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Numerical analysis of coupled thermo-hydraulic problems in geotechnical engineering

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HIGHLIGHTS

- Investigation of the behaviour of numerical analysis of highly convective problems.
- Coupled thermo-hydraulic boundary condition is presented and investigated.
- Recommendations on simulating highly convective problems are provided.
- Results of numerical simulations of open-loop system agree with approximate models.
- The computed time to thermal breakthrough is not affected by element type or size.

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ABSTRACT

Ground source energy systems, such as open-loop systems, have been widely employed in recent years due to their economic and environmental benefits compared to conventional heating and cooling systems. Numerical modelling of such geothermal system requires solving a coupled thermo-hydraulic problem characterised by a convection-dominated heat transfer which can be challenging for the Galerkin finite element method (GFEM). This paper first presents the coupled thermo-hydraulic governing formulation as well as the coupled thermo-hydraulic boundary condition, which can be implemented into a finite element software. Subsequently, the stability condition of the adopted time marching scheme for coupled thermo-hydraulic analysis is established analytically. The behaviour of highly convective problems is then investigated via a series of analyses where convective heat transfer along a soil bar is simulated, with recommendations on the choice of an adequate discretisation with different boundary conditions being provided to avoid oscillatory solutions. Finally, the conclusions from the analytical and numerical studies are applied to the simulation of a boundary value problem involving an open-loop system, with the results showing good agreement with an approximate solution. The main objective of this paper is to demonstrate that the GFEM is capable of dealing with highly convective geotechnical problems.

1. Introduction

Diminishing fossil fuel reserves and growing energy demand have led to an increased interest, as well as technological advances, in the renewable energy sector. In recent years, geotechnical engineering has experienced challenges associated with utilising shallow geothermal energy – the energy stored in the ground up to depths of 300 m[1] – as ground source energy systems are becoming increasingly popular.

These geothermal systems are used to extract and/or inject heat from and into the ground by either directly abstracting water from an aquifer through a well and returning it through another well located at a distance (open-loop

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systems), or pumping a fluid through a system of pipes buried in the ground or placed in buildings' foundations (closed-loop systems).

Open-loop systems can provide a higher energy yield than closed-loop systems, however, they have a higher financial risk due to running costs and a higher environmental risk associated with possible groundwater pollution.[2] Spacing of the wells is a particularly important aspect of the design of open-loop systems. If the wells are too close, the thermal plume of cold or warm water from the injection well may reach the abstraction well and reduce the efficiency of the system.[1] This phenomenon is known as thermal breakthrough.

To model open-loop systems, two types of numerical methods—the finite difference (FD) method and the finite element (FE) method, have been adopted in the literature. Todd and Banks[3] and Gandy et al.[4] used SHEMAT,[5] which is a finite difference code, to model an open-loop well doublet scheme located in the UK. One of the most widely used finite element codes for thermo-hydraulic (TH) analysis is FEFLOW,[6] which has been used by Lo Russo and Civita,[7] Nam and Ooka,[8] and Bridger and Allen,[9] amongst others, to simulate open-loop systems. However, the details of the FE analysis, particularly in terms of the numerical method or the boundary conditions, have been the subject of limited discussion.

Open-loop ground source energy systems are characterised by convection-dominated heat transfer and can be modelled numerically as coupled thermo-hydraulic problems. To obtain the solution to this complex problem in a finite element program, it is necessary to develop a formulation which couples the governing equations for groundwater flow and ground heat transfer, as well as appropriate boundary conditions. As the processes of both pore water flow and heat transfer are time dependent, a stable time marching scheme is also required. However, it has been noted in the literature that, when the FE method is used to simulate a highly convective problem, the extensively used Galerkin finite element method (GFEM) often produces numerical oscillations, if the mesh is too coarse.[10,11] To eliminate this problem, the use of upwind finite element methods, including the Petrov–Galerkin method,[10,11] the Petrov–Galerkin least square method,[12] and the shock capturing method,[13] is recommended. However, these methods obtain the solution by either modifying the weighting function or introducing an artificial damping which changes the physics of the problem and results in a reduction in accuracy. Diersch[6] compared some of these methods in simulations of a model test of a well doublet system and concluded that, although the upwind methods ensure a non-oscillatory solution, using GFEM can also lead to stabilised results provided the mesh and the time marching scheme are chosen adequately. Nonetheless, limited information has been provided on quantifying the effect of the mesh or the boundary conditions on the oscillations encountered when using GFEM.

In this paper, the behaviour of numerical analysis of highly convective geotechnical problems has been investigated using the Imperial College Finite Element Program—ICFEP,[14] which has recently been upgraded to simulate fully coupled thermo-hydro-mechanical (THM) behaviour of porous materials. Firstly, the coupled thermo-hydraulic formulation implemented in ICFEP is validated and the need for a coupled thermo-hydraulic boundary condition is illustrated. Moreover, the stability condition of the time marching θ-method, which is adopted in ICFEP for solving the heat conductive–convective equation, is studied analytically. Subsequently, studies on the behaviour of numerical solutions to highly convective problems with different boundary conditions are presented. Lastly, the resulting findings, including the obtained stability condition as well as the conclusions from the numerical studies, are applied to simulate an open-loop ground source energy system, with the predicted time to thermal breakthrough being compared to an available approximate solution.

2. Coupled thermo-hydraulic finite element analysis

2.1. Governing formulation

2.1.1. Pore fluid flow

The continuity equation defined by Eq. (1) must be satisfied by incompressible pore fluid flow in a fully saturated porous medium, such as soil.

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} - Q^w = \frac{\partial \varepsilon_v}{\partial t} \quad (1)$$

where v_x, v_y, v_z are the components of the superficial velocity of the pore fluid in the x, y and z directions, respectively, ε_v is the volumetric strain of the soil skeleton due to stress changes, Q^w represents any pore fluid sources and/or sinks, and t is time. The seepage velocity, $\{v_w\}^T = \{v_x, v_y, v_z\}$, is assumed to be governed by Darcy's law, which can be written as:

$$\{v_w\} = -[k_w]\{\nabla h\} \quad (2)$$

where $[k_w]$ is the permeability matrix and ∇h is the gradient of the hydraulic head. In a coupled thermo-hydraulic problem, if the effect of temperature gradients on pore fluid flow through a fully saturated soil is assumed to be negligible and the soil skeleton is assumed to be rigid, Eq. (1) reduces to the equation for steady state seepage, which can be expressed as:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = Q^w. \quad (3)$$

2.1.2. Heat transfer

There are three main modes of heat transfer in a fully saturated soil: conduction, convection and radiation. However, the effect of radiation is often assumed to be negligible compared to the effects of conduction and convection,[15] and therefore is not taken into account in this formulation. The equation governing heat transfer is based on the law of conservation of energy, and can be written as:

$$\frac{\partial\left(\Phi_\theta dV\right)}{\partial t} + \nabla \cdot \{Q_\theta\}\, dV = Q^\theta dV \quad (4)$$

where Φ_θ is the heat content of soil per unit volume, Q_θ is the heat flux per unit volume including heat conduction