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Present situation and prospect of mechanical research on frozen soils in China

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A B S T R A C T

Engineering construction in cold regions and artificial ground freezing projects require an understanding of the mechanical properties of frozen soils. An understanding of properties such as strength and deformation are important for engineering design purposes. In the past decades of years, because of the increase of the engineering, such as the Qinghai–Tibet Railway (QTR), the Qinghai–Tibet Highway and the Golmud–Lhasa Oilpipe (GLO), constructed in frozen soil regions on the Qinghai–Tibet Plateau, the study on the material properties of frozen soils in China was being developed quickly, and numerous research results were achieved. This paper summarizes these research fruits in four aspects: (1). Strength property of frozen soils, (2). Deformation behavior of frozen soils, (3). Constitutive models for frozen soils, (4). Dynamical property of frozen soils. This summary would be helpful for their convenient application in practical engineering, as well as for supplying foundation and developing direction of mechanical property research on frozen soils.

Contents

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1. Introduction

Frozen soil is a kind of special geotechnical material. The definition of frozen soil was being improved with the information accumulation of its mechanics tests (Roman, 2005). At present, the widely accepted definition of frozen soil is the soils and rocks with a temperature at or lower than 0 °C and with ice content (Zhou et al., 2000). According to the life length of frozen soil, it can be divided into artificially frozen soil, seasonally frozen soil and permafrost. Frozen soil is widely distributed on earth. All kinds of frozen soil and permafrost areas account for 50% and 25% of continent area, respectively, which are mainly distributed in 48 countries, such as Russia, America, Canada, China and so on (Zhang et al., 2006). The frozen soil area in China ranges the third in the world. Seasonally frozen soil and permafrost areas account for 53.5% and 21.5% of China's land area, respectively (Xu et al., 2001). The permafrost in China is mainly distributed on the Qinghai–Tibet Plateau, high mountains in the northwest, Great and Lesser Xing'an Mountains in the northern of the northeast and Songnen Plain. The seasonally frozen soil in China is distributed in the regions to the west of Helan Mountain–Ailaoshan Mountain line and the regions to the east of this line and to the north of the Qinling Mountains–Huaihe River line. Numerous mine, energy, forest and soil resources, which are necessary for human living, exist in the wide frozen soil regions in China.

With economical and social progress, highway, mineral engineering, and energy engineering constructions have been conducted in frozen soil regions. In 1904, the 9446 kilometers long Siberia Railway was constructed in Russia. For mineral and forest exploitation, highways were constructed in Alaska and northwest of Canada. A highway going across Alaska and Canada was constructed in 1942 (Jiao, 2011). Due to the need of economical constructions, engineering construction in frozen soil regions rises in China, which mainly includes the Qinghai–Tibet Highway, the Xining–Yushu Highway, the Qinghai–Tibet Railway, the Golmud–Lhasa Oilpipe, China–Russia Oilpipe and the West Route of South-to-North Water Diversion. Besides the engineering constructed in natural frozen soil regions, the subway construction in southeast of China and deep mining engineering, in which the artificial freezing method is used, also meet frozen soil problems (Chen et al., 2009; Jin, 2008). In frozen soil engineering, the safety and stability of engineering can be ensured only if the frozen soil has enough ability to resist failure and deformation under the action of external loads. The ability of frozen soil resisting failure is characterized by its strength and its deformation property determined by stress–strain relation. Both of them are main research subjects of frozen soil mechanics, and also an important foundation for design, construction and maintenance of frozen soil engineering.

The engineering construction in frozen soil regions greatly sped up the appearing and development of frozen soil mechanics. The mechanical property of frozen soil is a main scientific subject in frozen soil mechanics, especially strength and deformation. The mechanical properties of frozen soils are influenced by internal factors, such as mineral component, grain size distribution, equivalent moisture content determined by ice content and unfrozen water, salt content, organic content, and external factors, such as temperature, loading rate, stress path, stress-stain history and stress level. The influences of these factors are not independent, but coupled with each other. External factors influence the mechanical properties of frozen soils through internal ones. All these factors make the mechanical behavior of frozen soil be more complicated than that of unfrozen soil. Many tests and theoretical researches on the strength and deformation properties of frozen soils have been carried out by different researchers from different viewpoints. With the development of engineering construction in cold regions and the using of artificial freezing method, the research on the strength of frozen soils started in China in 1960s, and a systematical research on the strength and creep of frozen soils started in 1970s (Zhu, 1988). Strength and creep theories are gradually established, and the research results have widely been used in frozen soil engineering in China. Up to now, a series of significant research results on frozen soil mechanics have been achieved in China and a great amount of mechanical test data are accumulated. There are several Chinese scholars to have reviewed the researches on frozen soils from different aspects (Li et al., 2001; Ma and Wang, 2012; Qi and Ma, 2010). Li et al. (2001), Qi and Ma (2010) analyzed freezing-thawing process of soil in cold region, and their cited research results were focus on theoretical models of freeze-thaw related problems. Ma and Wang (2012) mainly retrospected the development history of frozen soil mechanics research in China during past 50 years. In this paper, in order to understand the property of material of frozen soils in China for readers, according to relative references, the research results on frozen soil mechanical properties in China are summarized and introduced in four aspects: (1). Strength property of frozen soils, (2). Deformation property of frozen soils, (3). Constitutive models for frozen soils, (4). Dynamic property of frozen soils.

2. Strength property of frozen soils

In engineering design, strength is used to check bearing capacity of frozen soil structures. According to failure time, the strength of frozen soils can be divided into three types of strengths, i.e., instantaneous strength, long-term strength and long-term strength limit. Instantaneous strength is the strength under fast failure. Long-term strength is the failure stress under given failure time. Long-term strength limit is the stress value that, when the actual stress is lower than it, the failure will never happen, i.e., the failure time is infinite. Research results show that, the strength of frozen soil is influenced both by soil factors like equivalent moisture content, salt content and dry density, and by ambient factors like temperature, strain rate and confining pressure (Wu and Ma, 1994). The influences of these factors are not independent, but being coupled with each other. The strength property of frozen soils and its influencing factors will be synthesized in this section.

2.1. The influence of soils on strength

The internal factors, influencing the mechanical properties of frozen soil, include soil type, equivalent moisture content, dry density and salt content. The influences of these factors are to be analyzed according to existing research results.

2.1.1. The influence of soil type

Generally, soil type has an obvious influence on the strength of frozen soil. The artificial freezing shaft sinking technology was used in mine construction in the Huainan and Huaibei coal fields (Lianghuai regions). Wu and Ma (1994) systematically studied the artificial frozen soils in Lianghuai regions in China. Their result is that plastic index was strength influencing factor for clay. The compressive strength of frozen clay increases with plastic index, because the plastic index indirectly reflects the grain size and mineral content and component, as well as the liquid limit water content. The compressive strength of artificial frozen expansive soils increases quickly with the decrease of liquid limit water content. There are three types of the frozen coarse-grain soils in this region. The first one is frozen fine sand, which has less clay and larger compressive strength (but still smaller compared with typical frozen fine sand). The second one is frozen gravel, grit and medium sand, whose compressive strength was similar to that of the first type due to weathering of the mineral grain. The last one is frozen gravel and medium gravel with more fine particles, whose compressive strength is small due to severe weathering of the mineral grain, similar to cohesive soil.