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Dynamic shear modulus and damping ratio of thawed saturated clay under long-term cyclic loading

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ABSTRACT

Dynamic properties of subgrade soil under the long-term traffic loading are crucial for designing the subgrade structures and evaluating the long-term performance of traffic infrastructures in seasonally frozen regions. In this study, the dynamic shear modulus and damping ratio were employed to evaluate the long-term dynamic behaviors of thawed saturated clay by conducting a series of cyclic tri-axial tests. Effects of freeze-thaw cycles, dynamic stress amplitude, confining pressure and multi stage cyclic loading on the evolution rules of dynamic shear modulus and damping ratio versus shear strain were analyzed. The results indicate that both dynamic shear modulus and damping ratio decrease with the increasing shear strain during the long-term cyclic loading. Repeated freeze-thaw cycles have tremendous effects on decreasing the dynamic shear modulus and increasing the damping ratio. Increasing dynamic stress amplitude has a decreasing effect on dynamic shear modulus, and an increasing effect on damping ratio. Increasing confining pressure has no obvious effect on the evolution of damping ratio, but has an increasing effect on increasing the dynamic shear modulus before the shear strain reaches a certain level. Multi stage cyclic loading can be an alternative method to determine the evolution of dynamic shear modulus during the long-term cyclic loading, but it is not applicable for the damping ratio. Finally, the Martin-Davidenkov model and a hyperbolic model which can be used for predicting the evolution of dynamic shear modulus and damping ratio, respectively, were proposed and validated. The results show that both the two models can give satisfactory prediction. The results achieved in this study contribute to a better understanding of the long-term dynamic behavior for cohesive subgrade soils in seasonally frozen region.

1. Introduction

Long-term dynamic behaviors of subgrade soil in seasonally frozen regions are more complicated than that of subgrade soil in non-frozen regions, because the mechanical properties of the subgrade soil could be changed by the effects of repeated freeze-thaw cycles (Cui et al., 2014; Qi et al., 2006; Wang et al., 2007, 2015a). Moisture content has been proved to be one of the main influencing factors that determine the effects of freeze-thaw cycles on the properties of soils (Feng et al., 2017; Wang et al., 2015b; Zhao et al., 2009; Zheng et al., 2015). The moisture within the soil structures would migrate and accumulate due to the effects of freeze-thaw cycles (Harlan, 1973; Kane and Stein, 1983; Othman and Benson, 1993; Perfect and Williams, 1980; Sheng et al., 2014; Zhang and Michalowski, 2015). These mean that the subgrades, commonly built at the optimum moisture contents, typically stay in an unsaturated condition, have a high risk of turning into saturated state during the spring thawing period due to the water and moisture accumulation occurred in winter freezing period. Especially in the clay-rich seasonally frozen area, many constructed or being constructed subgrades are suffering from special disasters involving freeze-thaw effects, such as frost heave, thawing settlement, frost boiling and uneven settlement, because the clays are more sensitive to the impact of repeated freeze-thaw cycles compared with the coarse grained soils (Hansson and Lundin, 2006; Özgan et al., 2015). These special disasters not only affect the stability of subgrades, but also destroy the pavement structures and threaten the traffic safety. Thus, it is urgent to investigate the evolution of dynamic properties for thawed saturated clay under long-term cyclic loading.

Dynamic shear modulus and damping ratio are the two main parameters that contribute to variation in the stiffness and energy dissipation during the cyclic loading of soils, which are being used for defining the dynamic properties of soil induced by earthquake, wave and traffic cyclic loading. In the past decades, many advances have been made in investigating the evolution of dynamic shear modulus and damping ratio for soils (Brennan et al., 2005; Ishibashi and Zhang, 1993; Rollins et al., 1998; Seed et al., 1986; Wang et al., 2012), these

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investigation were mostly conducted on unfrozen soils. It appears that few contributions could be found in literature that the soils in cold regions were focused on. Compared with thawed soils in cold region engineering, some studies have been done to investigate the dynamic shear modulus and damping ratio of frozen soils. Stevens (1975) studied the stiffness and damping properties of frozen soils subjected to vibratory loads and to define the significant factors affecting these parameters by using of one dimensional wave test. Czajkowski and Vinson (1980) found that the dynamic Young's modulus of frozen silt decreases with increasing axial strain amplitude and temperature, increases with increasing frequency, and is unaffected by confining pressure. Al-Hunaidi et al. (1996) used the resonant-column test to determine the dynamic shear modulus and damping ratio of naturally frozen soil. Ling et al. (2013, 2015) found that, for frozen clay the stiffness increases and damping ratio decreases with the increasing number of repeated loading cycles; For the frozen sand, the dynamic shear modulus increases with increasing initial water content, temperature, loading frequency and confining pressure. The damping ratio increases with increasing initial water content, while decreases with increasing temperature and loading frequency.

In general, these findings mentioned above can be helpful in understanding the evolution of dynamic shear modulus and damping ratio for soils subjected to freezing conditions. But for the soils which experienced thawing conditions, only few contributions could be found in recent years. Zhang and Hulsey (2014) found that the freeze-thaw cycles resulted in an increase in both the dynamic shear modulus and the damping ratio of the Marble Creek silt. Wang et al. (2014) studied the changes in dynamic modulus and damping ratio of compacted subgrade soil after been subjected to different freeze-thaw cycles, the results showed that the dynamic modulus decreases with the increase of freeze-thaw cycles, but the relationship between damping ratio and freeze-thaw cycles was not clear. Tang et al. (2014) proved that the freeze-thaw action can actually decrease the dynamic elastic modulus of mucky clay, and the dynamic elastic modulus decreases remarkably with the increasing of cyclic stress amplitude, while the accumulated plastic strain behaves adversely. Wang et al. (2015a, 2015b) observed that the dynamic modulus of silty sand sharply decreases while the damping ratio increases with incremental increase in freeze-thaw cycles, the changes level off after six freeze-thaw cycles. It could be noticed that almost all the evolutions of dynamic shear modulus and damping ratio in these studies were just employed to evaluate the effects of freeze-thaw cycles. The experimental data usually obtained by means of a series of multi stage cyclic loading, that is, dynamic stress was imposed by steps and each step corresponding to a stress amplitude and lasted for several cycles. However, little research has been directed towards understanding the evolution of dynamic properties for thawed saturated clay.

In this study, the evolution of dynamic shear modulus and damping ratio for thawed saturated clay under long-term cyclic loading were investigated firstly. Secondly, the relationships between the dynamic shear modulus G and the cyclic shear strain γ, which are typically expressed by the curves of $G/G_{\max}$ versus γ, together with the relationships between the damping ratio λ and shear strain γ were employed to analyze the dynamic characteristics of thawed saturated clay under long-term repeated cyclic loading. Thirdly, the influencing factors such as dynamic stress amplitude and confining pressure were discussed. Effects of multi stage cyclic loading on the dynamic shear modulus and damping ratio were also compared with that of the long-term loading. Finally, empirical models for dynamic shear modulus and damping ratio were proposed and validated, respectively.

2. Experimental procedures

2.1. Properties of soil

The soil used in this study was obtained from Harbin, it is widely used to fill the subgrade in northeast of China. The grain size distribution is showed in Fig. 1. According to guidance of the Test Methods of Soils for Highway Engineering (JTG E40-2007) issued by the Ministry of Transport, China. The optimal water content and maximum dry density were obtained by the heavy compaction apparatus, together with the other physical properties of the soil, namely specific gravity, liquid limit, plastic limit are shown in Table 1. The soil is named as low liquid limit clay and classified as CL according to the classification method of the Test Methods of Soils for Highway Engineering (JTG E40-2007).

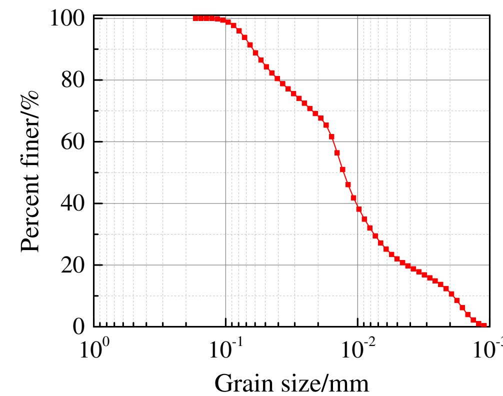

Fig. 1. Distribution curves of particle size.

2.2. Preparation of specimen

2.2.1. Specimens preparation

All the procedures on preparing the thawed saturated specimen were performed in a laboratory environment. The air dried clay powder was sieved firstly from a sieve with pores of 2 mm and was mixed with distilled water to achieve the optimal water content of 17.4%. Then the soil was stored in a closed container for 12 h to make sure the uniform distribution of the water. Specimens were obtained by compacting the wet clay powder in a steel cylinder though equal five layers. All the specimens have the sizes of 100 mm in diameter, 200 mm in height, shown in Fig. 2(a), and the compaction degrees of the specimens are controlled at 94%. During the compaction procedure in the steel cylinder, the layer height was controlled to ensure the compactness degrees among the five layers are uniform. Saturating process on the specimens was conducted by the suggestion of Standard for Soil Test Method (GB/T 50123-1999(2008)). The specimens were fixed with the customized saturators first, shown in Fig. 2(b), and then were placed in a seal barrel for vacuuming, the deaired water was supplied for the barrel to ensure the specimens were saturated in the water, shown in Fig. 2(c). The vacuuming and saturating procedures were lasted for 2 h and 12 h respectively. Saturation degrees of the specimens were also checked after the saturation procedures to make sure all the saturation degrees of the specimens reach more than 95%. The eligible specimens were sealed with plastic wrap and adhesive tape to prevent water evaporation, shown in Fig. 2(d). After 7 freeze-thaw cycles, 12 specimens were selected randomly to check the changes in volume and mass. Results showed that changes in volumes and masses of 12 specimens range from 0.32% to 2.92%, and from 0.11% to 0.44%, respectively.

Table 1
Basic physical properties of soil specimens.

Specific gravity	Liquid limit/%	Plastic limit/%	Plastic index	Maximum dry density/g/cm^3	Optimal water content/%
2.75	36.98	25.19	11.79	1.74	17.4