ELSEVIER

Comput. Methods Appl. Mech. Engrg. 190 (2001) 1985–2016

Computer methods
in applied
mechanics and
engineering

www.elsevier.com/locate/cma

Micromechanical computational modeling of secondary consolidation and hereditary creep in soils

Márcio A. Murad *, João N. Guerreiro, Abimael F.D. Loula

Laboratório Nacional de Computação Científica, Rua Getulio Vargas 333, 25651-070 Petrópolis, Rio de Janeiro, Brazil

Abstract

A computational modeling of a fluid-saturated deformable porous media characterized by two levels of hydrodynamics (flow in micro and macropores) is proposed based on a micromechanical analysis of dual porosity systems, i.e., media locally characterized by a porous matrix composed of permeable cells containing micropores and the surrounding system of macropores, void spaces or bulk flow paths (e.g., fissured rock or aggregated soil). The homogenization technique is applied to upscale the constitutive and geometric information available in the fine structure to the field scale leading to a microstructure model of dual porosity type, wherein the poroelastic cells act as distributed sources/sinks of mass and momentum to the global macroscopic medium. The theory provides a rigorous derivation of some secondary compression and hereditary creep effects in soils due to the delayed drainage of the fluid within the micropores under consolidation. Application of the Green's function method reduces the dual porosity system to a single-porosity viscoelastic integrodifferential system of Volterra type in which the constitutive law for the macroscopic stress tensor is given in terms of an hereditary integral with memory. A two-level finite element method is proposed to solve the coupled micro–macro governing equations of dual porosity type. Numerical experiments are performed showing the strong potential of the proposed formulation in solving consolidation problems with microstructure. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Microstructure; Dual porosity; Secondary consolidation; Creep; Homogenization; Two-level finite element method

1. Introduction

The development of theories to model fluid flow in saturated, deformable, porous media as a coupled flow-deformation process began with Terzaghi [52] and Biot [8]. Essentially, Terzaghi and Biot developed linear poroelastic models based upon phenomenological approaches conducted at the field scale. These models are now well established and numerous works have provided a theoretical basis for Biot's theory. For example, the classical theory of poroelasticity has been rigorously reproduced by applying the mixture theory approach to an elastic two-phase solid–fluid mixture [15], or by upscaling the local pore scale problem where the solid is considered linearly elastic and the fluid is assumed to be Stokesian (see [5,61]).

The classical theory of poroelasticity applies to porous media with single structure, i.e., a two-phase system composed of the fluid-saturated wide void spaces and impermeable elastic solid phase. On the other hand many types of porous media exhibit two hierarchical geometric structures with properties radically different from each other. For example, a fissured rock is composed by a number of porous and permeable blocks or cells separated from each other by a developed system of highly permeable fissures. Aggregated or cracked soils (e.g., montmorillonite swelling clays) possess a similar structure wherein porous soil aggregates (clay clusters) are surrounded by an interconnected network of cracks or wide void spaces (macropores). The cohesive aggregates play the whole of the matrix blocks in the fissured medium and have a

---

[*] Corresponding author. Tel.: +11-55-24-233-6149; fax: +11-55-24-233-6165.
E-mail address: murad@lncc.br (M.A. Murad).

PII: S 0 0 4 5 - 7 8 2 5 (0 0) 0 0 2 1 8 - 8

structure that can be loosely identified as a mixture of macromolecules (clay platelets) and adsorbed water lying in the interlamellar spaces. Although everything derived in this paper can be applied to a general porous media, exhibiting a dual structure, for ease of exposition we henceforth restrict our discussion to dual porosity poroelastic systems.

In the macroscopic picture of a dual porosity medium, the interconnected network of macropores (voids, fissures) provides most of the global permeability for macroscopic flow whereas the relatively low-permeability cells (matrix blocks, clay clusters) merely serve to provide storage and play the role of distributed source/sinks transfer functions of mass and momentum to the global medium. Wilson and Aifantis [62] extended Biot's poroelasticity theory from single to double porosity media. In their theory the fracture network and permeable matrix are considered distinct, interacting porous structures. A simplified constitutive theory for the source/sink transfer function is adopted, where this quantity is treated as a classical exchange term, assumed proportional to the difference between the corresponding fracture and matrix (mean) potentials. This approach may be embedded in a framework common for the so-called lumped-parameter models [6,60]. Lumped parameter models, defined in the sense of Zimmerman et al. [65], are characterized by a time-scale assumption. At each time, a quasi-steady state flow in the permeable matrix is assumed, i.e., the fluid within the matrix is assumed uniformly distributed throughout the cell domain reaching equilibrium instantaneously when disturbed by the fissure system. The treatment of the matrix-void interaction in a lumped-parameter fashion (i.e., proportional to a pressure difference) overlooks microstructural details such as cell geometry and disparity between the space and time scales inherent to the coupled global and local hydro-mechanical processes. The hierarchical structure of dual porosity systems with their multiple time and space scales demand multiple scale analysis to better quantify the interaction between global and local systems (see e.g. [45]). As this interchange at the macroscale is strongly influenced by microstructural effects, an accurate pore scale description is crucial to correctly predict the overall response of the medium.

To illustrate the paramount importance of micromechanical analysis consider the so-called time-dependency aspects of the consolidation process. It is well known that consolidation usually comprises two different phenomena. The primary consolidation stage, where the soil deformation is mainly dictated by the coarse-grained structure of the soil, in particular by the pore-water pressure dissipation in the macropores of the primary structure. In addition, soils also exhibit creep or secondary consolidation, referred to as the additional deformation of the skeleton associated with the delayed response of the microstructure due to hydro-mechanical perturbations of the primary stage. Secondary compression is a typical microstructural phenomenon; it may arises from several local mechanisms (e.g., structure breakdown of soil, adjacent viscofrictional cell sliding [25]. In the case of swelling clay soils, Bolt [10] suggested that secondary compression is strongly related to physico-chemical interaction between the double layers of the fine-grained structure. Zeevart [64] related secondary consolidation to a process of high viscous characteristics, strongly related to the interlamellar water in the narrow pore spaces. Sridharan and Rao [48] suggested that secondary compression is related to the strength of the soil skeleton at microlevel, in particular it arises as a consequence of the delayed drainage of the absorbed water within the clay clusters, after the bulk water has been drained from the larger pores (see also [23]).

In contrast to primary consolidation, where effective stress/strain relationship is intrinsically time-independent, the macroscopic constitutive response associated with secondary effects is characterized by a viscoelastic behavior of the soil structure, usually given in terms of macroscopic rheological models where stress depends on strain rates. Classical poroviscoelastic models idealize the macroscopic medium as a Kelvin body consisting of an elastic spring connected in parallel with a dashpot which accounts for the time-dependent aspects of the soil (see e.g. [21,27,58,64]). Other viscoelastic approaches consider the stresses represented in terms of functionals of the strain history (see e.g. [12,14,59]). Application of this approach leads to macroscopic viscoelastic models with fading memory, wherein the stress/strain relation is represented in terms of hereditary constitutive laws (e.g., Hooke's law with memory). The analysis of the influence of delayed secondary compression on the overall settlement of the soil structure remains controversial and has been pursued within two different schools of thought. It can be assumed that both primary and secondary mechanisms occur simultaneously (see e.g. [21,53–55]), or that the secondary stage only begins after the primary stage is complete (see e.g. [27,29,49,64]).