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Energy geotechnics: Advances in subsurface energy recovery, storage, exchange, and waste management ☆

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ABSTRACT

Energy geotechnics involves the use of geotechnical principles to understand and engineer the coupled thermo-hydro-chemo-mechanical processes encountered in collecting, exchanging, storing, and protecting energy resources in the subsurface. In addition to research on these fundamental coupled processes and characterization of relevant material properties, applied research is being performed to develop analytical tools for the design and analysis of different geo-energy applications. The aims of this paper are to discuss the fundamental physics and constitutive models that are common to these different applications, and to summarize recent advances in the development of relevant analytical tools.

Contents

1. Introduction

Geotechnical engineers have traditionally been at the core of the energy sector, solving problems associated with resource recovery, energy transportation, and energy waste management. In the last few years, geotechnical engineering has expanded its presence in the energy sector by forming the new research area of Energy Geotechnics. Energy Geotechnics builds upon past experience and analyses to solve new challenges associated with recovery and characterization of existing and new energy resources, utilization of heat exchange processes in civil engineering infrastructure, storage of energy in the subsurface in different forms, and containment of carbon and nuclear waste in engineered systems. At the core of this expansion has been research into the behavior of soils and rocks under complex and extreme conditions involving coupled mechanical, hydraulic, thermal, and geochemical processes, and development of analytical tools and constitutive models capable of considering the range of phenomena encountered in the subsurface. In response to new research area, the International Society of Soil Mechanics and Geotechnical Engineering

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(ISSMGE) has formed Technical Committee 308 as a clearinghouse for knowledge on this topic. Developments in the area of Energy Geotechnics are expected to play a key role in the energy arena in the near future due to the increase in energy demands and the corresponding need for energy efficiency in the next decades associated with economic development and population growth worldwide. The goal of geotechnical engineers is to provide sustainable solutions for these energy-related needs of society.

Energy Geotechnics encompasses a large number of different applications, with a common thread of needing to understand coupled flow, deformation, and reaction processes encountered when collecting, exchanging, storing, and protecting energy resources in the subsurface. Energy generation applications involving geotechnics include recovery and characterization of gas hydrate-bearing sediments, development of enhanced geothermal systems (EGS) for electrical power generation, and collection of hydrocarbons from challenging geological settings. Recent contributions in EGS and hydrocarbon recovery are primarily related to permeability enhancement of rock deposits via hydraulic fracturing and proppant placement. Another important application is the protection of the environment through the disposal of energy waste, including both high-level radioactive waste disposal and geologic sequestration of carbon dioxide. The design of radioactive waste containment systems relies on prediction of the long-term behavior of engineered and natural barriers, while geologic sequestration of carbon dioxide requires an understanding of natural aquitards and permeability enhancement of subsurface aquifers. Energy geo-storage applications include both storage of thermal energy in borehole arrays, thermohaline salt caverns, or aquifers, as well as storage of energy in the form of compressed air in caverns or aquifers. In addition to design and construction concerns, the primary question in geo-storage applications is the long-term efficiency of energy recovery. The use of geotechnical infrastructure such as building foundations, walls, or embankments as thermal energy exchangers to form energy geo-structures is reaching the point of maturity from a research perspective. However, new challenges are still being encountered as this technology is implemented into practice. Finally, there are several activities related to operations in the energy sector that are widely implemented in engineering practice but are seeing new developments. These include the construction of pipelines, design of foundation systems for the unique loading conditions of offshore wind or tidal energy infrastructure, mining operations associated with oil sands, design of dams for pumped-hydro energy storage, and quantification of embodied energy in geotechnical infrastructure. This paper will summarize the key literature relevant to these applications.

2. Fundamental developments

An underlying theme among the different topics within Energy Geotechnics is the need to predict the flow of fluids and transfer of heat in porous or fractured media, and understand the coupled role of, or impacts on, the mechanical response of the media (i.e., volume change, changes in stiffness, changes in strength). The governing equations for coupled heat transfer and water flow are well-established in the literature for deformable, water-saturated porous media [37,295,38,300,294]. The governing equations for coupled heat transfer and flow of water in liquid and vapor forms are similarly well-established for unsaturated porous media in nondeformable conditions [255,53,334,214,339], deformable conditions [244,338], and in the presence of pore fluids containing chemicals [64,119]. Going hand in hand with the governing equations is the development of coupled, nonisothermal constitutive relationships for deformable and nondeformable soils, including the soil–water retention curve (e.g. [353,117,265,367,385]), hydraulic conductivity function (e.g., [66,389,91]), and thermal conductivity function [75,146,194].

Thermal, hydraulic (both gas and liquid) and mechanical (THM) processes have been implemented in fully-coupled research codes (some of them freely-available), such as CODE_BRIGHT [244], COMPASS [340] and LAGAMINE [69]. Other researchers have opted for coupling two (or more) codes to model multiphysics process in porous media, as for example Rutqvist [273], who coupled the commercial mechanical finite difference program FLAC3D [148] with TOUGH2 [259], a finite volume program for simulating the coupled transport of water, vapor, non-condensible gas, and heat in porous and fractured media. More recently, commercial finite element software packages capable of modeling THM processes in geological media, such as COMSOL [321], have become available. The validation of coupled thermo-hydro-mechanical and chemical numerical codes is a critical step toward reliable predictions. Although there are a limited number of calibration data sets for boundary value problems involving coupled heat transfer and fluid flow in saturated soils [196,94] and unsaturated soils [85,377,63,31], challenges still exist in accurately measuring and relating relevant variables (e.g., changes in temperature, water content, water vapor fluxes, suction, thermal conductivity). This is especially the case in deformable porous media. In this context, it is worth highlighting the DECOVALEX project [71]. DECOVALEX (DEvelopment of COupled models and their VALidation against Experiments) is an international research and model comparison collaboration (initiated in 1992), for advancing the understanding and modeling of coupled THM and THM and chemical (THMC) processes in geological systems intended for the disposal of radioactive waste and spent nuclear fuel (e.g. [17]). Other research efforts, like the MUSE (Mechanics of Unsaturated Soils for Engineering) research network [100], and the 'Methane Hydrate Reservoir Simulator Code Comparison Study' [227] have also contemplated the validation of constitutive models and coupled computer codes.

The mechanical behavior of soils and rocks subjected to simultaneous multiphysics actions is a prime interest of geotechnical/-geomechanical engineers. Constitutive models predicting the mechanical response of soils under saturated and unsaturated conditions have been under continuous development since the formulation of the theory of critical state soil mechanics [299]. A significant advance was made when Alonso et al. [15] proposed an extension of the modified Cam-Clay model to account for the effects of capillary pressure (i.e. matric suction) on the mechanical behavior of unsaturated soils. This elasto-plastic model is known as the Barcelona Basic Model (BBM). In this model, an increase in capillary pressure induces an expansion of the yield surface (i.e. a hardening of the material, with the corresponding increase of the preconsolidation stress). It is also considered that as suction increases, the shear strength and soil stiffness also increase. Suction reduction has the opposite effect on soil behavior. The BBM is also able to reproduce the plastic deformations associated with the collapse-compression behavior observed in unsaturated soils under wetting [149]. This model has become very popular and several modifications and improvements have been suggested afterwards (e.g., [368,340,16,369,111,383**,384]). Of these models, the model of Wheeler et al. [369] is useful to consider the impact of hydraulic hysteresis on the behavior of soil [156], while the model of Zhou et al. [383**,384] permits consideration of a smooth transition in the compression curve noted for unsaturated soils under constant suction through the incorporation of a nonlinear change in compressibility and a model to account for changes in effective saturation.

Models reproducing the thermo-mechanical response of saturated clays at elevated temperatures have been published in various studies, and have been developed based on empirical observations from a range of studies focused on evaluating the

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