation on expansive performance of the expansive soil using electrical responses

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ABSTRACT

Light structures, such as highways and railroads, built on expansive soils are prone to damages from the swelling of their underlain soil layers. Considerable amount of research has been conducted to characterize the swelling properties of expansive soils. Current swell characterization models, however, are limited by lack of standardized tests. Electrical methods are non-destructive, and are faster and less expensive than the traditional geotechnical methods. Therefore, geo-electrical methods are attractive for defining soil characteristics, including the swelling behavior. In this study, comprehensive laboratory experiments were undertaken to measure the free swelling and electrical resistivity of the mixtures of commercial kaolinite and bentonite. The electrical conductivity of kaolinite-bentonite mixtures was measured by a self-developed four-electrode soil resistivity box. Increasing the free swelling rate of the kaolinite-bentonite mixtures (0.72 to 1 of porosity of soils samples) led to a reduction in the electrical resistivity and an increase in conductivity. A unique relationship between free swelling rate and normalized surface conductivity was constructed for expensive soils by eliminating influences of porosity and *m* exponent. Therefore, electrical response measurement can be used to characterize the free swelling rate of expensive soils.

1. Introduction

Light structures, such as highways and railroads, built on expansive soils are prone to damages from the swelling of their underlain soil layers (Nelson and Miller, 1992; Pedarla et al., 2011). Hence, it is important to evaluate the total volume change (swelling or shrinkage) potentials of these soils. Both direct and indirect methods have been developed for such purpose (Seed et al., 1962, Sridharan et al., 1986, Puppala et al., 2006). Direct method measures the swelling potential of two grams of clay in deionized water (ASTM D5890-11, 2006), while indirect methods correlate soil classification designation or other soil properties (i.e. electric resistivity and conductivity) to swell potential (Chen, 1983; Puppala et al., 2006). Thomas et al. (2000) suggested that swell behavior can best be predicted by examining a combination of physical and mineralogical properties. However, because the mineralogical and chemical properties are not easy to be measured, it is hard to apply them to grade swelling potential in engineering practice. Therefore, finding a new swelling potential index (electric resistivity and conductivity), which should be easily measured and strongly correlated with the mineralogical and physical properties of expansive soils, is of attracted considerable concern to professionals and planners.

Electric response is a non-invasive method that can provide useful information about moisture condition, structural characteristics, salinity and contamination of subsoil (Fukue et al., 1999; Yoon and Park, 2001; Ya et al., 2015). The use of electrical conductivity in subsurface investigation has become very popular among geotechnical engineers (Kibria et al., 2014; Abu-Hassanein et al., 1996; Mitchell and Soga, 2005; Lesmes and Friedman, 2005). Furthermore, the most influential property of an expansive soil on volume change is its mineralogical properties (such as montmorillonite content MC, clay content CC and specific surface SSA) (Zheng et al., 2008; Li et al., 2014), which electrical response is also sensitive to (Abdul et al., 1990; Liu et al., 2004; Keller and Frischknecht, 1966; Delaney et al., 2001; Fukue et al., 1999; Demond and Roberts, 1993; Mitchell and Soga, 2005; Santamarina et al., 2001). Based on the response on physical and mineralogical properties of subsoil, Electric response ground surveys can be used to correlate to swell parameters (i.e. free swelling rate) of expansive soils (Lesmes and Friedman, 2005). To date, however, the relationships between electric resistivity (conductivity) and free swelling rate of expansive soils have not been well documented in the literature. Consequently, it is important to develop reliable swell methods for better volume change predictions.

The goal of this study is to establish a new model relating free swelling rate of expansive soils to their electrical resistivity. Laboratory tests

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Table 1
Index properties of kaolinite and bentonite.

Parameter	Bentonite	Kaolinite
w_{opt} (%)	7.10	12.95
w_L (%)	281.2	65.8
w_p (%)	39.4	34.5
Clay content (%)	40.26	22.19
G_s	2.67	2.70

are carried out on mixtures of bentonite and kaolinite at different ratios to simulate wide range of free swell rates of expansive soils. The quantitative relationships between either the swelling deformation or structural parameter (porosity) and resistivity will be obtained with a self-developed improved four-electrode soil resistivity box (Chu et al., 2016). On the basis of the test results, theoretically based models, which capture the intrinsic connections between the normalized surface conductivity (σ_s/σ_w) and free swelling rate and is simple enough to be applied in the field, are established.

2. Background

In fact, it is important to note that resistivity (ρ) collapses to the reciprocal of conductivity (σ) $\sigma = 1/\rho$ (de Lima and Sharma, 1990). So, the conductivity was used to analyze the function of conductivity (σ), porosity (φ) and free swelling rate (δ).

Based on the experimental results of a sedimentary rock under fully saturated conditions, Archie (1942) suggested a widely-used empirical equation, which is suitable for characterizing the electrical conductivity of both coarse-grained soils and marine sediments (i.e. fine-grained soils in high-salinity environments) (Choo et al., 2016b; Salem and Chilingarian, 1999; Mitchell and Soga, 2005). Archie's equation relates the electrical resistivity of saturated soils (ρ_{mix}) to the resistivity of pore water (ρ_w) and porosity (φ):

$$\rho_{mix} = \varphi^{-m} \cdot \rho_w, \sigma_{mix} = \varphi^m \cdot \sigma_w \quad (1)$$

where σ_{mix} is electrical conductivity of mixed soils, σ_w is conductivity of pore fluid, φ is porosity, m is a fitting parameter. Archie's equation (Eq. (1)), however, may not be applicable to fine-grained soils, whose surface conduction contributes significantly to the electrical conductivity (Choo et al., 2016a; Santamarina et al., 2001). Therefore, electrical conduction (G_{mix}) of fine-grained soils, such as the montmorillonite-rich expansive soils in this study, should be expressed as the sum of the pore fluid conduction (G_w) and the surface conduction (G_s) as shown in Eq. (2) (Bussian, 1983; Choo and Burns, 2014; Glover, 2010; Glover et al., 2000; Klein and Santamarina, 2003; Mitchell and Soga, 2005; Pfannkuch, 1972).

$$G_{mix} = G_w + G_s \quad (2)$$

Among the formulas of previous studies (Bussian, 1983; Feng and Sen, 1985; Choo et al., 2016b; Niwas et al., 2007), the work of Glover (2010) and Bussian (1983) (i.e. a theoretically derived electrical conductivity formula based on the Hanai-Bruggeman equation) is suitable for the interpretation of electrical conductivity of clayey soils. Both researchers suggested a modified equation under the assumption that two different conductions as follows:

$$\sigma_{mix} = \sigma_w \varphi^m + \sigma_s \cdot (1-\varphi^m) \quad (3)$$

where σ_s is matrix surface conductivity in clayey soils, m is the cementation factor, and strongly reflects the depolarization factor of dispersed particle (i.e. the path for pore water conduction) (Bussian, 1983; Feng and Sen, 1985; Niwas et al., 2007). The surface conductivity, which is relate to the mineralogical properties (i.e. free swelling rate), can be calculated by Eq. (3).

3. Materials and experimental methods

3.1. Materials

Expansive soils used in the test were prepared by mixing the commercial kaolin (Suzhou Kaolinite, Nanjing, China), primarily composed of kaolinite and bentonite (Sunan Bentonite, Zhenjiang, China), primarily composed of sodium montmorillonite. Index properties of KA and BE are listed in Table 1. Distilled water (electrical conductivity ranging from 2.44 to 2.74 μs/cm at temperature 22.0 ± 0.5 °C) was used as the control samples.

Two natural expansive soils (Hanzhong expansive soils and Black Cotton soils BC) were used as references. Both soils were excavated, wrapped with plastic bags, transported to the laboratory, and then stored in a moisture room until used. Both soils were classified as high plasticity clay (CH) according to the unified soil classification system (ASTM D422-63), and their index properties was shown in Table 2. A scanning electron microscopy (SEM) test (SEM S-3400N, Hitachi, Tokyo, Japan) was performed on mixed soils (Fig. 1). SEM imaging suggested that larger face-to-face (FF) aggregations have induced with the additional of bentonite fraction (BF). And the structure of particle surface or micro-porosity in the clay interior is also changed.

3.2. Experimental method

Free swelling rate and free swelling index experiments were performed on kaolinite-bentonite mixtures and natural expansive soil samples according to ASTM D5890-11 standard and Chinese JTG E40-2007 standard. The volume level was recorded after the minimum 16-h hydration period from the last increment addition until rate of expansion is <0.0002 in/h.

The conductivity experiments were performed by a self-developed four electrodes soil resistivity testing cylinder (5 cm × 15 cm, diameter × length) (Fig. 2) at 22 °C in accordance with ASTM D G57-06 (1995). The cylinder is constructed with polyvinyl chloride (PVC), which is an electrical insulator (electrical resistivity about 10^{16} Ω cm). Alternating current (AC) (16 V and 50 Hz) was used to avoid electrophoretic phenomena, which could alter water content, soil structure, and pore-fluid chemistry (Hamed et al., 1990). The frequency of 50 Hz was selected for two reasons: (1) It is the frequency of the household power supply in China, and (2) it is sufficiently low to avoid electrode polarization at higher frequency (>500 Hz) (Arulanandan and Smith,

Table 2
Index properties of natural expansive soils. S1: sample one of Hanzhong expansive soils, S2: sample two, S3: sample three.

Soils	w/%	r/kN/m³	Gs	pH	LL/%	PL/%	PI	δ%	Particle concentration %		
									<0.005	0.005–0.075	>0.075
S1	28.41	2.34	2.72	7.2	119.80	46.18	73.63	92.8	30.06	62.40	7.54
S2	31.23	2.24	2.70	8.6	115.27	35.87	79.40	106	46.06	47.40	6.54
S3	25.33	2.08	2.73	7.5	123.28	36.92	86.35	118.5	46.72	47.64	5.64
BC	/	/	2.74	7.6	187.18	37.77	149.41	225	/	/	/