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Effects of freezing-thawing and cyclic loading on pore size distribution of silty clay by mercury intrusion porosimetry

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ABSTRACT

With the development of urban rail transposition, the long-term deformation of soft clay under the subway vibration loading has drawn wide attention by researchers and engineers recently. In addition to the situ tests and laboratory triaxial tests, the microscope tests also provide an effective way to clarify the dynamic characteristics of soft clay. Moreover, the variations of the pore size distribution (PSD) of the silty clay before and after freezing-thawing have less been investigated. In this paper, the mercury intrusion porosimetry (MIP) tests were conducted to study the microscope pore structures of the silty clay before and after freezing-thawing which had experienced the cyclic loading by the cyclic triaxial tests. A bottleneck phenomenon with the pore radii of 0.1–0.6 μm exists in the mercury intrusion process. The log-differential pore volume curves of the silty clay show a unimodal mode, where the mode with pore radii range from 0.05 to 0.6 μm represents intra-aggregate pores. After freezing-thawing, the final mercury intrusion volume and the most probable pore size of the samples without cyclic loadings increase about 6.0% and 30.64%, respectively. Under the same cyclic loadings, the mercury intrusion volume increases with the freezing temperature decreasing. The lower the frequency and the larger the cyclic stress ratio (CSR) of cyclic loadings are, the larger the deformations of the samples are and the smaller the most probable pore size becomes. The pore volume of samples after freezing-thawing (F) with frequency of 2.5 Hz is 8.74% larger than that with 0.5 Hz, while it is 5.03% of undisturbed samples (U). The most probably pore size of the samples after freezing-thawing with CSR of 0.125 is about 81.2% larger than that with CSR of 0.375. The process of mercury intrusion in MIP tests is similar to the air injection in a saturated soil as described along the drying water retention curve (WRC). The mercury intrusion pressure and the normalized volume are equivalent to the soil suction and the air volume within the soil, respectively. The MIP derived WRC is suitable for the prediction of the soil-water characteristic curves with the van Genuchten model. In addition, the microscope pore structures of the silty clay exhibit fractal characteristics with the thermal fractal dimension model in MIP tests.

1. Introduction

With the rapid development of the subway rail transit in Shanghai, the effect of the cyclic vibration loadings on the surrounding foundations and buildings has been an area of intense investigation. The soft clay, with multiscale heterogeneity of structure, is characterized by high water content, high compressibility, high sensitivity, low permeability and low bearing capacity (Cui and Zhang, 2015). Generally, the soil mass is mainly constituted of two parts, skeleton particles and pore water. For silty clay, the component of the skeleton particles includes original minerals (feldspar, quartz and mica, etc.), clay minerals (kaolinite, illite, montmorillonite, etc.), soluble salts, and so forth. In particular, the clay minerals are of critical importance in controlling the characteristics of the soft clay. Flocculated structure and dispersed structure have been found to be two representative structures for clayey soils, which have a profound influence on the mechanical behavior of soil (Prashant and Penumadu, 2007; Pillai et al., 2011). However, the complexity of soft clay is not only determined by the mineral composition, but also the pore water inter- or intra-aggregates structures. As the soil becomes finer, the coarse content in the soil descends and the soil structure gradually changes from a coarse controlled structure to a fines-controlled structure which is easily affected by a wetting or drying process (Zhang and Li, 2010). With the water content of soil increasing, the soil structure changes from good integration to flocculation that the particles connect to each other mainly by edges and angularities. Irrespective of how complexity of the microstructure was, the reduced total

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porosity and altered PSD occurred in the clay under the compaction conditions by external dynamic or static loadings (Thom et al., 2007). In addition, the knowledge on the PSD which affects permeability, consolidation and strength is important to the component of the skeleton particles of soft clay, even if both are of considerable interest.

To guarantee the safety in the construction of subway tunnel in soft soil areas, the artificial freezing method has been widely utilized in the construction of by-passes of the subway tunnel due to its unique advantages as both a structural support and a water barrier. In the freezing process, the ice crystal aggregates gradually increased. Chamberlain and Gow (1979) found a reduction in void ratio and an increase in vertical permeability with four fine-grained soils before and after freezing-thawing, which attributed to the formation of polygonal shrinkage cracks. The denser the microstructure is, the stronger the ice crystals aggregate, and soil exhibits higher mechanical and strength characteristics (Liu and Zhang, 2014). However, it also brings some problems, such as frost heave, thawing settlement, differential settlement and structural leakage (Tang and Yan, 2015). After freezing-thawing, the dynamic elastic modulus descends with the dynamic strain increasing (Cui et al., 2014). Moreover, large thaw settlement appeared in centrifuge model test, with great improvement in permeability after artificial ground freezing-thawing (Zhou and Tang, 2015). The changes in these phenomena, including deformations, cracks, excess pore water pressure, and strength degradation, are controlled by the state of the microscope pore structures of soil to a great extent. Therefore, it is of primary importance to conduct accurate measurements of the PSD of the silty clay before and after freezing-thawing.

Recently a growing number of researchers have tried to interpret those phenomena based on the variation of the soil microstructures. The microstructure ($< 100\,\mu m$) refers to the pore structure, crystal structure and mineral composition which can be observed by the scanning electron microscope (SEM), the MIP, the transmission electron microscopy (TEM), the X-ray diffraction (XRD), the computerized X-ray tomography (CT) and so forth (Ninjgarav et al., 2007; Lubelli et al., 2013; Wei et al., 2013; Zong et al., 2015). Among these technologies, the MIP has been routinely used to quantitatively examine the wide range of pore sizes. The microstructure of soil can be better characterized by the PSD, which can be measured using the MIP (Penumadu and Dean, 2000). Initially, the adequacy of the MIP was questioned that whether the intrusion pressure will impose minimal disturbance to the soil fabric or not. In spite of high pressure applied by the MIP, the force acting to cause damage was moderate, particularly in fine pores. In recent years, some researchers have given the data derived from the SEM and MIP tests, which indicated that the damage from the MIP was negligible (Simms and Yanful, 2002, 2004). The results of inter- or intra-aggregates structures by the SEM and the MIP were of the same order of magnitude and the PSD measured by the MIP was close to the actual PSD. MIP has been proposed to be reliable and suitable for study of the soil microstructures.

The MIP tests were carried out by Penumadu and Dean (2000) to evaluate the compression occurred in PSD of cohesive kaolin samples. The tests showed substantive initial compression before the occurrence of actual intrusion resulting in errors associated with the interpretation of pore diameters in the range of 0.4–200 μm. Remarkably differences of the PSD of Pusan clay, with a decline in the inter- and intra-aggregate pore spaces caused by increase in consolidation pressure, were recognized by the mean pore size which effectively represent characteristics of the PSD (Ninjgarav et al., 2007). The same results of compaction effects on the PSD of silty loam were obtained by Lipiec et al. (2012), as well as the effects of aggregate size. It is confirmed from the MIP tests that there exist two major groups of pores within the soft clay, inter- and intra- aggregate pores. It was impossible to find a correspondence between the total porosity volume and the intra-aggregate pore volume, though the pore water volume was found to agree closely with the intra-aggregate pore volume (Monroy et al., 2010). In the drying process, the inter-aggregate pore water first evaporates, followed by the intra-aggregate pore water. Among the inter-aggregate pores, smaller diameter pores are more sensitive to the changes of moisture content (Sasanian and Newson, 2013). In addition, only the inter-aggregate pores are changed and the intra-aggregate pores remain almost the same during the drained triaxial shearing (Yu et al., 2016).

Compared to the cases of soil microstructures researches, the effect of freezing-thawing on the dynamic behaviors of the saturated soft clay under the subway vibration loading has yet to be fully defined. Additionally, the effects of freezing-thawing and cyclic loading on the PSD of silty clay are much more complicated and less research work has been documented. Therefore, the primary concern in this paper is to study the microscope pore structures of the silty clay before and after freezing-thawing under the subway vibration loading. In the following sections, the MIP tests following the cyclic triaxial tests of the silty clay of layer No. 5 in Shanghai, were conducted to investigate the variation of the PSD of the silty clay before and after freezing-thawing. The effects of the frequency, the CSR and the freezing temperature on the microstructure parameters were analyzed. The relationships between the intrusion process and the water drying process were discussed and the MIP derived water content and suction were utilized to predict the water retention curves of soft clay with the van Genuchten model. In addition, the thermal fractal dimension model was adopted to analyze the fractal characteristics of the silty clay from the MIP data.

2. Test methods

2.1. Material properties

The samples were obtained from the grey silty clay of layer No. 5 (about 15–30 m in depth and 5.3–8.4 m in thickness) in Shanghai by drilling holes. In order to guarantee the uniformity and undisturbed state in preparation, the samples were obtained from continued drilling column without interlining and carefully put in thin-walled stainless steel tubes, 100 mm in diameter and 300 mm in length. Each tube was excavated carefully, both ends sealed with wax, transported to the laboratory and stored in a humidity room. In this study, some samples were put into the freezing box for time over 72 h with three different constant freezing temperatures, − 30 °C, − 20 °C and − 10 °C, respectively. After that, these samples were put into the humidors to thaw sufficiently. The properties of the silty clay are summarized in Table 1. Note that F represents the clay after freezing-thawing and U represents the undisturbed clay in the following sections.

2.2. Cyclic triaxial test

In this paper, one-way stress-controlled cyclic triaxial tests with sine waves were conducted on the soil samples under the consolidation and undrained conditions.

Table 1
Physical and mechanical properties of the silty clay samples.

Soils	Nature water content (%)	Initial density (g/cm^3)	Initial void ratio	Liquid limit	Plastic limit	Cohesion (kPa)	Internal friction Angle (°)	Permeability coefficient (m/s)
F	36.7	1.78	1.06	38.4	21.2	8.699	28	2.51×10^{-9}
U	35.4	1.81	1.013	36.7	21.3	7.461	30	1.1×10^{-9}