20 Thermohydromechanical Behavior of Poroelastic Media

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20.1 INTRODUCTION

The classical problem in geomechanics dealing with the stress-induced isothermal flow of a fluid through a deformable porous medium, usually referred to as the process of soil consolidation, is a cornerstone in the development of the subject of *soil mechanics* and is generally regarded as the start of multiphasic treatment of the mechanics of porous media. Although the development of the theory of 1D soil consolidation is generally attributed to Terzaghi [1], the important contributions of others, Fillunger [2] in particular, are now being recognized [3,4]. The 1D theory certainly provides an explanation of the processes involved in soil consolidation but does not constitute a formal theory. The formal theory of isothermal soil consolidation presented by Biot [5] is a generalization of the 1D theory to three dimensions. This is a complete theory, which is rigorous in the sense of a continuum formulation applicable to a medium with voids. It is also an elegantly simple theory that continues to flourish after seven decades. The theory employs linear elasticity to characterize the mechanical behavior of the porous skeleton, and Darcy's law governs fluid flow through the accessible porous space. Extensive expositions of both the fundamental aspects of Biot's theory of isothermal poroelasticity and its applications to the analytical solution of problems in geomechanics are documented by Mandel [6], de Josselin de Jong [7], McNamee and Gibson [8], Cryer [9], de Wiest [10], Agbezuge and Deresiewicz [11], Gaszynski and Szefer [12], Chiarella and Booker [13], Rice and Cleary [14], Booker and Small [15,16], Booker and Randolph [17], Bear and Corapcioglu [18], Whitaker [19–21], Kassir and Xu [22], Ehlers [23], de Boer and Ehlers [24], Atkinson and Craster [25], Detournay and Cheng [26], Selvadurai and Yue [27], Yue and Selvadurai [28,29], Lan and Selvadurai [30], Oyen [31], and Galli and Oyen [32]. The volumes by Coussy [33], Selvadurai [34], Cheng et al. [35], Thimus et al. [36], Lewis and Schrefler [37], Drew and Passman [38], Wang [39], de Boer [3], and Verruijt [40] also give recent advances in the applications of Biot's theory. These references, along with the review articles by Scheidegger [41], Paria [42], Schiffman [43], Selvadurai [44], and Cowin [45], inter alia, contain a significant number of references to further work concerning the application of Biot's classical theory of 3D poroelasticity, via both analytical and computational modeling, to a wide range of problems in environmental geosciences, geomechanics, biomechanics, materials science, and materials engineering. The classical theory of isothermal poroelasticity is now firmly established in terms of the formulation of the governing equations and the availability of relevant existence and uniqueness theorems [46]. An alternative to Biot's approach to the formulation of the governing equations uses developments based on the continuum theory of mixtures; examples of these are given by Bowen [47,48], Green and Naghdi [49], Green and Steel [50], Crochet and Naghdi [51], Crochet [52], Mills and Steel [53], Atkin and Craine [54], Bedford and Drumheller [55,56], Drumheller [57], Bennethum and Cushman [58], Coussy [33], Murad et al. [59], Gajo [60], Rajagopal and Tao [61], and Dell'Isola and Romano [62]. While the mixture theory approaches are certainly elegant and complete from the point of view of continuum formulations, there appears to be no significant advantages offered, at least from the point of view *of linearized theories of poromechanics* and their applications to the solution of initial boundary value problems in the area. The mixture theory–based formulations have advantages when dealing with nonlinear theories of material behavior, where the porous skeleton can experience large strains or large strain nonlinear viscoelastic and viscoplastic phenomena that have corresponding influences on the fluid transport problem, which is of interest to modeling living biological tissues.

The extension of Biot's classical theory of isothermal poromechanics to include nonisothermal effects has been prompted by applications to a number of areas of particular interest to energy and environmental geomechanics. The inclusion of thermal effects when considering poromechanical behavior of fluid-saturated media, particularly in the context of geomechanics, becomes important to areas such as deep geologic disposal of heat-emitting nuclear fuel wastes (Holister et al. [63], Gnirk [64], Selvadurai [65,66], Selvadurai and Nguyen [67,68], Nguyen and Selvadurai [69,70], Rutqvist et al. [71], Stephansson et al. [72], Nguyen et al. [73], Alonso et al. [74], Chijimatsu et al. [75]), frictional heating during earthquake slip along fault zones (Lachenburch [76], Mase and Smith [77,78], Aagaard et al. [79], Sulem et al. [80], Rice [81]), geothermal and ground source energy extraction and seafloor hydrothermal systems (Dickson and Fanelli [82], Duffield and Sass [83], Jupp and Schultz [84), Knellwolf et al. [85]), mechanics of freezing action in soils (Selvadurai et al. [86,87], Michałowski and Zhu [88], Gens [89]), response of rock masses containing deep geologic repositories to glaciation loadings (Selvadurai and Nguyen [90], Chan et al. [91]), and geomechanical modeling of the geologic sequestration of greenhouse gases (Rutqvist et al. [92], Selvadurai [93,94]. Vargas et al [95]). In these subject areas, the coupled processes associated with mechanical deformations of the porous skeleton, fluid movement through the accessible pore space under thermal, hydraulic, and mechanical effects, and conductive heat transfer through the saturated porous medium are necessary to examine the problem areas of practical importance. Further related studies are given by Smith and Booker [96], Jiang and Rajapakse [97], Seneviratne et al. [98], Bai and Roegiers [99], Wang and Papamichos [100], Bai and Abousleiman [101], Giraud et al. [102], Zhou et al. [103], Selvadurai [104], Wu et al. [105], and Belotserkovets and Prevost [106].

An early development in the extension of Biot's classical theory of poroelasticity to include thermal effects is due to Schiffman [107] who presented a thermoelastic theory of soil consolidation, with applications in geoenvironmental and geophysical heat transfer. The work of Brownell et al. [108] dealt with applications relevant to geothermal reservoirs and the work of Morland [109] examined the