Investigations on numerical analysis of coupled thermo-hydraulic problems in geotechnical engineering

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SCOPE

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 (Banks, 2012) – 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 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 (Boennec, 2008). 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 rejection well may reach the abstraction well and reduce the efficiency of the system (Banks, 2012). This phenomenon is known as thermal breakthrough.

To model highly convective geothermal problems, such as open-loop systems, it is necessary to adopt a formulation which couples groundwater flow and heat transfer. Numerical methods, including finite difference methods (e.g. Clauser, 2003) and finite element methods (e.g. Diersch, 2014), are used to obtain solutions to this complex formulation.

Recently, the Imperial College Finite Element Program – ICFEP (Potts & Zdravković, 1999) has been updated to model fully coupled thermo-hydro-mechanical behaviour of porous materials. This paper aims to explain some important aspects of numerical modelling of highly convective geotechnical problems. Firstly, the coupled thermo-hydraulic formulation implemented in ICFEP is validated and the need for the newly developed thermo-hydraulic coupled boundary condition is illustrated. Secondly, studies on the behaviour of numerical solutions to highly convective problems are presented. Lastly, the new capabilities are tested in a boundary value problem involving an open-loop ground source energy system.

SUMMARY OF COUPLED THERMO-HYDRAULIC FORMULATION AND BOUNDARY CONDITION

The coupled thermo-hydraulic formulation has been developed based on the principles of the volume conservation of pore fluid flow and the energy conservation of soils. In order to validate the coupled thermo-hydraulic formulation, a simple one-dimensional analysis on a bar of soil was conducted. A heat source of a constant temperature of 30 °C was applied at the left-hand side of the bar, while the pore water was assumed to flow from left to right. A sharp increase in temperature was observed at the right-hand boundary of the soil bar, which means that water leaves the mesh but the energy equivalent to the volume of water remains. As this scenario is obviously physically impossible, a thermo-hydraulic coupled boundary condition was implemented to avoid this issue. It involves applying a heat flux to the boundary where water leaves or enters the mesh in order to balance the change of energy associated with the flow of pore water through the boundary. A one-dimensional test with the new boundary condition applied to the right-hand side of the mesh showed an excellent match between the numerical and the analytical solutions of temperature along the bar of soil.

INVESTIGATION ON NUMERICAL ANALYSIS OF CONVECTIVE HEAT TRANSFER

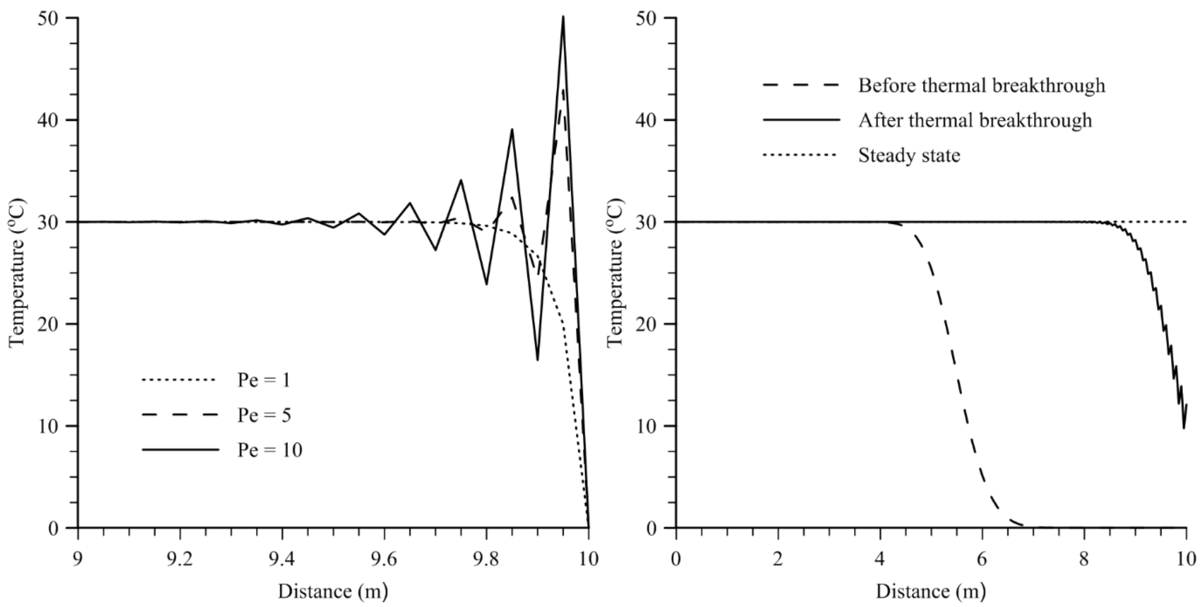
In thermo-hydraulic problems, the heat flow is often characterised in terms of Péclet number (Pe) which represents the ratio between the convective and the conductive transport rates. A high Péclet number indicates a flow that is dominated by convection, whereas a low Péclet number represents a conduction-dominated flow. It is defined as:

$$Pe = vL/\alpha$$

where L is the characteristic length, v is the flow velocity and α is the thermal diffusivity. In a two-phase material, such as a saturated soil, v is the pore fluid velocity and α should be based on the density and the specific heat capacity of the pore fluid. In the context of the finite element method, L is the element length in the direction of fluid flow.

Several studies on the behaviour of numerical solutions to highly convective problems with different values of Péclet number, as well as element type and size, were conducted. Firstly, one-dimensional tests with quadrilateral linear elements were performed on a bar of soil where a constant temperature was prescribed at each end: 30 °C and 0 °C on the left and the right sides of the mesh, respectively. The pore water flow was from left to right. The temperature distribution along the bar after the heat front had reached the end of the mesh for analyses with Péclet number of 1, 5 and 10 is presented in Figure 1(a). The results show an increasing amplitude of spatial oscillations with increasing Péclet number. This behaviour has also been observed by Al-Khoury (2012). It should be noted that quadratic elements experience smaller oscillations than linear elements, as these were observed to depend on the distance between two adjacent nodes. Therefore, it is recommended to use the condition $Pe \leq 2$ for linear elements and the condition $Pe \leq 4$ for quadratic elements in order to avoid such temperature oscillations.

Secondly, the above one-dimensional tests were repeated with the coupled thermo-hydraulic boundary condition prescribed at the right-hand side boundary of the mesh, instead of fixed temperature. The value of Péclet number, as well as element size and type, were varied. Figure 1(b) shows the temperature distribution along the soil bar for an example case with linear elements and Péclet number of 60. In this problem only slight oscillations are present. Similarly to the previous study, the oscillations reduce as Péclet number decreases.



(a) (b)

Figure 1 (a) Temperature distribution for analyses with fixed temperature boundary condition and different values of Péclet number; (b) temperature distribution for analysis with coupled thermo-hydraulic boundary condition and Péclet number of 60

APPLICATION TO OPEN-LOOP SYSTEMS

In order to test the performance of the new boundary condition, a boundary value problem involving an open-loop ground source energy system, where convection is the predominant method of heat transfer, was chosen. An open-loop system consisting of a well doublet in a 50-m thick homogenous sandstone aquifer with an initial temperature of 10 °C, and a constant pumping rate of 10 l/s was simulated. The temperature of the injected water was kept at a constant temperature of 20 °C. A series of two-dimensional plane strain coupled thermo-hydraulic analyses, where the element type as well as element size were varied, was performed using ICFEP.

Figure 2 presents the temperate evolution at the abstraction well for analyses with different meshes with linear elements – coarse and fine, with a maximum Péclet number of 64 and 16 respectively. It is clear that the Péclet number has no effect on the estimated time to thermal breakthrough. A comparison with an analysis performed using quadratic elements showed that the element type has no significant effect on the time to thermal breakthrough either.

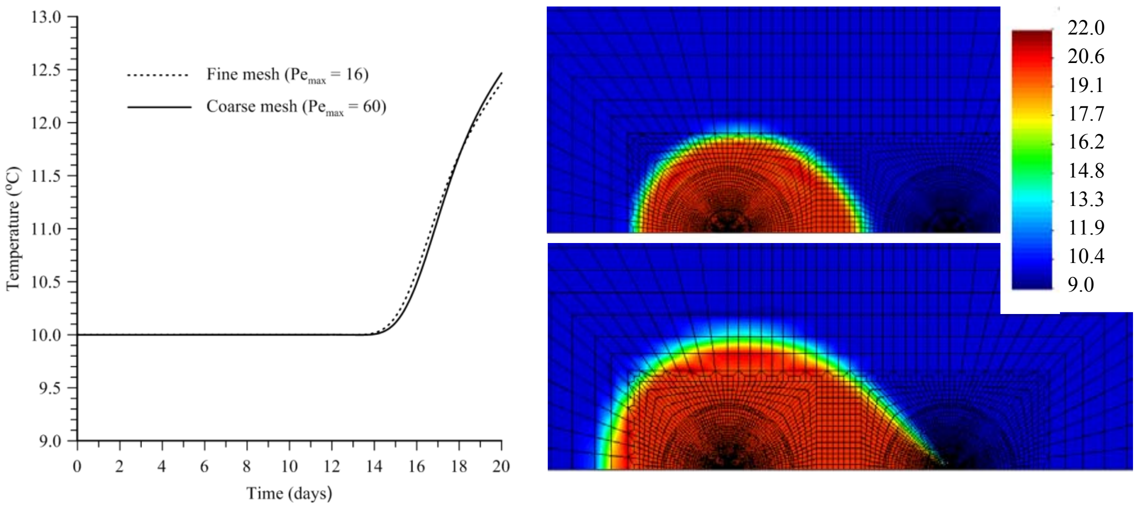


Figure 2 Temperature at the abstraction well for analyses with different meshes (left); contours of accumulated aquifer temperature (right)

CONCLUSIONS

This paper presents the summary of the formulation, validation and application of the thermo-hydraulic coupling as well as the new thermo-hydraulic coupled boundary condition. The studies on the effect of convective heat transport on the numerical solution have shown that the combination of fixed temperature boundary condition and high Péclet number may result in spatial oscillations of temperature. Therefore, a Péclet number below 2 for linear elements or below 4 for quadratic elements is recommended for a non-oscillatory solution. The thermo-hydraulic boundary condition performs better, showing only slight oscillations with a higher Péclet number. The simulation of an open-loop ground source energy system, where analyses with meshes with different element types and sizes are compared, shows that Péclet number has no significant effect on the time to thermal breakthrough.

The paper shows that ICFEP is capable of simulating highly convective coupled thermo-hydraulic problems. The presented analyses can be extended to study of the effect of hydraulic gradient and well spacing, as well as properties of the material, on the performance of open-loop systems.

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