Computers and Geotechnics 104 (2018) 22–28

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

One-dimensional nonlinear consolidation theory for soft ground considering secondary consolidation and the thermal effect

Quan Liu, Yue-Bao Deng*, Tian-Yuan Wang

Institute of Geotechnical Engineering, Ningbo University, Ningbo 315211, China

ARTICLE INFO

Keywords:
Consolidation theory
Thermal effect
Secondary consolidation
Nonlinear
Analytical solution

ABSTRACT

Based on the assumption that the change of the void ratio is caused by effective stress, creep effect and temperature, a one-dimensional nonlinear consolidation theory considering the thermal effect is established that contains the heat balance equation and the continuity equation. Verification and calculation examples are performed. The results show that the dissipation rate obtained using the present method is slower than that obtained using the traditional method. The pore water dissipation rate or consolidation rate considering the secondary consolidation and temperature is higher than that when only considering secondary consolidation. Heating accelerates the dissipation rate of pore water, especially in the early stage of consolidation.

1. Introduction

Based on the principle of effective stress, Darcy's law and continuum mechanics, Terzaghi (1925) was the first to establish a classical one-dimensional (1-D) consolidation theory for the time-dependent settlement analysis of soft ground. Terzaghi's theory assumed that the stress-strain relationship of soil was linear in order to simplify the solution for practical use. However, it has been widely recognized that the compressive property of soft clay exhibits significant nonlinearity. Therefore, many researchers have developed 1-D nonlinear consolidation theory. Davis et al. [1] were the first to obtain an analytical solution for the 1-D nonlinear consolidation analysis of soft ground. There was an important assumption in Davis's research that the permeability coefficient and the compressibility coefficient of soil in the consolidation process changed simultaneously, i.e., $C_c/C_k = 1$. Following Davis's approach, Xie et al. [2], Lekha et al. [3], and Li et al. [4] obtained an analytical solution for 1-D nonlinear consolidation under stepwise loading, large strain, instantaneous loading, non-Darcy flow conditions and a composite foundation. In addition, Wang et al. [5] obtained a semianalytical solution for the 1-D consolidation problem for viscoelastic saturated soils.

Soil mechanics have shown that the time-dependent settlement of soft ground under loading can be divided into two parts, which are primary consolidation settlement caused by effective stress change and secondary consolidation settlement under constant effective stress. Traditional classical soil mechanics indicate that secondary consolidation begins after the completion of the primary consolidation [6]. However, an increasing number of researchers believe that because of the rheology, secondary consolidation for soft soil exists throughout the entire process of long-term deformation [7]. Scholars have conducted extensive research studies on the effect of secondary consolidation for soft soils [8–11]. However, few researchers have studied the consolidation of soft ground considering the secondary consolidation effect. Sun and Wang [12] established a controlling equation for 1-D nonlinear consolidation considering secondary consolidation effects but did not solve it. Huang et al. [13] and Brandenburg [14] used the finite element method and the finite difference method, respectively, to solve the 1-D nonlinear consolidation considering secondary consolidation.

It is important to consider secondary consolidation when studying the long-term settlement of a soft soil foundation. In fact, the temperature effect is also one of the factors affecting the long-term settlement of soft soil ground. Based on the analysis method for fluid-structure interaction problem, Biot [15] deduced and solved a thermal-fluid-structure coupling equation. Booker et al. [16] used the Laplace transform method to solve the problem of thermal consolidation for a spherical heat source buried deeply in a saturated thermoelastic ground. Cheng et al. [17] proposed a semianalytical method to study the thermal consolidation problem. Note that the abovementioned studies did not consider the coupling effect of secondary consolidation and thermal consolidation.

In summary, to date, no paper has reported on 1-D nonlinear consolidation considering both the secondary consolidation effect and the temperature effect. In this paper, based on the existing one-dimensional nonlinear consolidation theory, a 1-D nonlinear thermal consolidation

* Corresponding author.
E-mail address: dengyuebao@nbu.edu.cn (Y.-B. Deng).

https://doi.org/10.1016/j.compgeo.2018.08.007
Received 30 May 2018; Received in revised form 10 August 2018; Accepted 11 August 2018
0266-352X/

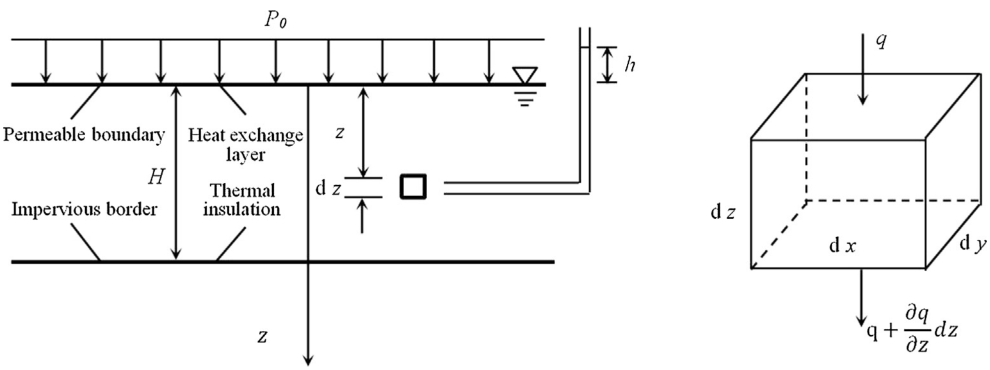

Fig. 1. Schematic diagram of one-dimensional consolidation theory (a) Foundation section; (b) Soil element.

equation is deduced. The coupling effects of secondary consolidation and temperature are taken into account simultaneously. These equations are solved analytically.

2. Problem description

2.1. Physical model and basic assumptions

Fig. 1 shows the physical model for the 1-D consolidation problem. The thickness of the soft soil layer is *H*. The top surface is permeable and free of deformation, whereas the bottom boundary is impermeable and fixed. Regarding the temperature boundary, the top surface is a fixed value (room temperature), and the bottom surface is an insulated boundary for temperature exchange.

The basic assumptions for this problem are as follows: (1) the soil is homogeneous, isotropic and fully saturated and is a thermal elastomer; (2) the volumes of soil particles and pore water do not change under the effect of pressure, but it will change under the effect of temperature; (3) the deformation of the soil is very small; (4) the seepage flow of pore water with respect to the soil skeleton obeys Darcy's law, and its inertial force is ignored; (5) the increase in soil temperature is small enough such that the water does not undergo phase change; (6) a thermal equilibrium occurs between soil particles and pore water; (7) when the soil skeleton is heated and expanded, no structural change occurs, which means that the linear expansion coefficients of the soil skeleton and the soil granules are the same, and the volume expansion coefficients of the soil skeleton and the soil particles are also the same; and (8) during consolidation, the coefficient of soil permeability, k_v, varies with the amount of consolidation and is described by the *e*-log k_v curve:

$$e - e_0 = C_{kT}\log(k_v/k_{v0}) \tag{1}$$

2.2. Constitutive equation

The constitutive equations of soil describe the relationship of soil skeleton stress. According to the theory of linear thermal stress, i.e., the Duhamel-Neumann and strain theory [18], the deformation of soil elements in 1-D conditions can be divided into three parts, i.e., primary consolidation, secondary consolidation and the strain caused by temperature change. Fig. 2 shows the variation of soil's void ratio (*e*) during consolidation and temperature change. In this figure, 'AC' indicates the total change of *e* during consolidation at normal temperature. 'AC' can be divided into two parts, i.e., 'AB' and 'BC'. 'AB' represents the change of the void ratio caused by effective stress variation, and 'BC' denotes the change of the void ratio caused by secondary consolidation. Moreover, 'CE' denotes the change of the void ratio under temperature variation.

(1) The void ratio change due to the variation of effective stress is:

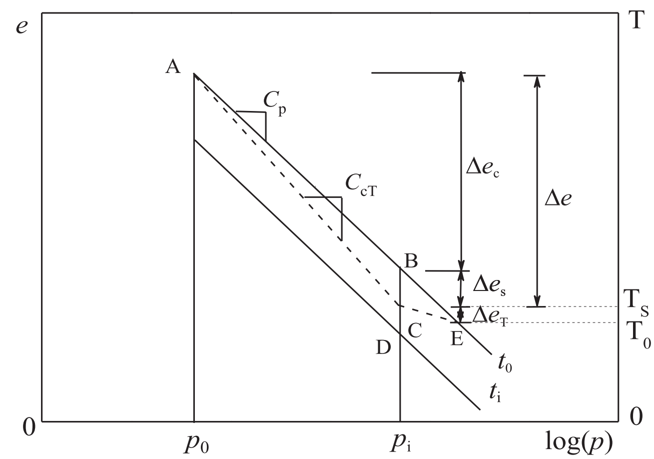

Fig. 2. The change of *e* with *p* and temperature.

$$e_c = e_0 - \Delta e_c = e_0 - C_p \lg\frac{\sigma'}{\sigma'_0} \tag{2}$$

where σ'_0 is the initial effective stress, e_0 is the initial void ratio, e_c is the void ratio under primary consolidation stage, Δe_c is the void ratio change caused by the variation of effective stress, and C_p is the compression index.

(2) The temperature-induced void ratio is:

$$e_T = e_0 - \Delta e_T = e_0 + \alpha T(1 + e_1) \tag{3}$$

where α is the linear expansion coefficient of the soil skeleton, and *T* is the variation of temperature.

(3) The void ratio caused by the secondary consolidation is:

$$e_s = e_p - \Delta e_s = e_p - C_\alpha \lg\frac{t}{t_p} \tag{4}$$

where e_p is the void ratio when the effective stress change is completed, e_s is the void ratio during the secondary consolidation stage, Δe_s is the void ratio change caused only by the secondary consolidation, and C_α is the secondary consolidation coefficient.

The total amount of compression can be calculated by Eqs. (2)(4), that is:

$$\Delta e = \Delta e_c + \Delta e_T + \Delta e_s = C_p \lg\frac{\sigma'}{\sigma'_0} - \alpha T(1 + e_1) + C_\alpha \lg\frac{t}{t_p} \tag{5}$$

2.3. Continuity equation

Based on the physical model shown in Fig. 1 and the schematic diagram of the void ratio change in Fig. 2, the change of void ratio by