Cold Regions Science and Technology 112 (2015) 51–65

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

An experimental study on the mechanical properties of silty soils under repeated freeze–thaw cycles

Tian-liang Wang [a,b], Yao-jun Liu [a,b,*], Han Yan [c], Lei Xu [a,b]

[a] School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, China
[b] Key Laboratory of Roads and Railway Engineering Safety Control of Ministry of Education, Shijiazhuang Tiedao University 050043, China
[c] Northwest Corp., China Railway Construction Engineering Group, Xi'an 710119, China

ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form 17 December 2014
Accepted 13 January 2015
Available online 21 January 2015

Keywords:
Silty soil
Freeze–thaw cycle
Unidirectional freezing
Dynamic modulus
Thaw subsidence ratio

ABSTRACT

In this study, the subgrade fill material from the Nagqu Logistics Center Yard (NLCY) along the Qinghai–Tibet Railway was investigated. And the thaw subsidence properties and dynamic properties were thoroughly analysed in laboratory tests.

1) From the determined thaw subsidence properties, the following results were obtained: samples with a higher degree of compactness exhibited heave deformation, whereas those with a lower degree of compactness exhibited compressive deformation after repeated freeze–thaw cycles. However, there is a critical compactness level at which the height of the samples does not change after repeated freeze–thaw cycles. The consolidation effect of the load restrains frost heave deformation; however, the amount of thaw subsidence deformation increases. The thaw subsidence ratio first increases, then decreases and becomes steady after the fifth freeze–thaw cycle as the number of freeze–thaw cycles increases. It is recommended that the thaw subsidence properties of silty soils be assessed after 5–6 freeze–thaw cycles.
2) From the determined dynamic properties, the following results were obtained: the dynamic stress vs. strain curves clearly show a nonlinear trend. The dynamic modulus greatly decreases, whereas the damping ratio increases with additional freeze–thaw cycles; and changes level off after the sixth freeze–thaw cycle; the dynamic properties after 6–7 freeze–thaw cycles are suggested for use in designing and calculating indexes. Moreover, the dynamic modulus increases and the damping ratio decreases as the confining pressure and compactness increase.

1. Introduction

The Nagqu Logistic Center Yard (NLCY) of the Qinghai–Tibet Railway is located at an elevation of 4500 m on the Qinghai–Tibet plateau. The total area of the NLCY is approximately 5.0 km^2, where the maximum frozen depth is greater than 2.81 m, and the soil type is deep seasonal frozen soil. The area is covered with high to extremely-high frost-susceptible soils, such as silty soil, soft silty soil and silty clay (Wang et al., 2014). Based on failure investigations and analyses, it was found that the damage caused by repeated freeze–thaw cycles frequently occurred (see Fig. 1), such as road pavement cracks, subgrade subsidence and building wall cracks. The maximum frost heave deformation has been found to be greater than 160 mm, and the maximum thaw subsidence deformation has been found to be greater than 130 mm, which significantly affects the service performance of NLCY subgrade. Engineering practices and studies at home and abroad have shown that most of the railway and highway subgrade damage results from repeated frost heave and thaw subsidence, which affects its strength in deep seasonal frost regions (DCR, 2002; TRSDI, 1994).

The thaw subsidence properties, particularly the repeated frost heave and thaw subsidence properties, are important factors in evaluating the service performance of structures and preventing freeze damage in deep seasonal frost regions. So far, studies on the mechanism of frost heaving and thaw subsidence and preventing freeze damage have achieved some success in defining the process. In terms of the thaw subsidence properties, Morgenstern and Nixon (1971) and Shoop et al. (2008) created a subsidence calculation model. Klinova et al. (2010) studied influential factors, such as water content, temperature and compactness, which affect thaw subsidence properties through laboratory tests. Based on a large-scale model test, Tanaka et al. (2009) studied the thaw subsidence properties of soils, which were also done by Chen et al. (1999) in China. Peng and Liu (2010) determined the frost heave and thaw subsidence properties of silty clay under cyclic loads. However, the aforementioned studies only investigated the

---

* Corresponding author at: School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, China. Tel./fax: +86 10 15032173068.
E-mail address: wtl820520@163.com (Y. Liu).

http://dx.doi.org/10.1016/j.coldregions.2015.01.004
0165-232X/

Fig. 1. Damage to engineering structures in the NLCY.

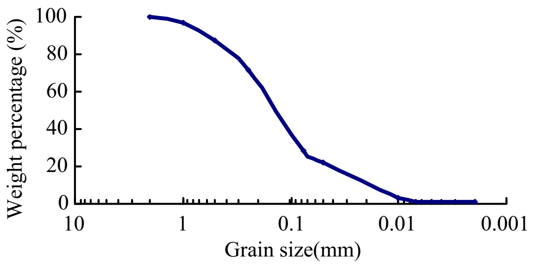

Fig. 2. Grain size distribution curve.

thaw subsidence properties after a single freeze–thaw cycle, and the studies on multiple freeze–thaw cycles were only focused on the moisture and salt migration (Bao et al., 2006; Chen et al., 2009, and Li et al., 2009). There are only a few studies on frost heave and thaw subsidence properties under repeated freeze–thaw cycles (Fu and Wang, 2010; Liang et al., 2006), where these studies have been limited to the freeze–thaw cycles of three-dimensional freezing and closed systems (Liang et al., 2006), which do not simulate the freeze–thaw pattern at a site well.

In conclusion, the aforementioned studies have shown that frost heave deformation and thaw subsidence deformation are important factors that influence the service performance of structures. However, the strength properties, particularly the dynamic soil parameters under repeated freeze–thaw cycles, are also important influential factors. Therefore, it is necessary to fully investigate the deformation and strength properties under repeated freeze–thaw cycles and to confirm reasonable design values to fully characterise the service performance of structures in deep seasonal frost regions. In terms of strength properties, the dynamic modulus and damping ratio are two important parameters when analysing the dynamic responses of soils under train loads, seismic waves, vibration load, etc. (Chen et al., 2012). Thus far, the studies on the strength properties of silty soil have focused on static responses (Liu et al., 2012; Lu et al., 2007; Salgado et al., 2000; Xiao et al., 2010). For the dynamic responses of silty soils, Chen et al. (2012) and Jiang and Xing (2007) studied the dynamic shear modulus of silty soil. Based on a model test, Cai et al. (2012) studied the dynamic modulus and damping ratio of silty soil subgrade loaded by an airplane. In terms of determining the anti-freeze–thaw properties of silty soils, the works by scholars at home and abroad have primarily focused on the physical properties (Othman and Benson, 1993 and Qi et al., 2008), unconfined compressive strength (Ahmed and Ugai, 2011; Kamei et al., 2012; Ma et al., 1999), and stress–strain properties (Shoop et al., 2008) under repeated freeze–thaw cycles; there have only been a few works on the dynamic responses of silty soil under repeated freeze–thaw cycles.

Therefore, the objective of this study was i) to determine mechanical properties, such as the thaw subsidence properties, water intake, dynamic modulus and damping ratio, under repeated freeze–thaw cycles; and ii) to determine reasonable design values and systematic testing methods to evaluate the service performance of railway subgrade in deep seasonal frost regions. To achieve these objectives, the thaw subsidence ratio, dynamic modulus and damping ratio with different numbers of freeze–thaw cycles, compactness levels, confining pressures and loads were studied by conducting frost heave and thaw subsidence tests and dynamic triaxial tests.

2. Experiment process

2.1. Material properties

The soil used in this study was silty soil, which is the subgrade fill material from the NLCY with a soil thickness greater than 3.6 m. The grain size distribution of the soil is shown in Fig. 2, where particles at sizes less than 0.075 mm account for 28.4% of the total weight. The physical properties are given in Table. 1.

2.2. Tests for frost heave and thaw subsidence

2.2.1. Testing system for frost heave and thaw subsidence

The testing system to determine frost heave and thaw subsidence consisted of a sample cell, top and bottom cold plates, NESLAB constant-temperature cold baths, a Markov bottle, insulation cotton, temperature and displacement sensors and a data acquisition system, as shown in Fig. 3. In the test, the lateral restraint of the sample cell,

Table 1
Physical properties of the silty soil.

Specific gravity	Max. dry density (g/cm^3)	Opt. water content (%)	Freezing temperature (°C)	Salt content (%)	Permeability coefficient (cm/s)
2.70	1.83	11.7	-1.03	0.15	5.87×10^{-4}