Computers and Geotechnics 73 (2016) 189–198

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

A study on the one-dimensional consolidation of double-layered structured soils

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ARTICLE INFO

Article history:
Received 24 February 2015
Received in revised form 8 December 2015
Accepted 14 December 2015
Available online 29 December 2015

Keywords:
Structured soils
Drainage condition
Structural yield stress
Double-layered soils
Coefficient of permeability
Coefficient of volume compressibility

ABSTRACT

The governing equations for the one-dimensional consolidation of double-layered structured soils under time-dependent loading are established in this paper. Using simplified k–σ' and m_v–σ' models, the double-layered structured soils can be analyzed with three- or four-layered soils in which the thicknesses of the upper and lower layers change gradually. Approximate solutions for the governing equations are then obtained for two types of boundary conditions, and a computer program is developed. Using these solutions and the computer program, the consolidation behavior of double-layered structured soils is investigated.

1. Introduction

Because of their sedimentary history and consolidation, the majority of natural soft soils are structured soils. The structure of the soil significantly influences its engineering properties. Previous research has shown that if the effective stress is greater than the structural yield stress (the effective stress changes to reach yielding), then the soil structure will be damaged, the soil compressibility will increase [1–3], and the soil permeability will significantly decrease [4–6]. Structured soil is a different concept than conventional over-consolidated soil. One of the important distinctions is that the void ratio of structured soil is greater than that of remolded soil under the same stress, whereas the void ratio of over-consolidated soil is less than that of normal consolidated soil. Over-consolidated soil is a result of the stress history, unloading and erosion, and it is not related to cementation; structured soil is the product of cementation and sedimentary history, and it is not related to the largest consolidation pressure in the history. Therefore, soil structure can have an important impact on soil consolidation because soil consolidation differs considerably depending on whether the structure is considered [7–10]. However, few studies have focused on the consolidation of structured soils because of the complexity of the problem.

To develop an approximate solution for the one-dimensional consolidation of a soft soil foundation, Wang et al. [11,12] used the structural yield stress as the segmentation point, assuming that regardless of when the structure of the soil was damaged, the coefficients of permeability and consolidation were constants. Considering the geostatic stress, nonlinear compression and permeability, Tang et al. [13] developed a semi-analytical solution for the one-dimensional consolidation of a structured soft soil foundation by applying the concept of one-dimensional consolidation of layered soils. Cao et al. [14] investigated the nonlinear compression characteristics of soils, the continuous changes in compressibility and permeability, and the time-dependent loading throughout consolidation. An equation for the one-dimensional nonlinear consolidation of a natural structured soil was derived using the Crank–Nicolson finite difference form considering single-layer soils.

In this paper, one-dimensional consolidation governing equations for double-layered structured soils under time-dependent loading are established. Then, approximate solutions for the equations are provided. Finally, a computer program is developed. The consolidation behavior of double-layered structured soils is analyzed.

2. Mathematical modeling

The one-dimensional consolidation of double-layered structured soils is based on the schematic diagram shown in Fig. 1(a).

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http://dx.doi.org/10.1016/j.compgeo.2015.12.007
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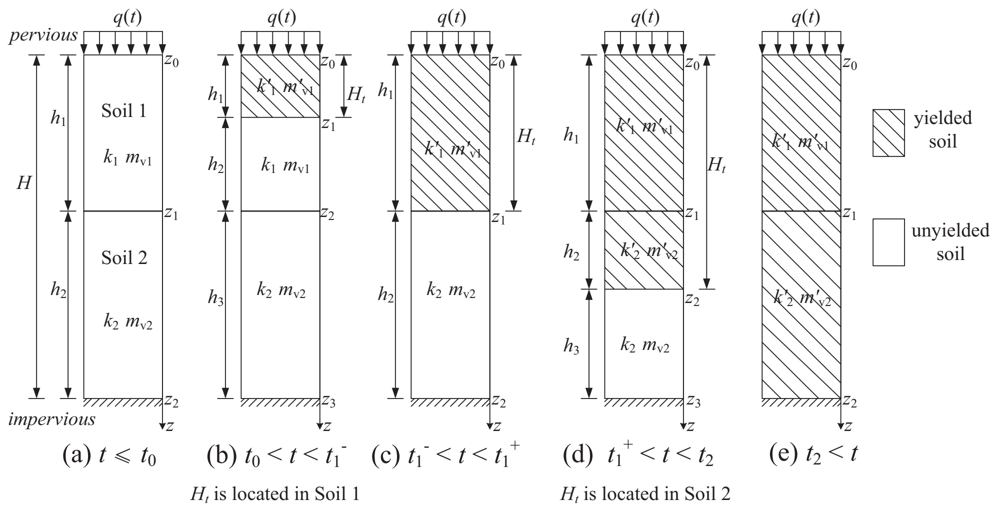

Fig. 1. Classification diagram for double-layered structured soils (single-drainage situation).

The soil consists of double contiguous layers, and the total thickness is H. The co-ordinate z has its origin at the top surface. The vertical distance from the top surface ($z = 0$) to the bottom of Soil i is denoted by z_i ($i = 1, 2$). k_i is the vertical coefficient of permeability and m_{vi} is the coefficient of volume compressibility prior to the collapse of the structure; k_i' is the vertical coefficient of permeability and m_{vi}' is the coefficient of volume compressibility after the collapse of the structure. σ_{pi}' is the structural yield stress of Soil i, and $q(t)$ is the uniformly distributed load applied on the top surface of the soil, as shown in Fig. 2, where q_0 and q_u $\left(q_u > \sigma_p'\right)$ are the initial and ultimate loads, respectively, and t_c is the construction time.

During the consolidation process, if the applied loading is less than the structural yield stress, then the structure will not collapse and the coefficients of permeability and volume compressibility will be the same as those of the undisturbed soil. If the applied loading is greater than the structural yield stress, then the upper layer soil structure will be damaged first and its coefficients of permeability and volume compressibility will both change. However, the coefficient of permeability of the lower layer soil will be the same as that of the undisturbed soil. With consolidation, the soil layer that has been damaged gradually increases in thickness such that the soil structure will eventually be completely damaged. We use t_1^- as the time when Soil 1 has all yielded, t_1^+ as the time when Soil 2 starts to yield, and t_2 as the time when Soil 2 has all yielded.

According to subsistent testing, the structured soil compression curve descends steeply. When the effective stress is greater than the structural yield stress, the compressibility sharply increases. Simultaneously, the coefficient of permeability decreases sharply and trends toward a constant [15]. To obtain approximate solutions, this paper assumes that the coefficients of permeability and volume compressibility are constants and uses simplified k–σ' and m_v–σ' models to describe the changing relationships between the effective stress and coefficients of permeability and volume compressibility.

As shown in Fig. 3, k and m_v are the vertical coefficient of permeability and the coefficient of volume compressibility of the undisturbed soil, respectively; k' and m_v' are the vertical coefficient of permeability and the coefficient of volume compressibility after the collapse of the structure, respectively.

3. Solutions

3.1. Single-drainage situation

For a single-drainage situation, when the applied loading increases to σ_{p1}', the upper structure of Soil 1 starts to become damaged; when the effective stress of the subsoil layer increases to σ_{p2}', damage begins to occur in Soil 2. In the formation of the soil structure, the particle of the lower soil connects more firmly, $\sigma_{p2}' \geqslant \sigma_{p1}'$; thus, the structure failure surface can move from the top to the bottom.

(1) When $0 < t \leqslant t_0$, the soil structure is not damaged; in this case, the initial excess pore water pressure is uniformly distributed, and the excess pore water pressure $u(z)$ can be determined using existing one-dimensional consolidation solutions for time-dependent loading [16].

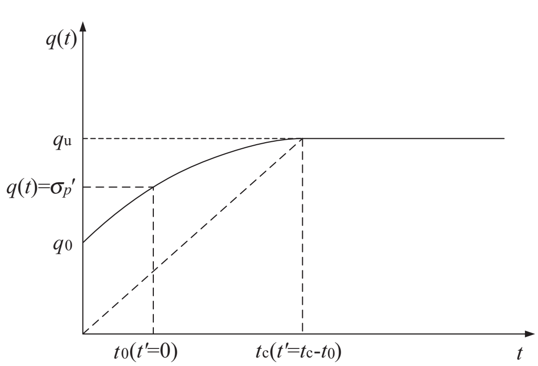

Fig. 2. Loading curve.

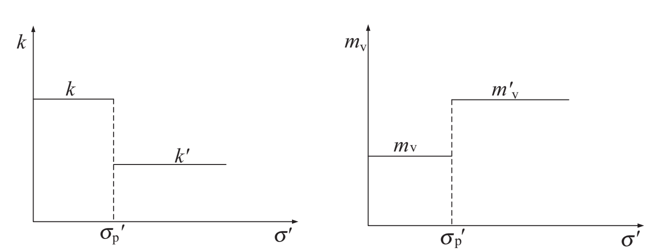

Fig. 3. Simplified k–σ' and m_v–σ' models.