Analysis of influence factors on thermal conductivity of mucky silty clay in Nanjing floodplain based on thermal needle testing

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ABSTRACT: To investigate the thermal characteristics of mucky silty clay in floodplain, based on thermal needle test, the influence factors, such as the water content, dry density and porosity on the thermal conductivity of mucky silty clay was analyzed in detail. The results revealed that the critical water content of mucky silty clay in Nanjing floodplain can reach 25%. With the increase of dry density, the thermal conductivity increased linearly, and the thermal conductivity decreased exponentially with the increase of porosity. This study can provide a further understanding for the heat transfer mechanism of mucky silty clay in floodplain, and give more reasonable thermal parameters for the design of thermal related structures in mucky silty clay and the analysis of surrounding temperature field.

Keywords: Thermal conductivity; influence factors; mucky silty clay; thermal needle test

1. Introduction

Thermal characteristics of rock and soil have important influence on the exploitation and utilization of geothermal energy and the design of thermal engineering structure [1-3]. The main purpose of studying heat transfer is to strengthen or weaken heat transfer by studying the basic law of heat transfer. Thermal conductivity is a key parameter in soil heat transfer analysis, which can directly reflect the heat transfer characteristics of soil [4, 5]. Mucky silty clay contains some organic matter, usually with high water content. Unlike clay or silty clay, the presence of organic matter can reduce the thermal conductivity of soil [6, 7]. The mucky silty clay in the floodplain of Nanjing is widely distributed and thick, which influences the construction of geotechnical engineering. Many oil and gas pipelines, high-voltage cables, energy piles and underground heat exchanger systems pass through silty clay layers [8, 9]. Therefore, the study of thermal conductivity of mucky silty clay in floodplain of Nanjing can provide important thermal parameters for geothermal related structures.

The thermal conductivity of soils is affected by many factors, such as water content, dry density and porosity [3, 5,10-14]. In recent years, a large number of scholars have studied the factors affecting the heat transfer characteristics of soil. For example, Zhang et al. [5] and Gangadhara et al. [10] investigated the variation of thermal conductivity of clay and sand under different water contents and dry densities. Tong et al. [11] found that the effective thermal conductivity of porous media was affected by mineral composition, temperature, saturation, porosity and pressure by analyzing a large number of experimental data. Xu et al. [12] studied the thermal conductivity of muddy silty clay under high temperature of fire. The results showed that temperature and water content had a great influence on the thermal conductivity of muddy silty clay. For the influence factors of thermal conductivity, the current research mainly focuses on sand, silt and clay. However, there are few studies on mucky silty clay in the existing literature.

In this paper, the effects of water content, dry density and porosity on the thermal conductivity of mucky silty clay in Nanjing floodplain were studied by thermal needle test. It is helpful to understand the heat transfer mechanism of mucky silty clay in Nanjing floodplain more comprehensively and provide a more reasonable basis for thermal parameter selection of mucky silty clay in geothermally related structures.

2. Experimental methodology

2.1 Materials

Mucky silty clay is widely distributed in Nanjing (China), and the thickness of mucky silty clay layer is about 8-10.5m. The test soil specimens were selected from the underground soil of a project in Jianye District, 11.9m below the ground, which were characterized by high sensitivity, high compressibility, and low strength. According to field drilling, field test and laboratory geotechnical engineering test results, the basic physical parameters are shown in Table 1.

Table 1. Some physical properties of mucky silty clay

Physical properties	Value
Liquid limit (%)	32.12
Plastic limit (%)	21.43
Plasticity index (%)	10.69
Liquid index (%)	1.40
Dry density (g/cm^3)	1.34
Saturation (%)	91.50
Specific gravity	2.74

2.2 Test method

In this paper, the thermal conductivity of mucky silty clay in floodplain of Nanjing River is measured using MTN01 thermal needle, as shown in Fig. 1. Assuming that there is infinite uniform space in the soil, the temperature of the soil depends on the heating time of the thermal needle and the thermal conductivity of the soil [3, 5]. The length and outer diameter of the thermal probe are 120 mm and 3.5 mm respectively.

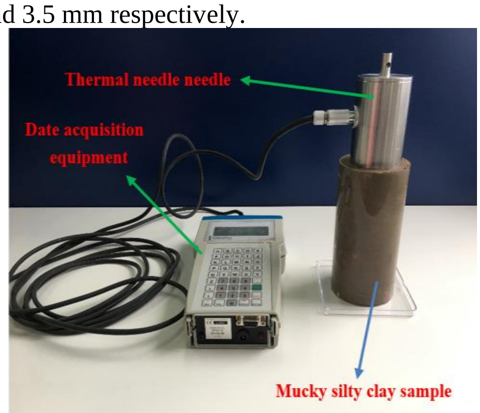

Fig. 1 Mucky silty clay specimen and thermal needle system

After the thermal needle is inserted into the specimen, the sensor begins to monitor temperature changes. Temperature gradient ΔT is:

$$\Delta T = \left(\frac{Q}{4\pi\lambda}\right) ln(t + E) \qquad (1)$$

Thermal conductivity λ can be calculated as follows:

$$\lambda = \left(\frac{Q}{4\pi\Delta T}\right) \ln\left(\frac{t_2}{t_1}\right) \qquad (2)$$

where Q represents the heat transferred into the soil per unit needle length, W/m; λ represents thermal conductivity of soil, W/m·K; t represents time, s; E represents constant; ΔT represents the difference between t_1 and t_2, ℃, $t_2 - t_1 = 150$s。

After air-drying and sieving, the specimens were prepared into 40 groups of soil specimens with different water contents (5, 10, 15, 20, 25, 30, 35 and 40%) and different dry densities (1.0, 1.1, 1.2, 1.3 and 1.4 g/cm^3) to investigate the thermal properties of mucky silty clay in Nanjing floodplain. Porosity of soil specimens can be calculated by equation (3). The prepared soil specimens were placed in a transparent plexiglass cylindrical container with a diameter of 5 cm and a height of 15 cm (Fig. 1) for 24 hours in a constant temperature curing room (temperature 20±2℃, relative humidity 95%). Specific test methods can be referred to Cai et al. [3]

$$n = 1 - \frac{\rho_d}{d_s \rho_w} \qquad (3)$$

where ρ_d denotes the dry density, g/cm^3; d_s denotes the relative density; ρ_w denotes the density of water, g/cm^3.

3. Results and discussion

3.1 Influence of water content

Fig. 2 indicated the variation curve of thermal conductivity of mucky silty clay with water content in floodplain of Nanjing River. It can be seen that the thermal conductivity of the mucky silty clay in the floodplain of Nanjing River increased first and then tended to be stable with the increase of water content under the condition of constant dry density. When the water content was less than 25%, the thermal conductivity increased rapidly with the increase of water content. The lower the dry density was, the faster the thermal conductivity increased. However, when the water content exceeded 25%, the growth rate decreased until it reached a stable state. This was mainly due to the significant difference in the thermal conductivity of each component of soil. For example, the thermal conductivity of solid particles usually varies from 1 to 5 W/m·K, while that of water and air is 0.6 and 0.024 W/m·K, respectively (Cai et al. 2015; Zhang et al. 2017). In the dry state the main way of heat transfer of mucky silty clay in floodplain was through the contact of solid particles. With the addition of water, water film formed between soil particles, which increased the effective contact area between particles. With the further increase of water content, the water film thickness between soil particles reached the upper limit, and the effective contact area between particles no longer increased. At this point, the thermal conductivity of soil depended on the thermal conductivity of pore water and soil particles. Therefore, after reaching the optimal water content, the thermal conductivity hardly increased further [5]. The critical water content of mucky silty clay in floodplain of Nanjing area is considered approximately 25% [15].

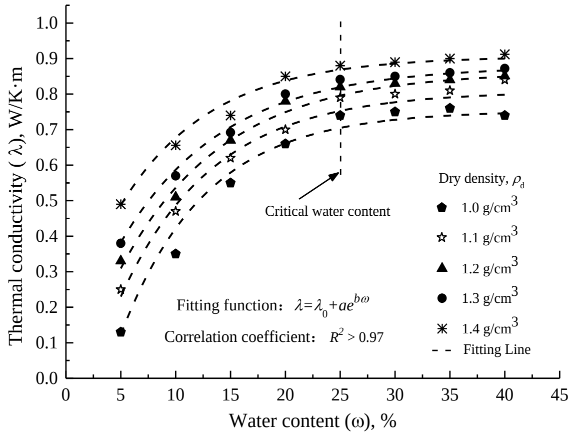

Fig. 2 The relationship between thermal conductivity of mucky silty clay and watecr content

3.2 Influence of dry density

Dry density is one of the main factors affecting the thermal conductivity of soil [16-19]. Fig. 3 showed the effect of dry density on thermal conductivity of mucky silty clay in floodplain of Nanjing River under different water content. Under the same water content, the thermal conductivity of mucky silty clay increased linearly with the increase of dry density. In addition, when the water content was less than the critical water content, the smaller the water content, the faster the thermal conductivity increased with the dry density. When the water content exceeded the critical water content, the thermal conductivity changed slightly with the increase of dry density and tended to be stable.

When the dry density of soil specimens were small, the thermal conductivity of soil increased with the increase of water content. As the dry density of soil specimen increased, the volume of soil specimen decreased, and the air and water in the pore of soil specimen were squeezed out. Each unit volume contained less air molecules and more soil particles. The contact between soil particles became more compact, and the number of contact points increased significantly. Since the thermal conductivity of soil particles is higher than that of air and water, the heat transfer mode in soil is mainly soil particles, supplemented by pore water.

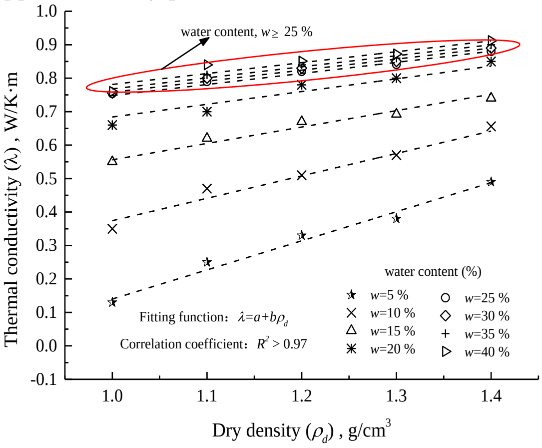

Fig. 3 The relationship between thermal conductivity of mucky silty clay and dry density

3.3 Influence of porosity

Porosity can directly reflect the degree of soil compaction. The higher the porosity, the lower the density and the smaller the effective contact area between soil particles. The effective contact area between particles directly affects the heat transfer path of geotechnical materials, and then affects their thermal conductivity [15, 20]. As can be seen from Fig. 4, the thermal conductivity of mucky silty clay in floodplain of Nanjing River decreased exponentially with the increase of porosity. Under the condition of compactness, the thermal conductivity of soil specimen mainly depended on soil particles, and the influence of water was weak. With the increase of porosity, the number of contact points between soil particles began to decrease, resulting in a rapid decrease in the thermal conductivity of mucky silty clay. With the increase of porosity, the contact point between soil particles gradually decreased to the minimum, and air molecules and water filled the whole pore. At this point, the main way of heat transfer was through soil particles and air. Therefore, the thermal conductivity of soil specimen changed slowly with the increase of porosity until it reached the minimum value.

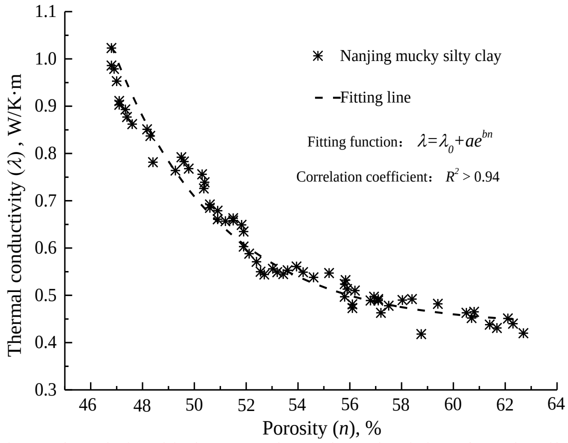

Fig. 4 The relationship between thermal conductivity of mucky silty clay and porosity

4. Conclusions

In this paper, the thermal conductivity of mucky silty clay in Nanjing floodplains was systematically analyzed. The research results can provide more reasonable thermal parameters for thermal engineering design and analysis of surrounding temperature field of mucky silty clay in floodplain of Nanjing. The main conclusions drawn are as follows:

(1) The thermal conductivity of mucky silty clay in floodplain of Nanjing River increased exponentially with the increase of water content, and the critical water content was 25%. When the moisture content exceeded 25%, the thermal conductivity changed slowly and tended to be stable gradually.

(2) The thermal conductivity of silty clay increased linearly with the increase of dry density. The thermal conductivity of mucky silty clay increased exponentially with the increase of porosity. At low dry density or high porosity, heat transfer was mainly accomplished by soil particles and air.

Acknowledgments

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