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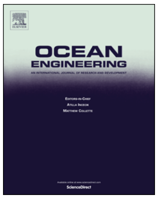

Permeability of muddy clay and settlement simulation

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ABSTRACT

In this study, the permeability characteristics of hydraulic-filled mud from Yueqing port and natural clays from the Minghang River, China, were investigated in a laboratory. The obtained experimental results, when combined with other researchers' experimental data, indicate that the void ratio and clay content are two major factors influencing the permeability of muddy clays. The variation of the permeability with the void ratio is best represented by a linear e *vs.* $\lg k$ relationship. Furthermore, the permeability decreases as the clay content increases. Then, a new empirical formula of the form $\lg k = A(P)e + B(P)$ is proposed to calculate the permeability of fine-grained muddy clays with the clay content P as a parameter. By using this formula and Gibson's equation, the complete settling process of a reclamation foundation that has been newly filled with dredged mud is simulated. The simulation results show that the variation of the void ratio and temporal settlement amount are in line with the measured field data.

1. Introduction

In China, the given increasing population and rapid economic development, reclaiming land from the sea is considered an effective solution to the extreme shortage of land resources. To provide for sufficient agricultural land, the amount of land allocated to industrial and urban areas is rigorously controlled in every municipality (Lin and Ho, 2003). In coastal cities, land reclamation has been used to great effect. China has a coastline of about 18,000 km (Chen and Chen, 2002) and an intertidal zone of about 21,700 km^2; however, 20% of these are muddy. In recent years, dredged mud from port and waterway engineering projects has been hydraulically filled in various reclamation projects in China (Shang et al., 1998; Wang et al., 2014; Liu and Liu, 2008; Shen et al., 2006). However, hydraulic-filled mud shows different characteristics compared to sand or soil taken from dry land. In particular, reclaimed hydraulic-filled mud foundations usually have high water contents, high void ratios, high compressibility, and very low loading capacity. Therefore, such foundations tend to show large deformations during settling (Huerta and Rodriguez, 1992; Liu and Zhou, 2005).

Many studies have focused on the settling process. In the 1960s, the theory of one-dimensional, nonlinear large deformation consolidation of saturated soft clay was proposed (Mikasa, 1965; Gibson et al., 1967). Many studies investigated the fundamental aspects of the consolidation of soft clays as the control variables governing the large deformation consolidation equation (Lee and Sills, 1981; Li and Williams, 1995; Lamcellotta and Preziosi, 1997) and mathematical methods and assumptions for solving the equation (Carter et al., 1977; Mesri and Choi, 1985). From these equations, it is obvious that the variation of the permeability decisively influences the foundation settling process. If this variation is known while the foundation is deforming, the equation that depends on the void ratio can be solved numerically. Therefore, it is essential to precisely determine the soil permeability in order to predict settlement based on the consolidation theory.

Permeability is one of the most fundamental properties of soils. Different soils show considerably different permeabilities. For sands, the permeability can be determined easily as it is closely related to some characteristics of the grain-size distribution (Hazen, 1911; Loudon, 1952; Kenney et al., 1984; Alyamani and Sen, 1993; Chapuis, 2004; Odong, 2007). For muddy clay, however, the permeability is more difficult to determine as it is influenced by many factors, the relationships among which have not yet been identified. Studies have shown that the permeability of clay is roughly related to the void ratio by a log-linear relationship (Taylor, 1948; Mesri and Olson, 1971; Tavenas et al., 1983a, 1983b; Al-Tabbaa and Wood, 1987; Lapierre et al., 1990; Nagaraj et al., 1994; Yang and Aplin, 1998, 2007). However, these empirical formulae are only applicable to specific clay types, and the global factors controlling the permeability of different clays remain unclear. Recently, Park (2011) proposed an artificial neural network

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(ANN) model and showed that it could be used to reasonably estimate the permeability coefficient—modeled as a function of six variables including the natural water content, specific gravity, and grain size—using various permeability test sets. Considering the fact that the gravel content may strongly influence the permeability of granule–clay mixtures (Dunn and Mehuys, 1984; Shakoor and Cook, 1990; Shelley and Daniel, 1993; Indrawan et al., 2006; Shafiee, 2008), presumably, the clay content may also directly influence the permeability of muddy clay. Yang and Aplin (2010) showed that the clay content, defined as the mass fraction of particles less than 2 μm in diameter, was a control factor in the definition of the permeability–void ratio relationship. Using clay content as the quantitative lithology descriptor, they constructed a permeability–void ratio relationship for fine-grained clastic sediments. However, the effect of clay content on the permeability–void ratio relationship has not yet received extensive attention.

The present study aims to investigate the relationships among the clay content, void ratio, and permeability of muddy clay and to simulate the settling of a newly reclaimed hydraulic-filled mud foundation. Permeability experiments were conducted using three types of muddy clay. From the obtained results, combined with Tavenas et al. (1983b) and Leroueil et al. (1990) data, a new equation for calculating permeability was proposed, and a settlement model based on this equation was successfully applied to predict settlement in two engineering cases.

2. Experiments

Experiments were conducted using a TST-55 permeameter that consists of a cutting ring, two porous stones, a lantern ring, a top cover, a bottom cover, and several screws, as shown in Fig. 1. The permeameter had an outer diameter of 118 mm and height of 155 mm. The test sample inside the permeameter was 61.8 mm in diameter and 40 mm in height, which just fitted the chamber. Both the porous stones were 61.8 mm in diameter and 10 mm in height. The permeability coefficient of the porous stone was larger than 10^{-3} cm/s, which was much higher than that of the mud samples. Because the permeability of the saturated muddy clay would be very low, it was measured using the variable head permeability test; this test consisted of the following steps, as outlined in the National Standards of China (GBT 50123-1999):

Fig. 1. TST-55 permeameter.

2.1. Experimental setup

Fig. 2 shows a schematic of the experimental setup. A steel tape was affixed vertically to a wall. Then, a glass tube with 10 mm diameter and 1.4 m length was vertically affixed to the steel tape. A hose was used to connect the lower end of the tube to the inlet of the permeameter. The permeameter was horizontally installed on a small platform that was 0.1 m above the ground. The water flows from the upright tube into the permeameter through the inlet, and then, it passes through the experimental clay samples from the bottom to the top before running out from the outlet. Before starting a test, the bubbles in the permeameter and tube had to be completely removed by injecting tap water and shaking the tube.

2.2. Preparation of experimental samples

Experimental samples were taken from Zhejiang Yueqing north port and two different reaches of the Shanghai Minghang River (sample I was taken from the reach in Shanghai Jiao Tong University and sample II was taken from the reach near Long Wu Road). The median sizes and clay contents of the samples are listed in Table 1. The clay samples were first dried in an oven at a temperature of 105°. Then samples with different water content levels were prepared by mixing dried clay samples with various amounts of tap water. An ultrasonic mixer (1200 W) was used to uniformly mix the clay sample. Clay samples with different void ratios—1–4 depending on the amount of added water—were obtained.

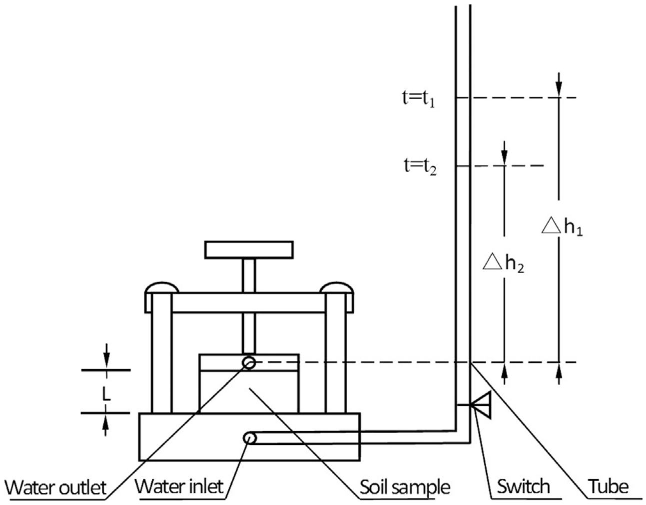

Fig. 2. Schematic plot of experimental setup.

Table 1
Basic properties of investigated muddy clay.

Soil samples	Median grain size d_{50} (μm)	Clay content P
Yueqing	5.98	5%
Minghang I	6.17	23%
Minghang II	3.1	35.5%