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Study on thaw consolidation of permafrost under roadway embankment

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ABSTRACT

In order to analyze thaw consolidation of permafrost beneath roadway embankment, the concept of the effective consolidation time is established. A 3-D large strain thaw consolidation model based on Eulerian description is presented and applied to analyze consolidation behaviors of thawed permafrost layer under embankments of the Qinghai-Tibet highway. It is found that thaw consolidation is controlled by several factors, including load, the effective consolidation time as well as the characteristic drainage length. Combination of these factors makes the effect that in the initial operation years of the highway, degree of thaw consolidation increases. After a certain number of years, it decreases mainly due to the increase in the characteristic drainage length and decrease in the effective consolidation time. Pore water then accumulates in the post-thawed domain, which would take some residual consolidation time to dissipate. This explains the phenomenon that in some permafrost areas on the Qinghai-Tibet plateau permafrost has already completely thawed, while settlement of roadway embankment continuously develops.

1. Introduction

During thaw consolidation of ice-rich frozen soil, large amount of pore water is drained out of the soil, resulting in the decrease in soil volume and subsequent large settlement. Investigations on the Trans-Alaska pipeline showed that thaw settlement is the major danger to the pipeline, and large thaw settlement usually occurs in sections with ice-rich permafrost (Lachenbruch, 1970). A series of studies on the Qinghai-Tibet highway and railway have indicated that continuous thawing of underlying permafrost is the main cause of embankment settlement (Cheng, 2005; Cheng and Yang, 2006; Ma et al., 2009; Wu et al., 2008). At the same time, the embankment sections seriously damaged by thaw settlement usually lie in sites underlain by permafrost with high ice contents (Liu et al., 2002; Qi et al., 2007). With more and more infrastructures constructed in permafrost regions, there is an urgent need for a better understanding on thaw consolidation of permafrost.

Thaw consolidation of ice rich frozen soil is a typical large strain problem similar to consolidation of unfrozen soils with high water content, which is characterized by compression of soil with pore water being drained out. It is therefore expedient to have a retrospect on the development of consolidation theories for unfrozen soils. One dimensional large strain consolidation theories in convective coordinates were first proposed by Mikasa (1965) and Gibson et al. (1967; 1981). The former focuses on the problems with constant loading, while the later can be more generally applied to solve problems with changing loads (Pane and Schiffman, 1981). Further experimental and theoretical works have been carried out following Gibson's work and proved its applicability in practice (Morris, 2003; Olson, 1977; Schiffiman and Cargill, 1981). However, most of these studies are limited to 1-D problems. In order to deal with the problems with complex boundary conditions, 3-D large strain consolidation theories have been proposed. Carter et al. (1977) established a 3-D large strain consolidation theory based on Eulerian description and developed the corresponding finite element code; while Chopra and Dargush (1992) derived the large strain consolidation equations based on Lagrangian description. It has been found that the Eulerain description can provide better performance in dealing with problems with high nonlinearity (Xie, 1998).

When thermal transfer equations are used to determine the thawed zone of frozen soils where consolidation theories for unfrozen soils are applied, thaw consolidation theories are borne. Foriero and Ladanyi (1995) proposed a large strain thaw consolidation theory by combining Gibson's 1-D large strain consolidation theory with moving boundaries defined by a semi-empirical equation according to Morgenstern and Nixon (1971). Correspondingly, the theory is still limited to 1-D problems. Yao et al. (2012) proposed a 3-D large strain thaw consolidation theory and proved its applicability with laboratory testing results. Generally speaking, there are no technical obstacles for these thaw consolidation theories to be applied in solving problems with a constant thermal boundaries. However, it is not the case for practice in permafrost regions. Due to seasonal temperature variations in the top soil layer, consolidation is only available in a certain time period of a year and therefore may not accomplish in the year when a new layer of permafrost thaws. Engineers are therefore faced with a series of questions, for instance, how does the pore

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water pressure dissipates after the underlying permafrost thaws, and when will thaw settlement finish?

This paper will first establish the concept of the effective consolidation time for the thawed permafrost. A 3-D large strain thaw consolidation theory will be applied in a case study of an embankment section of the Qinghai-Tibet highway. Degree of consolidation and residual consolidation time will be discussed.

2. Effective consolidation time for the thawed permafrost layer

Field observation on some sections of the Qinghai-Tibet highway shows that the development of embankment settlement and ground temperature cannot be interpreted with the current recognitions. Take the embankment in the Tuotuohe basin on the plateau as an example. The site lies in a discontinuous permafrost area with the altitude of 4500 m. The mean annual air temperature is about −2.5 °C and the mean annual ground temperature is about 0 °C. Along the highway, the soil strata are mainly a silty clay underlain by highly weathered mudstone. In some locations, there is a gravelly fine sand layer on the top. The soil properties are described in detail in Section 3.2. On this site, the soil strata are silty clay and highly weathered mudstone. Ground temperature monitoring shows that the permafrost layer underlying the embankment is thawed completely, as is shown in Fig. 1(a). However, settlement still remains at a notable rate and shows no attenuation (Fig. 1(b)).

In order to clarify the mechanism of the above mentioned phenomenon, field observation of settlement and thermal development for an embankment underlain by permafrost are illustrated in Figs. 2 and 3. This site lies in a continuous permafrost area in the Kaixinling hilly region with the altitude of 4700 m. The mean annual air temperature is about −5 °C and the mean annual ground temperature is about −1.5 °C. The soil strata are a gravelly fine sand on the top, underlain by ice-rich silty clay and highly weathered mudstone with the volumetric ice contents of 30–50%. It can be seen from Fig. 2(a) that settlement mainly occurred during April and November every year. Settlement development in 1 year of 2004 is demonstrated in Fig. 2(b), where more details can be found, i.e., settlement occurred mainly in two periods, phase A and phase B. Phase A started from late March until middle May when the top soil layer was continuously thawed as is indicated by temperature monitoring in Fig. 3(a). The reason that the settlement started developing relatively quick in this period is that the top layer often had high water content from both precipitation accumulated during the cold seasons and water transported from beneath layers during refreezing of the last year. After a relatively gentle period, Phase B appeared starting from

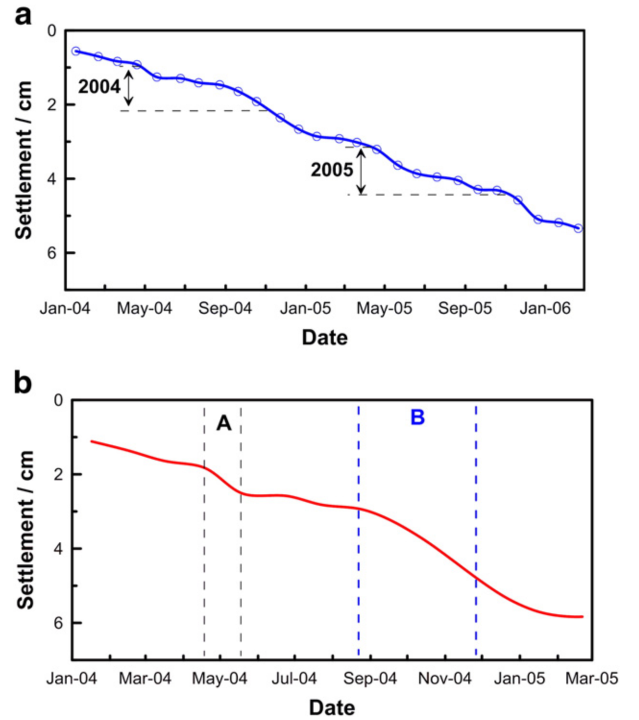

Fig. 2. Settlement monitoring of an embankment in Kaixinling hilly area. (a) 2-year settlement development. (b) 1-year settlement development.

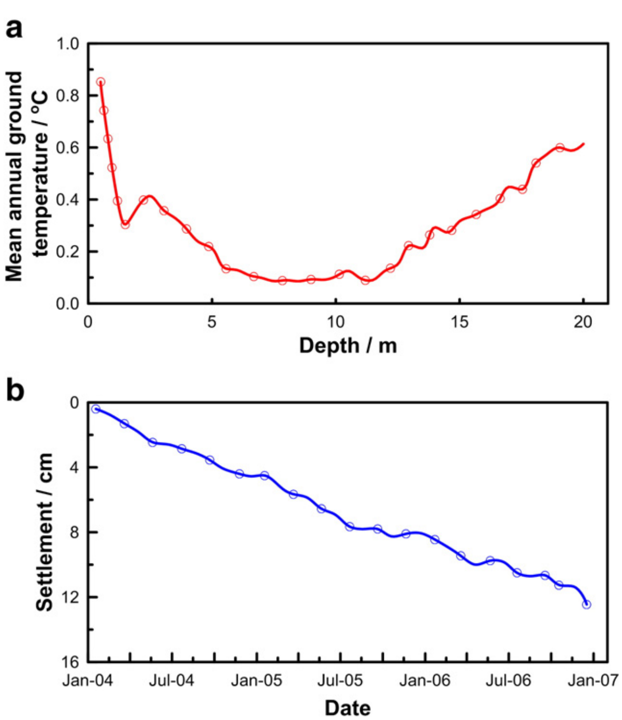

Fig. 1. Field observation on an embankment in Tuotuohe Basin. (a) Mean annual ground temperature vs. depth. (b) Settlement of embankment vs. time.

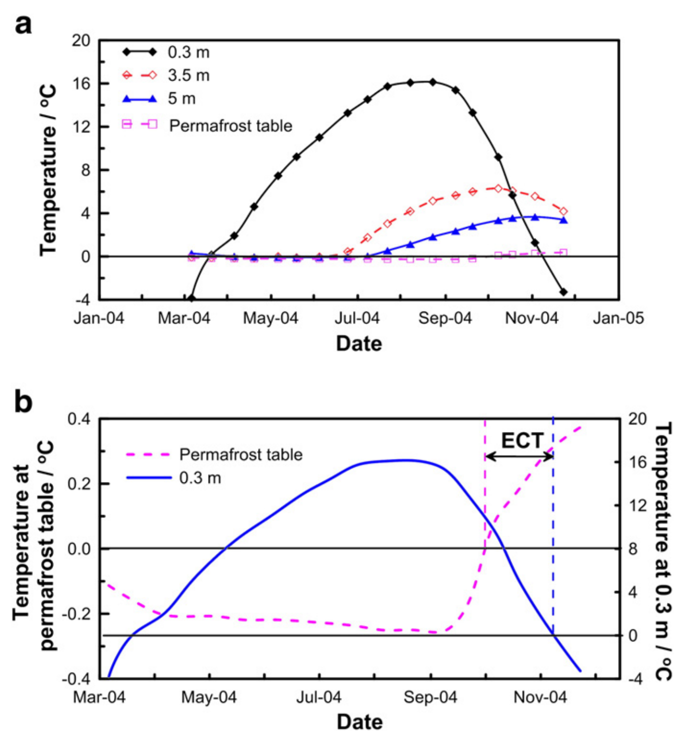

Fig. 3. Ground temperature monitoring of an embankment in Kaixinling hilly area. (a) Ground temperature at different depths. (b) Definition of effective consolidation time.