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Thaw consolidation behaviours of embankments in permafrost regions with periodical temperature boundaries

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ABSTRACT

A modified simulation method based on large strain thaw consolidation theory was proposed for the thaw consolidation behaviours of permafrost embankment. It was verified using monitored data that the new method has a good performance in simulating seasonal changes of thaw settlement. For permafrost embankment with different thermal and mechanical properties, the consolidation process in the post-thawed layer of top ground surface will accomplish during initial operating period. After that, thaw consolidation degree will decrease continuously. The decreasing rate of thaw consolidation degree (D_r) is proportional to thaw consolidation ratio (R) of deep permafrost layer. Regression analysis indicates that D_r is a power function of R.

1. Introduction

It has been widely recognized that thaw settlement caused by permafrost degradation under the background of global warming and large scale engineering activities in cold regions is one of the main causes of damage to infrastructures (Cheng and Yang, 2006; Qi et al., 2007; Wu et al., 2002 & 2008). From the point view of physical mechanism, thaw settlement of permafrost is a consolidation process with thawing of frozen soil and pore water drainage. In the past decades much research work has been carried out to get a better understanding on thaw consolidation behaviours. A one dimensional thaw consolidation theory was proposed by combining Terzaghi's consolidation theory and semi-empirical thawing boundary (Morgenstern and Nixon, 1971). The theory was based on small strain assumption with unavoidable large prediction errors when high ice content was involved. Based on this consideration, taking the void ratio as an independent variable, Foriero and Ladanyi (1995) developed a 1-D large strain thaw consolidation theory. In order to extend the applicability of large strain theory to complex boundary conditions, Yao et al. (2012) proposed a three dimensional large strain thaw consolidation theory based on Eulerian description and proved its validity with laboratory test results. From the solutions of the abovementioned works, thaw consolidation behaviours with constant thermal boundaries can be described well, i.e., thaw settlement developing successively and consolidation degree kept as a constant during thawing process. As for the thaw settlement of actual engineering cases with periodical thermal boundary (Liu et al., 2013; Niu et al., 2008), solutions of the theories with constant thermal boundaries are not applicable anymore. On the Qinghai–Tibet highway for example, embankment thaw settlement usually occurs in the warm season and ceases in the cold season (Liu et al., 2002; Qi et al., 2007), which implies that thaw settlement does not take place over the whole year and occurs periodically as pavement temperature rising above 0 °C. Therefore, it is important to study thaw consolidation behaviours of permafrost embankment for engineering applications, i.e., under periodical drainage boundaries.

Due to the lack of understanding of thaw consolidation behaviours of permafrost embankments, it is often assumed that thaw settlement is positively related with permafrost thawing rate and ice content of permafrost layers (Ma et al., 2011; Wu and Liu, 2005). To improve the understanding of this problem, an equivalent simulation method based on large strain thaw consolidation theory was proposed by Qi et al. (2012) and the general development of embankment thaw settlement was studied. It was shown that high ice content and thawing rate may not lead to a large settlement immediately due to the continuous decrease in thaw consolidation degree caused by an increase in the drainage path and decrease of effective consolidation time. This was further verified by in-situ monitoring (Yu et al., 2013). It seemed that previous studies showed completely different thaw consolidation behaviours for permafrost embankment compared with constant thermal boundaries. As for the influencing laws of thermal status and thermal and mechanical properties on thaw consolidation behaviours,

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there are few reports found with respect to permafrost embankments so far. In previous studies, it was stated that changes in and magnitude of thaw consolidation degree were directly influenced by the thawing and consolidation rates (Morgenstern and Nixon, 1971; Nixon and McRoberts, 1973). As these properties change, how would the consolidation degree of permafrost embankment be changed? The answer to this question is significant for further investigations of the thaw consolidation behaviours of permafrost embankments. Furthermore, during the warm seasons when permafrost embankments stay in a post-thawed state each year, thaw settlement usually occurs only between August and November (Liu et al., 2002; Yu et al., 2002). The method proposed by Qi et al. (2012) cannot simulate it reasonably. A more efficient method needs to be employed to examine the thaw consolidation behaviours of permafrost embankment more comprehensively.

In this paper, two typical embankment cross sections along the Qinghai–Tibet highway are taken as study objects. A modified numerical simulation method will be proposed based on large strain thaw consolidation theory. The seasonal changes of thaw settlement will be analysed, and the influencing laws of thawing and consolidation rate on thaw consolidation behaviours will be further investigated.

2. Thaw consolidation theory and numerical implementation strategy

2.1. Large strain thaw consolidation theory

The most significant difference of a thaw consolidation theory from the common theory is that a thermal conductive equation should be employed to detect the post-thawed domain as follows:

$$\begin{cases} -h_{i'i} + h_v = \rho c \dfrac{\partial T}{\partial t} \\ h_i = -\lambda T_{'i} \end{cases} \tag{1}$$

where, h_v (W/m^3) is the volumetric heat source intensity; c (J/kg·°C) is the specific heat considering ice–water phase change and λ (W/m·°C) is the thermal conductivity. Here, c and λ are temperature dependent. The definitions can be referred to in the literature (Tan et al., 2011; Wang et al., 2013).

From Eq. (1) the temperature field can be defined, and then consolidation theory can be used to describe the mechanical behaviours of soil skeleton and fluid in the post-thawed domain. It is supposed that hydraulic permeability and mechanical properties are independent of temperature, and medium volume changes related to temperature are not taken into account in the post-thawed regime. In the frozen domain, the soil skeleton is uncompressible and impermeable. The current configuration is employed to define the kinematic variables based on Eulerian description, and the governing equations for mechanical behaviour of soil skeleton can be written as follows:

$$\sigma_{ij'j} + \rho g_i = \rho \frac{dv_i}{dt} \tag{2}$$

where, σ_{ij} is the total stress tensor, ρ is the medium density, v_i is the instantaneous velocity of material point and g_i (m/s^2) is the gravity. To eliminate the effect of rigid rotation caused by large strain, the total stress rate tensor can be corrected as,

$$\sigma'_{ij} = \frac{d\sigma_{ij}}{dt} - \sigma_{ik}\dot{\omega}_{ki} - \sigma_{jk}\dot{\omega}_{kj} \tag{3}$$

and elastic stress–strain relationship is used to describe mechanical behaviour of soil skeleton, i.e.,

$$\sigma'_{ij} = 2G\dot{\varepsilon}_{ij} + (K - 2G/3)\dot{\varepsilon}_{ii}\delta_{ij} - \delta_{ij}\,\dot{p}\ . \tag{4}$$

In Eqs. (3) and (4), p is the pore pressure, δ_{ij} is the Kronecker symbol, $\dot{\varepsilon}_{ij}$ and $\dot{\omega}_{ij}$ are the symmetric deformation and skew-symmetric spin rate tensor respectively, with Eulerian description, which have the same expression as small strain situation. When the strain is small enough, $\dot{\omega}_{ij}$ is equal to 0 and Eq. (3) will degenerate to the form of small strain situation. K and G are the bulk and shear modulus of drained soil and can be expressed by Young's modulus (E) and Poisson's ratio (v) as $K = E / 3(1 - 2v)$ and $G = E / 2(1 + v)$, respectively.

The Young's modulus, E can be expressed by compression modulus E_s as,

$$E = \beta E_s \tag{5}$$

where, $\beta = 1 - 2v^2/(1 - v)$.

Darcy's law is applied to describe the fluid flow through soil,

$$q_i = -k\left(p/\rho_w g_i - x_j\right)_{'i} \tag{6}$$

where, q_i (m/s) is the superficial velocity of the fluid relative to the soil skeleton, k (m/s) is the hydraulic permeability of soil, and ρ_w (kg/m^3) is the fluid density.

The general conservation equation for fluid mass can be written as (Biot, 1973),

$$-q_{i'i} + q_v = \frac{1}{M}\frac{\partial p}{\partial t} + \alpha\frac{\partial \varepsilon_v}{\partial t}, \varepsilon_v = \varepsilon_{ii}(i = 1, 2, 3) \tag{7}$$

where, q_v (1/s) is the volumetric fluid source intensity, α is the Biot's coefficient, M (N/m^2) is the Biot's modulus. If α is equal to unity, the grains are considered to be incompressible and the Biot's modulus M is equal to K_ω/n, where K_ω (N/m^2) is the fluid bulk modulus and n is porosity.

2.2. Numerical implementation strategy

The calculation of thaw consolidation behaviours is actually a problem of thermal–mechanical–fluid coupling. In conventional coupling problems, calculation domains for the three processes are usually coincident. However, for thaw consolidation analysis, thermal and consolidation calculating domains are not compatible (Qi et al., 2013; Yao et al., 2012). Thermal calculation is implemented in the whole domain, while consolidation calculation is applied only in the post-thawed domain which changes successively during the coupling analysis. For constant thermal boundary problems, numerical simulation was employed by the previous researchers (Sykes et al., 1974; Yao et al., 2012), i.e., the temperature field is estimated after each thermal calculating step, if the temperature of a zone rises above 0 °C, the memory for recording mechanical and fluid variables is assigned to those zones and consolidation calculation will be performed at the same time; otherwise, only thermal calculation is implemented in frozen zones. For the influence of periodical thermal boundary, there are always some domains changing their states between frozen and post-thawed repeatedly. If the consolidation calculation is implemented in the zones based on their state, then the memory for recording mechanical and fluid variables will be assigned as the zone post-thaws and erased when it freezes. This is obviously unreasonable. To avoid this problem, Qi et al. (2012) proposed a concept of effective consolidation time to simplify the numerical implementation as if it is a constant thermal problem. However, in this way thermal and consolidation processes were calculated separately, which could not reflect thermal and consolidation interactions. To overcome this shortcoming, a new strategy is employed so as to avoid memory erasing in the zones which state repeatedly changes. Once a zone is thawed the first time, it is specified as the ‘post-thawed’ zone where consolidation calculations will be always implemented. While in the other frozen zone, only the thermal calculation is performed.