This research monograph presents a systematic endeavor to generalize fundamental physical laws related to subsurface fluid flow that are important for a number of contemporary applications, such as recovery of subsurface energy resources, geological disposal of high-level nuclear wastes, CO$_2$ geological sequestration, and groundwater contamination in the vadose zone. The history of discovering these laws is also briefly presented within the context of discussing the ranges in which they are valid. This relatively new endeavor should be of interest to engineers, researchers, and students in the areas of reservoir engineering, hydrogeology, soil physics, and rock mechanics.

Darcy’s law is the fundamental law of subsurface fluid flow. For low-permeability porous media, however, Darcy’s law does not always hold because of the strong fluid–solid interaction. While this issue has been investigated by a number of researchers, Chap. 1 presents a new phenomenological relationship between water flux and hydraulic gradient, or a generalized Darcy’s law. The traditional form of Darcy’s law and two other generalizations for low-permeability media, proposed by other researchers, are shown to be special cases of our generalized Darcy’s law. The implications and applications of this “non-Darcian” flow behavior are also discussed.

Edgar Buckingham independently discovered the relationship between water flux and hydraulic gradient for unsaturated (or multiphase) flow in porous media that has often been called Darcy’s law in the literature. In this book, I call this relationship the Darcy-Buckingham law because in my view Buckingham’s contribution to the theory of subsurface multiphase flow has been historically underestimated; multiphase flow is more complex than the single-phase flow that Darcy’s law was developed for. The Darcy-Buckingham law, however, is only valid under the condition of local equilibrium. This condition does not hold in many cases, although the Darcy-Buckingham law has been used there because of the lack of alternatives. In Chap. 2, I introduce an optimality principle that unsaturated water flow patterns are self-organized in such a way that overall water flow resistance is minimal. Based on this principle, a generalized version of the Darcy-Buckingham
law is derived in which unsaturated hydraulic conductivity is not only a function of water saturation (or capillary pressure) assumed in the Darcy-Buckingham law, but also a function of water flux. The consistency between our theoretical results and observations is demonstrated.

It is well known that subsurface fluid flow is coupled with mechanical deformation of subsurface media where fluid flow occurs; in many cases, this coupling can play a dominant role. Hooke’s law is the most fundamental law governing elastic deformation of solids. Natural rocks, however, have unique features compared with other solids, one of which is the existence of small-scale deformation heterogeneities (such as microcracks). Acknowledgement of these unique features is important, because they justify that rock mechanics exists as a stand-alone discipline, rather than an adjunct of general solid mechanics. This also explains why elastic mechanical deformation of a natural rock does not follow exactly the traditional Hooke’s law; the related mechanical properties, unlike those assumed by Hooke’s law, are not constant under certain conditions. To better consider the impact of natural heterogeneity, Chap. 3 introduces the two-part Hooke model that was developed by dividing a natural rock into hard and soft parts. Remarkable consistency between the model and observations from different sources, for both rock matrix and fractures, has been achieved. The usefulness of the model in dealing with engineering problems is also demonstrated. Note that although a number of researchers have touched on the same issue by establishing empirical relations between stress and rock mechanical properties, the two-part Hooke model takes a much bolder and more systematic approach and is also more effective for practical applications.

Non-equilibrium thermodynamics (which is closely related to optimality principles) is the foundation for dealing with highly nonlinear problems. This branch of science, however, has not been well established yet. For example, contradictory optimality principles exist in the literature. As an applied scientist and engineer with a primary interest in applying basic scientific principles to my research areas, I initially tried to avoid, but eventually got into the study of the nonequilibrium thermodynamics because it is the true starting point to investigate subsurface multiphase flow and other related processes. Chapter 4 presents a new thermodynamics hypothesis that tries to answer under what conditions the optimality principles should apply and which of the simultaneously occurring physical processes, if not all, is subject to the optimization. This hypothesis seems to be able to reconcile different optimality principles proposed in several different areas.

The generalization of well-known fundamental physical laws is indeed an ambitious and a highly risky endeavor. It, however, was not motivated by academic interest, but by the needs of practical applications. As a modeler who is fully aware of and enjoys the increasing powerfulness of available computational capabilities, I am more and more convinced that the lack of appropriate physical laws at scales of practical interest is the weakest link in improving our modeling capability (especially the capability for prediction). For example, no matter how powerful computers are, we simply cannot use them to predict the observed non-Darcian flow
with the traditional Darcy’s law. Much more work is needed to substantiate our physical foundations for accurately modeling subsurface processes.

The generalization of the physical laws uses different approaches in this book, ranging from purely phenomenological ones to theoretical derivations based on newly introduced principles. But all generalized laws have the relatively simple mathematical form and a small number of parameters. This largely reflects my own research philosophy as an engineer: a good model or theory should be able to adequately capture the essence of physics and, at the same time, has a relatively simple form or structure. This happens to be consistent with the point of view of Nobel Laureate Richard Feynman, who in his celebrated book “Characters of Physical Laws”, concluded that the mathematical forms of well-known physical laws are always simple, although they describe very complex phenomena.

I did initially have a reservation to publish a book dealing with the physical laws that are at the heart of several research areas. I would feel much more comfortable doing so after the related work becomes more mature. At the same time, I also feel the urgency to get the message out that we do need to revisit the fundamental laws that have generally been viewed as sacrosanct doctrines by many people. Thus, I view this book as a messenger or a starting point for this revisiting. I would also like to make it clear that the focus of this book is on the work mainly done by me and my collaborators. Although I try to briefly cover the related work of others as well, the citation of their work is by no means intended to be exhaustive.

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