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Experimental inference on dual-porosity aggravation of soft clay after freeze-thaw by fractal and probability analysis

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ABSTRACT

Variation of micro-structure is very important and virtually the internal nature of macro-behaviours, especially when the macro phenomenon is complex and the mechanism is obscure. The dual-pore structure can be regarded as a special pore structure in clay with a primary network of large inter-aggregate pores overlapped by a secondary network of small intra-aggregate pores. The main hydrodynamic and mechanical properties of soils appear to be largely controlled by this hierarchical partitioning of porosity. Aiming to more specific mechanical properties control during artificial ground freezing from microstructure aspect, this paper focuses on the pore-structure characteristics and computational inference of soft clay after the action of artificial ground freezing. Mercury Intrusion Porosimetry (MIP), as a direct quantization method, was employed to obtain the soil pore-size distribution. And scanning electron microscopy (SEM) was conducted as well, as visible supplementary to describe and qualitatively characterize the microporosity structure. Based on these two aspects, experimental results show a dual-porosity characteristic aggravated after artificial freeze-thaw. Then the influence factor analysis of freeze-thaw effects including different freezing temperature and freezing time, was discussed under uniform design methodology. The influence of each parameter respectively on the variation of dual-pore structure has been discussed to provide valuable reference for AGF practice. Finally, a new comprehensive dual-porosity computational model of soft clay on freeze-thaw effects is developed based on fractal and probability analysis. The application of this model is discussed for the further study.

1. Introduction

In cross passage construction in soft clay with high water content and large void ratio, artificial ground freezing (AGF) technique has been preferred due to its unique advantages (Briley and Sopko, 2004; Hindle, 2006; Kayastha, 2011). Frost heave and subsequent thaw-induced settlement are two main soil responses (Andersland and Ladanyi, 2004), resulted in differential axial settlement on the subway tunnel, adjacent building tilting or concrete segment cracking. They are directly relevant to the subway operation and surrounding environment. Specifically, variations of soil properties due to freeze-thaw, such as permeability and compressibility, induce groundwater leakage around the subway tunnel concrete segment or larger settlement along the tunnel axis. Therefore, more attention has been paid for the influence of AGF construction after some damage cases occurred recently.

Variation of micro-structure is virtually the internal nature of macro-behaviours. It can provide significant supplementary information when the phenomenon is complex and the mechanism is obscure. Particularly in soil materials, as porous media, pore-structure characteristics can be employed to elucidate a variety of testing results for further application. That's why multi-scale analysis from macro to micro is preferred by many researchers during past decades (Bartoli et al., 2005; Burrough, 1983a, 1983b; Giménez et al., 1999; Li and Zhang, 2009; Western and Blöschl, 1999). The characterization of the micro-porosity structure of soils is strikingly challenging (Penumadu and Dean, 2000), especially in clay. Clayey soils usually encompass networks of interconnected pores with diameter from nanometre to millimetre, resulting from electrochemical bonds between clay minerals and water molecules. This special pore structure can be regarded as a dual-pore structure with a primary network of large inter-aggregate pores overlapped by a secondary network of small intra-aggregate pores. It can greatly influence important soil mechanical behaviours. Through the previous researches, how the soil pore-structure forms and changes during compaction, consolidation, saturation or drying processes, are well documented. Sridharan (1971) and Hodek (1972) investigated the pore size distribution in compacted clays and all concluded that there existed network of large inter-aggregate pores and small intra-aggregate pores. It was termed as "dual-porosity" or

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"double-pore" structure by Alonso et al. (1987) and referred by subsequent researchers (Musso et al., 2013; Sørensen, 2006; Tsakiroglou and Ioannidis, 2008). The permeability is dominantly controlled by large pores (Garcia-Bengochea, 1978a). Static compaction response was found to be at expense of the larger pores with little or no influence on pores about 0.1 μm in size (Hodek, 1972; Sridharan et al., 1971). Consolidation was regarded as being influenced by inter-aggregate pore when secondary consolidation (creep) was not in consideration (Griffiths and Joshi, 1989, 1991). Soil-water characteristic and capillary pressure are only contributed by small pores at high-pressure level (Fredlund et al., 2002). Saturation, porosity, relative permeability and hydraulic conductivity may be governed by both network of large pores and small pores under different wettability (Theodoropoulou et al., 2005). A large number of studies on dual-pore structure effects on engineering behaviours of soils have emerged recently (Li and Zhang, 2009; Musso et al., 2013; Tsakiroglou and Ioannidis, 2008) based on the dual-porosity modelling of the pore-structure (Bird et al., 2006; Ioannidis and Chatzis, 1993; Tang et al., 2011; Tsakiroglou and Ioannidis, 2008; Vogel and Roth, 2001a). Nevertheless, how the pore-structure of soft clay behaves under freeze-thaw is not documented much and totally lack of reference.

Fractals were found to provide an appropriate mathematical methodology to address the issues of structure and scale in soil science. Presently fractal geometry concepts have been widely applied as a tool for describing complex natural phenomena in soil science based on fractal theory (Baveye et al., 1998; Burrough, 2001; Perfect and Kay, 1995a). A fractal is a natural phenomenon or a mathematical set that exhibits a repeating pattern that displays at every scale. Fractal dimensions are used to measure the complexity of objects in phenomenon. Fractals attempt to model a complex process by searching for a simple pattern or process underneath by the characteristic of self-similarity or at least partially. The introduction of scaling properties of fractal has allowed a fractal presentation of soil properties, such as soil aggregate characteristics (Tripathi et al., 2012; Young and Crawford, 1991), soil porosity (Rieu and Sposito, 1991a, 1991b), soil density (Bird and Perrier, 2003), soil surface properties (Neimark, 1992; Pardini and Gallart, 1998; Zhang and Li, 1995; Zhang et al., 2006), soil water properties (Bayat et al., 2013; Ghanbarian-Alavijeh et al., 2011), particle size distribution (Erzan and Güngör, 1995; Liu et al., 2009; Millan et al., 2003; Tyler and Wheatcraft, 1992), soil structure properties (Bird et al., 2006; Perrier et al., 1999), etc. From above, it can be found the fractal analysis is generally combined with a specific experimental data to connect the soil properties by pore structure. Meanwhile the generally most used pore-structure model preferred by lots of researchers to describe pore-size distribution in clayey soil is represented as unimodal, bimodal or coupled with log-normal (Coppola, 2000; Fredlund et al., 2000; Heintzenberg, 1994; Li and Zhang, 2009; Romano et al., 2011; Seki, 2007; Tsakiroglou and Ioannidis, 2008). As for soft clay by freeze-thaw action, what kind of specific model is the most applicable pore-structure model is still need to be assessed based on experiments, such as Scanning Electron Microscopy (SEM), generally a qualitative analysis method; Mercury Intrusion Porosimetry (MIP), a direct quantization method.

Overall, specific freeze-thaw influences on soil properties of soft clay can be better inferred by pore-structure variations via fractal analysis as addressed above. It is of great significance to figure out the pore-structure development by freeze-thaw action for the AGF practice safe control in construction. Therefore, a comprehensive investigation of pore structure on soft clay after freeze-thaw has been performed by Scanning Electron Microscopy (SEM) and Mercury Intrusion Porosimetry (MIP) experiments. A serial of group samples under different freezing temperatures and freezing times were conducted to discuss the evolution of pore-size distribution due to freeze-thaw effects. The influence of each parameter respectively on the variation of pore structure has been discussed to provide valuable reference for AGF practice. Finally, a most applicable pore-structure model is proposed based on these experimental data and also assessed by the comparison of permeability test and pore structure results.

2. Materials and methods

2.1. Experimental program

The experimental program aimed to investigate the variation of pore-structure in soft clay due to the freeze-thaw effect both quantitatively and qualitatively. MIP and SEM tests were both conducted in undisturbed samples and freeze-thaw disturbed samples. Moreover, to determine some potential parameters for the damage model induced by freeze-thaw effect, the experimental program was designed into several groups to consider the evolution of the pore structure after freeze-thaw action by relating with different freezing times and freezing temperatures. A uniform design (UD) methodology was utilized here for considering the influence factors, which was proposed and developed by Fang and Wang (1994). The fundamental idea of UD is to choose a set of experimental points with smallest discrepancy among all possible designs for a given number of factors and experimental runs (Fang et al., 2000) in a deterministically uniform fashion. They use the global optimization algorithm, threshold accepting, to construct UD experimental design (UD's) with low discrepancy. The orthogonal design is one major kind of fractional factorial experimental design, globally well-known. UD's can greatly reduce the total number of experiments (shown in the notation of Table 1) but still maintain the orthogonal properties in experimental design. All of these approaches strongly depend on pure mathematics and statistic computation. The reader can refer to Fang's publications (Fang et al., 2000; Fang and Ma, 2001). Here the final application results related in experimental design by UD construction are tabulated in two tables called utilization table and level table (such as Tables 1 and 2). There are five steps for the use of UD's. Firstly, choose the factors and the experimental domain; determine a suitable number of levels for each factor. Secondly, choose a suitable UD table related to the number of factors and levels. Thirdly, record the responses of experiments implemented according to the UD. And then use regression analysis to establish a regression model that fits the experimental data well. Finally, find the 'best' combination of factor values that maximizes/minimizes the response and verify the claim with further experiments. In this experiment, freezing temperature and freezing time were both considered as six levels of Level 1–6, i.e., −5, −10, −15, −20, −25, −30 °C respectively in temperature and 5, 10, 15, 20, 25, 30 days in time. In comparison ordinary orthogonal design (36 group experiments) is time and energy consuming in this two-factor, six-level freezing program. But in uniform experimental design just 6 group covers 36 possibilities (Fang and Wang, 1994). Tables 1 and 2 are the utilization table and the six-level uniform design table, respectively. Table 1 shows that Factor 1 and 3 were used in the two-factor and six-level uniform designation. If Factor 1 is set as Freezing temperature and Factor 3 must be Freezing time; and the level of Factor 3 (freezing time) corresponding to each level of Factor 1(freezing temperature) is chosen following as Column Factor 3 of level values 3,

Table 1
Utilization table of uniform design $U_n(n^s)$[a].

Number of factors	List of factors used in Table 3			
2	1	3		
3	1	2	3	
4	1	2	3	4

[a] The notation is purposely chosen to mimic that commonly used for orthogonal design $L_n(q^s)$, where n is the number of experiments, equal to the number of levels of factors; s is the number of factors, and q the number of levels for each factor. In UD, number of experiments $N = n$; while in OD, $N = q * s / n * s$.