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Elasto-plastic behaviour of frozen soil subjected to long-term low-level repeated loading, Part I: Experimental investigation

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ABSTRACT

The elasto-plastic behaviour of frozen soil subjected to long-term low-level repeated loading is frequently characterized by resilient modulus and accumulated strain, which are significant factors for construction in cold regions. This paper presents an experimental investigation and test results in which accumulated behaviour, including the amount and direction of accumulated strain, is shown to be significantly affected by the initial stress state, repeated stress amplitude and frozen soil strength. Variations in the accumulated direction with increasing numbers of repeated loading cycles cannot be neglected. The resilient modulus, including the shear and bulk components, increases with the accumulation of plastic strain and is clearly dependent on the initial mean stress. These innovative discoveries may help elucidate the properties of frozen soil influenced by long-term low-level vibrations. Furthermore, this work will provide important data for the development of a constitutive model of frozen soil under long-term low-level repeated loading.

1. Introduction

In recent years, an increasing number of construction projects, such as railways, highways, and wind power plants, have been completed in the cold regions of China, and such construction has led to continuous vibrations in the frozen soil foundation system. Under these particular soil dynamics, although regular vibrations do not lead to immediate structural damage, even relatively low-level vibrations may lead to a reduction of serviceability or diminish the structure's lifetime because of accumulated plastic strain in the frozen soil foundation under a large number of loading cycles. A number of field measurements in cold regions have demonstrated non-negligible permanent displacements under a large number of loading cycles (Feng, 2009; Li et al., 2012). Therefore, permanent deformations induced by long-term low-level vibrations should be considered in the design process of such structures, and a more detailed understanding of the long-term low-level vibration mechanisms in frozen soil may also lead to economically advantageous designs. For these reasons, it is important to investigate the long-term elasto-plastic behaviour of frozen soil.

The accumulated strain and resilient modulus are widely used to evaluate elasto-plastic behaviour for geo-materials that experience long-term low-level vibrations. Laboratory tests are usually applied in such research, but because of the limitations of test equipment, complex vibrations in the foundation induced by the above-mentioned construction activities are usually simplified to repeated loading (one-way cyclic loading) in experimental investigations. Studies on the long-term elasto-plastic behaviour for different types of geo-materials under uniaxial, triaxial and direct shear conditions have been recently completed by a number of researchers, and general conclusions have been drawn. Nevertheless, most of the above studies are conducted by test evidences on unfrozen soil. Frozen soil is a complex mixture of mineral and/or organic particles, unfrozen water, polycrystalline ice and air (Vialov et al., 1965), and its mechanical behaviour is different from that of unfrozen soil (Lai et al., 2009b; Ma et al., 1999; Ting et al., 1983). Several studies have described the accumulation or resilient behaviour of frozen soil under uniaxial and triaxial conditions. The accumulated axial strain increases with an increasing number of loading cycles (loading times), repeated stress amplitude and initial deviator stress (Jiao et al., 2011; Zhao et al., 2002). Zhang et al. (2015) conducted the cyclic triaxial tests to study the cumulative plastic strain of frozen aeolian soil and the effects of temperature, the amplitude and frequency of dynamic stress, confining pressure and initial water content were investigated. The independence of the repeated deviator stress on the resilient modulus of frozen cohesive soil was detected by Lee et al. (1995). Simonsen and Isacsson (2001) compared the influence of the maximum mean stress on the resilient modulus for frozen gravel and frozen fine sand and observed that for frozen gravel, the resilient modulus increased slightly with increasing maximum mean stress, whereas no influence was

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found on frozen fine sand. In addition, temperature has a significant influence on the resilient modulus (Simonsen and Isacsson, 2001; Simonsen et al., 2002). Ling et al. (2013) first observed that the elastic modulus increased with the number of repeated loading cycles for frozen soil close to 0 °C, however such a study on frozen soil is incomplete and must be investigated systematically.

Although no comprehensive studies on long-term cyclic behaviour of frozen soils are conducted, a lot of attempts on unfrozen ones have been done. The accumulated strain is observed increasing with the number of loading cycles in a large number of long-term cyclic triaxial tests on unfrozen soils, whereas the accumulation rate decreases as the increasing loading cycles (Suiker et al., 2005; Wichtmann et al., 2005). Several experimental studies using cyclic stress or strain-controlled tests for various types of unfrozen soils indicated that the accumulated strain was significantly influenced by the cyclic or repeated stress/strain amplitudes (Marr and Chrisitian, 1981; Sawicki et al., 2009; Shi et al., 2014; Silver and Seed, 1971; Youd, 1972), and considerable increases in the accumulation rate were observed with increasing cyclic stress or strain amplitude. An effect on the accumulated volumetric strain was also reported by other researchers (Wichtmann et al., 2005; Youd, 1972), and similar conclusions were obtained. The definition of CSR or DSL (ratio between the cyclic or dynamic stress amplitude and shear strength) was widely introduced to study the effect on accumulated strain, and the results suggest that the accumulation rate increases with increasing CSR or DSL (Brown, 1996; Guo et al., 2013; Li and Selig, 1996; Wichtmann et al., 2005). The influence of confining pressure or initial mean stress on the accumulation rate for different types of soils was also studied by many researchers (Benoot et al., 2014; Guo et al., 2013), and the test results clearly showed that a higher confining pressure or initial mean stress resulted in a decreasing strain accumulation rate. In certain two-way cyclic simple shear or triaxial tests, the average mean pressure corresponding to the initial mean stress in a one-way cyclic test was chosen to study its effect on the accumulation rate. Certain researchers (Silver and Seed, 1971; Youd, 1972) concluded that the average mean pressure did not influence the accumulated strain. However, T. Wichtmann (Wichtmann et al., 2005) observed a significant decrease in the accumulation rate with increasing average mean stress. The influence on the accumulation rate from another portion of the initial stress state, the initial deviator stress, has also been studied. The initial deviator stress has been studied in terms of the stress ratio or average stress ratio in which the value of the deviator stress is compared against the mean stress in the static state. The larger stress ratio resulted in a higher accumulation rate under the same initial mean stress and cyclic stress amplitude(Wichtmann et al., 2005). The factors that contributed to the physical or mechanical behaviour of soil, such as the moisture content, initial density or initial void ratio, were selected to study their effect on the accumulated strain, and they were shown to exhibit a significant influence on the magnitude of the accumulated strain (Dong Cheng, 2014; Silver and Seed, 1971; Youd, 1972). Li and Selig (1996) introduced the static shear strength to describe the effects of physical–mechanical behaviour of silty soils. In addition to the above-mentioned factors, the dependence of the loading frequency on the accumulation rate has also been studied by certain researchers, but general conclusions have not been reached.

The accumulated direction, as well as the plastic flow direction in classical elasto-plastic theory, is proposed to express the coupling between accumulated shear strain and accumulated volumetric strain (Chang and Whitman, 1988; Wichtmann et al., 2006, 2014). To date, insufficient studies have been performed to address this problem. Chang and Whitman (1988) studied the accumulated direction by conducting triaxial cyclic tests on sand and observed that the accumulated direction was dependent on the average stress state (initial stress state) and not affected by the initial sand density, cyclic loading amplitude or loading cycle number. Wichtmann et al. (2006, 2014) investigated the influence of additional parameters on the accumulated direction based on cyclic triaxial tests for a number of sand types. Accumulated direction has been shown to be dependent on the average stress ratio but is independent of amplitude, polarization, pressure, void ratio and loading frequency. A slight increase in the volumetric portion with the increasing number of loading cycles was also reported.

The resilient modulus is an important index for charactering the elastic behaviour of soils and is frequently used to evaluate the behaviour of subgrade soil under traffic loading. The resilient modulus of soils is affected by several factors, and extensive research has been performed to study them. The dependence of dynamic deviator stress (repeated stress amplitude) on the resilient modulus has been proposed in certain experimental studies, although the results are inconsistent. With increases in the dynamic deviator stress, the resilient modulus has been found to be slightly increased, unaffected and slightly decreased (Brown et al., 1975; Drumm et al., 1990; Fredlund et al., 1977; Hicks and Monismith, 1971; Kim and Kim, 2007; Morgan, 1966; Pezo et al., 1991; Yang et al., 2008). In addition, results on the effect of confining pressure are also inconsistent, and a series of test results indicate that the resilient modulus increases with increasing confining pressure (Attia and Abdelrahman, 2010; Hicks and Monismith, 1971; Lackenby et al., 2007; Monismith et al., 1967). However, Lee et al. (1997) obtained considerably different values for different confining stresses, whereas other researchers observed little effect on the modulus of cohesive soils (Drumm et al., 1990). The above inconsistencies regarding the effects of dynamic deviator stress and confining pressure may have been caused by the use of different soil types and test conditions (e.g., drainage conditions). Moreover, in triaxial tests recorded in the literature, the specimens were loaded with isotropic stress before applying the cyclic or repeated loading. Therefore, the effect of the initial static deviator stress on the resilient modulus has not been studied until now. Furthermore, results on the effect of the number of repeated or cyclic loading cycles on the resilient modulus have also been inconsistent. Certain researchers (Seed et al., 1967; Thom and Brown, 1988) have found that the impact of loading duration was insignificant, whereas others demonstrated that the resilient modulus decreased with an increasing number of loading cycles for saturated or nearly saturated soil because of the generation of pore pressure (Guo et al., 2013). Moreover, a general increase in the resilient modulus with an increasing number of loading cycles for certain granular geo-materials has also been detected, and it may be induced by the compaction of soil particles (Lackenby et al., 2007; Ng and Zhou, 2014). Any other influence factors of soils, including the moisture content (also frequently described in terms of suction or saturation degree), initial density, freeze–thaw history, and temperature (Attia and Abdelrahman, 2010; Jin et al., 1994; Ng and Zhou, 2014; Suiker et al., 2005), alters the resilient modulus significantly. Lee et al. (1997) introduced a stress parameter that causes 1% strain ($S_{u,1.0\%}$) during a conventional unconfined compression test on cohesive soils with different moisture contents and proposed empirical correlations between the resilient modulus and $S_{u,1.0\%}$. Thus, $S_{u,1.0\%}$ has been regarded as an effective index to characterize the above mentioned factors of soil.

Certain consistent results were determined from the experimental studies mentioned above: (1) with an increasing number of loading cycles *N*, the accumulated strain increases, whereas the rate of accumulation decreases; (2) significant influencing factors caused by the accumulation behaviour of geomaterials can be divided into initial stress state, dynamic stress behaviour and current physical state; and (3) test conditions and soil type will affect the resilient modulus' evolution during the loading process and dependence on different influencing factors.

In this paper, a large number of triaxial tests under long-term low-level repeated loading for frozen soil have been conducted. Based on the test results, the accumulation and resilient behaviour have been studied systematically, and a number of influencing parameters on the magnitude of the accumulated strain, accumulated direction and resilient modulus have been identified. This study will lead to a deeper