Numerical Analysis on Feasibility of Thermally Induced Pore Fluid Flow in Saturated Soils

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ABSTRACT

The exact heat transfer mechanism in the soil media can be understood by analyzing the soil behavior surrounding the heat sources. In literature, heat conduction has been considered as a main heat transfer mechanism in soil, and less attention has been given to the natural heat convection in saturated soils. There is only limited research in the literature which shows the presence of thermally induced pore fluid flow in soil media. It has been observed that heat convection through pore fluid flow in sand facilitates heat transfer in the ground. Therefore, both heat conduction and heat convection must be considered to accurately model the heat transfer mechanism in soil. In this paper, the presence of natural convection of water in a 2D axisymmetric domain of soil with a vertical heat source has been numerically investigated in steady-state condition. The soil thermal response and heat transfer mechanism for different soil types are compared. Feasibility of thermally-induced pore fluid flow is analyzed for different soil types. The results determine the presence of thermally driven pore fluid flow in high permeability soil (e.g., coarse sand) and confirm that the effect of heat convection in low permeability silt and clay is negligible.

INTRODUCTION

In recent years, the interest to study the thermo-hydro-mechanical analysis of soil media is getting more in the field of geotechnical engineering. There are many practical applications in which soil temperature changes and it is important to identify the soil temperature response surrounding the heat sources. Heat sources can be divided into several categories including heat storage systems (Moradi *et al.*, 2016), energy geostructures (Ghasemi-Fare and Basu 2013, and 2016a; Stewart and McCartney 2013; Ahmadipur and Basu 2016; Joshaghani et al. 2018; Boushehri *et al*. 2019), Buried high-voltage cables (Hughes *et al*. 2015) and CO_2 geological storage (Ranganathan *et al*. 2012). These are considered as heat sources causing temperature gradient and consequently heat transfer in the ground.

One of the most interesting aspects of heat transfer is the natural convection mechanism in the saturated porous media. Despite the general belief in geotechnical communities that heat convection is negligible in soil media due to very low seepage velocity (Eskilson, 1987); there are many experimental (Krishnaiah and Singh 2004, Jalaluddin *et al.* 2011, Côté *et al.* 2011) and numerical (Zhao *et al*., 1998, Ghasemi-Fare and Basu, 2015a) studies disproving this belief by showing results of strong convection in soil medium due to the a dominantly pore fluid flow induced by temperature gradient even at the hydrostatic condition.

Aydin and Yang (2000) investigated the natural convection of a square cavity with localized heating at the bottom of the model with symmetrical cooling from the sidewalls. Hossain and Wilson (2002) studied natural convection flow induced by non-isothermal boundaries fluid-saturated porous medium. They observed significant changes in thermal response inside the cavity. In the field of geology and in large scale, Zhao *et al*. (1998) conducted a numerical study on convective pore-fluid flow and hydrocarbon transport in the Australian North West Shelf fluid-saturated basin. Anderson (2005) presented a comprehensive review of heat transfer using groundwater tracer by analyzing the temperature changes and heat transfer in ground water systems, including heat produced naturally in the subsurface and heat introduced in seepage from surface water. Recently, Ghasemi-Fare and Basu (2015a, 2017) emphasized on the importance of the thermally-induced pore fluid flow in saturated soil surrounding geothermal piles. Several other studies have dealt with natural convection and pore fluid flow in soil due to temperature gradient; however, less attention has been given to the natural convention mechanism in saturated soil with different permeability.

In the present study, the feasibility of pore fluid flow induced by isothermal vertical heat source is numerically investigated in 2D axisymmetric domain. Based on the results published in literature, the soil response surrounding a heat source is axisymmetric (Kramer et al. 2015, Ghasemi-Fare and Basu 2015b, and 2016b). The main objective of this study is to find a threshold in the intrinsic permeability of the soil in which the pore fluid flow does not have any significant effect on temperature distribution in the soil i.e. no considerable heat convection. Therefore, the potential for natural convection is investigated using the dimensionless Rayleigh (Ra) number, the ratio of buoyant forces to viscous forces, and Péclet (Pe) number which is the ratio between heat transfer by convection and heat transfer by conduction.

MATHEMATICAL FORMULATION

To model the heat and fluid flow in the porous media, the energy and momentum equations must be solved simultaneously. The generalized momentum, and energy equations which governs the flow in saturated porous media can be written as follows (Nield and Bejan, 2013):

$$\frac{\rho}{n}\left(\frac{\partial \mathbf{u}}{\partial t}\right) = -\nabla \mathbf{P} - \frac{\mu}{\kappa}\mathbf{u} + \rho g\left[1-\beta\left(\mathbf{T}-T_0\right)\right] \tag{1}$$

$$\left(\rho C_p\right)_m \frac{\partial \mathbf{T}}{\partial t} + \left(\rho C_p\right)_f \mathbf{u}.\nabla \mathbf{T} = \nabla.\left(k_m \nabla \mathbf{T}\right) \tag{2}$$

where, ρ is the density, n is the porosity, μ is dynamic fluid viscosity, κ is the intrinsic permeability of the medium, g is gravitational acceleration, k is thermal conductivity, C_p is heat capacity at constant pressure, and β is thermal expansion coefficient of the ground water. Furthermore, T_0 is reference temperature which in this problem is the constant temperature of the ground.

In Equations (1) and (2), $\mathbf{u}$, $\mathbf{P}$ and $\mathbf{T}$ are velocity, pressure, and temperature fields, respectively. To predict the density and specific heat capacity of the medium the Equations (3) and (4) are used.

$$\left(\rho C_p\right)_m = \left(1-n\right)\left(\rho C_p\right)_s + n\left(\rho C_p\right)_f \tag{3}$$

$$k_m = \left(1-n\right)k_s + nk_f \tag{4}$$

where, subscripts m, s, and f denote the medium, solid (porous matrix), and fluid, respectively. Moreover, the continuity equation must be satisfied as well. For incompressible fluid, continuity equation will define as follows:

$$\nabla.\mathbf{u} = 0 \tag{5}$$

The current study analyzed the feasibility of the thermally driven pore fluid flow in the soil media at the steady-state condition. Four assumptions have been considered in the modeling: (1) Porous medium is non-deformable, homogeneous, isotropic, and fully saturated with incompressible fluid; (2) The thermal and hydraulic properties of the fluid are assumed to be constant, except for the density in the buoyancy term of momentum equation where Oberbeck-Boussinesq approximation is applied; (3) Darcy's law is valid since seepage velocity in the porous medium is pretty low and the Forchheimer inertia effect can be neglected; and (4) Local thermal equilibrium between solid and fluid phase is assumed.

In order to compare the soil behavior in general condition, several important dimensionless numbers (e.g., Prandtl, Darcy, Rayleigh, and Péclet) are presented which will be used for analyzing the data in the next section:

$$\mathrm{Pr} = \frac{\nu}{\alpha} \qquad \mathrm{Da} = \frac{\kappa}{d^2}$$

$$\mathrm{Ra} = \frac{g\beta C_p \kappa H\left(T_H - T_0\right)}{\alpha\nu} \qquad \mathrm{Pe} = \frac{uH}{\alpha}$$

where $\nu = \mu / \rho$ is the momentum diffusivity and $\alpha = k / \rho C_p$ is the thermal diffusivity. d, H, and u are the mean particle diameter, characteristic length and characteristic velocity, respectively, T_H is the temperature of the heat source.

The physical meanings of the dimensionless numbers are as follows:

(1) Prandtl number (Pr): Characterizes the relative significance of the inertia term and the regime of convection,

(2) Darcy number (Da): Represents the relative effect of the permeability of the porous medium,

(3) Rayleigh number (Ra): Characterizes the relative significance of buoyant forces,

(4) Péclet number (Pe): Points out significance of heat convection through the ratio of heat convection over heat conduction,

The potential of natural heat convection in saturated porous media (soil, in this case) is often investigated using Ra number. Theoretically, the onset of natural convection in an infinitely extensive horizontal layer occurs when the Ra exceeds $4\pi^2$ (≈ 40) which is called critical Rayleigh (Ra_c) number (Schubert and Straus, 1979; Anderson, 2005). Also, Péclet number has been used to determine the significance of natural and forced heat convection in porous media in different scale (van der Kamp and Bachu, 1989, Romero, 1994). Pe highly depends on the choice of characteristic length (H); here, the modified Pe number defined by van der Kamp and Bachu (1989) which is called "geothermal Péclet number" is used to interpret the data.

NUMERICAL MODEL

The coupled nonlinear Equations (1), (2) and (5) are solved simultaneously using COMSOL Multiphysics™ v5.3a (COMSOL, 2018) to obtain the temperature and velocity field in the soil media. As mentioned earlier, heat transfer from a heat source to the surrounding soil is analyzed in a 2D axisymmetric plane. Temperature of the heat source is considered to be uniform and is placed at the center of the model. Accordign to the published research thermal response of the soil surrounding a uniform heat source is an axisymmetric (Ghasemi-Fare and Basu 2013, 2015a). Therefore, to have the valid assumption a constant temperature heat source is assumed in this study. A schematic view of the domain with initial and boundary conditions are presented in Figure 1.

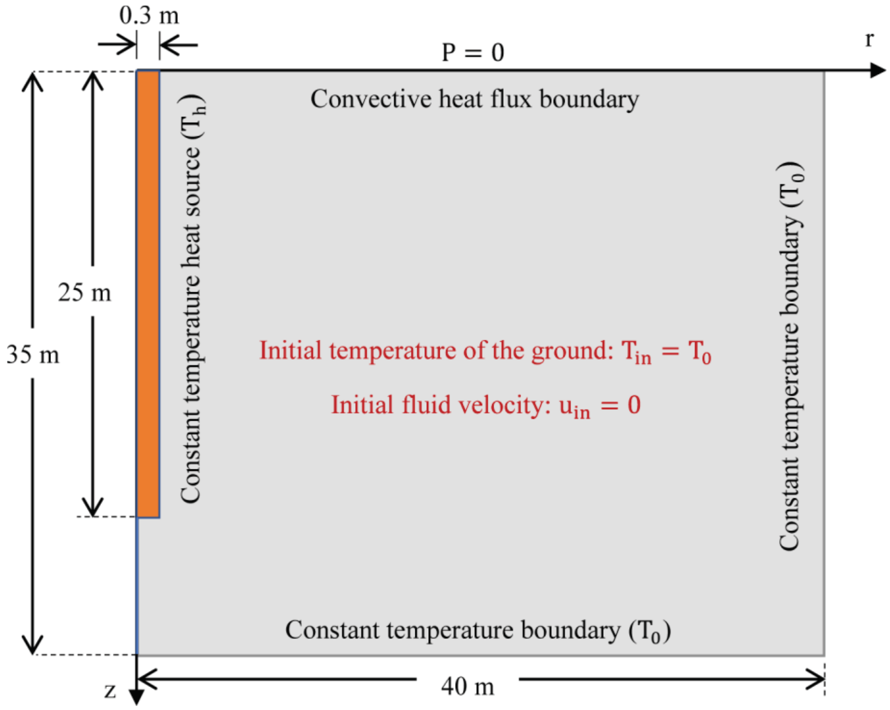

FIG. 1. The schematic view of the domain with described initial and boundary conditions

Constant temperature which represents far boundary is considered for the bottom and two sides of the model. However convective boundary condition is assumed at the top of the model. Table 1 includes all input constant parameters that are used in this study.

Table 1. Input parameters used in the FE analysis

Parameter	Value
ρ_f	$1000\ \mathrm{kg/m^3}$
ρ_s	$2000\ \mathrm{kg/m^3}$
μ	$0.001\ \mathrm{Pa.s}$
β	$4\times10^{-4}\ \mathrm{1/K}$
γ (Fluid Ratio of Specific Heat)	1
k_f	$0.60\ \mathrm{W/m.K}$
k_s	$3.70\ \mathrm{W/m.K}$
C_{pf}	$4200\ \mathrm{J/kg.K}$
C_{ps}	$1480\ \mathrm{J/kg.K}$
n	0.40
P_0 (Reference pressure)	$1.013\times10^5\ \mathrm{Pa}$
T_0	20 ℃
T_H	40 ℃
h	$1\ \mathrm{W/m^2.K}$

To calculate the non-dimensional values, the mean particle diameter (d) is assumed to be 1 mm. The mean seepage velocity of the medium is considered to be the characteristic velocity.

RESULTS AND DESCUSSION

Soil temperatures and the feasibility of natural convection of the ground water are presented in this section. The results are analyzed using the dimensionless numbers defined above. The fluid is considered as water and the Prandtl number is $\mathrm{Pr}=7$. Three different soil media with different permeability values are considered. The results for $\mathrm{Da}=0.0005$ ($\kappa=5\times10^{-10}\,\mathrm{m}^2$), 0.00005 ($\kappa=5\times10^{-11}\,\mathrm{m}^2$), and 0.000005 ($\kappa=5\times10^{-12}\,\mathrm{m}^2$) which represents different intrinsic permeability from high permeability class of soils (e.g. coarse sands) to medium permeability soils (e.g. silty sands) are presented in Figures 2, 3 and 4, respectively.

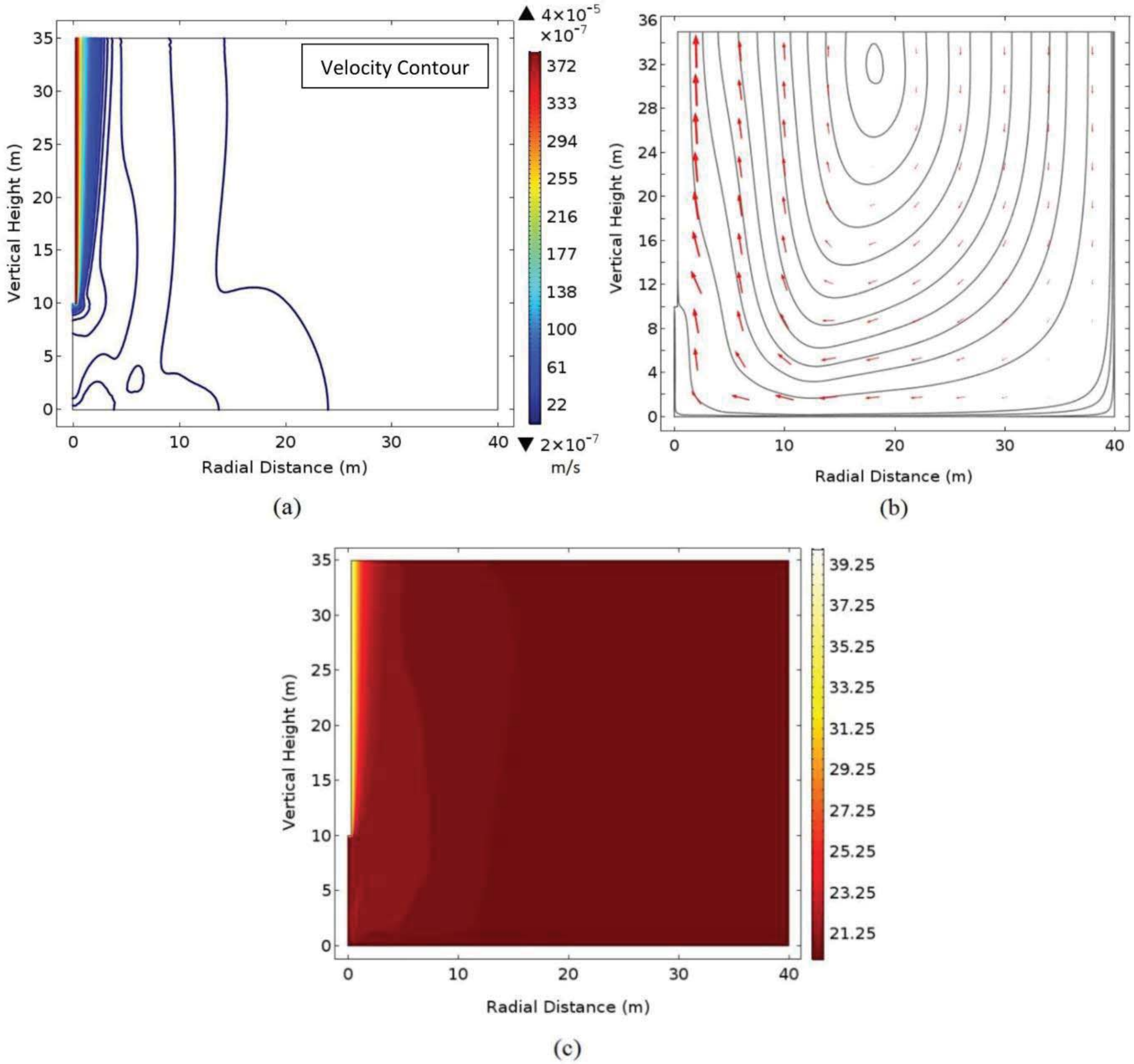

FIG. 2. (a) Velocity magnitude contour, (b) streamlines, (c) Isotherms for $\mathrm{Da}=0.0005$, $\mathrm{Ra}=6865$, $\mathrm{Pe}=6.7$ where $\mathrm{Pr}=7$

Figures 2-4 (a) show the thermally induced pore fluid in the medium. As it can be seen in the figure, the pore fluid velocity values are getting smaller for low permeability soils.

Figures 2–4 (b) depict the streamlines of the pore fluid flow. The size of the arrows is proportional to Darcy's velocity magnitude. The larger arrows closer to the heat source represents higher circulation of the fluid in the vicinity of the heat source. Figures 2-4 (c) show the isotherms and temperature distribution in the medium. It is evident from the figures that for the two cases with $\mathrm{Da} = 0.0005$, 0.00005, convective heat transfer changes the temperature distribution contours in the soil. This confirms that for high permeability soil heat convention through thermally induced pore fluid flow is a dominant mechanism. Large value of the Ra for high permeability soil represents the stronger heat convection.

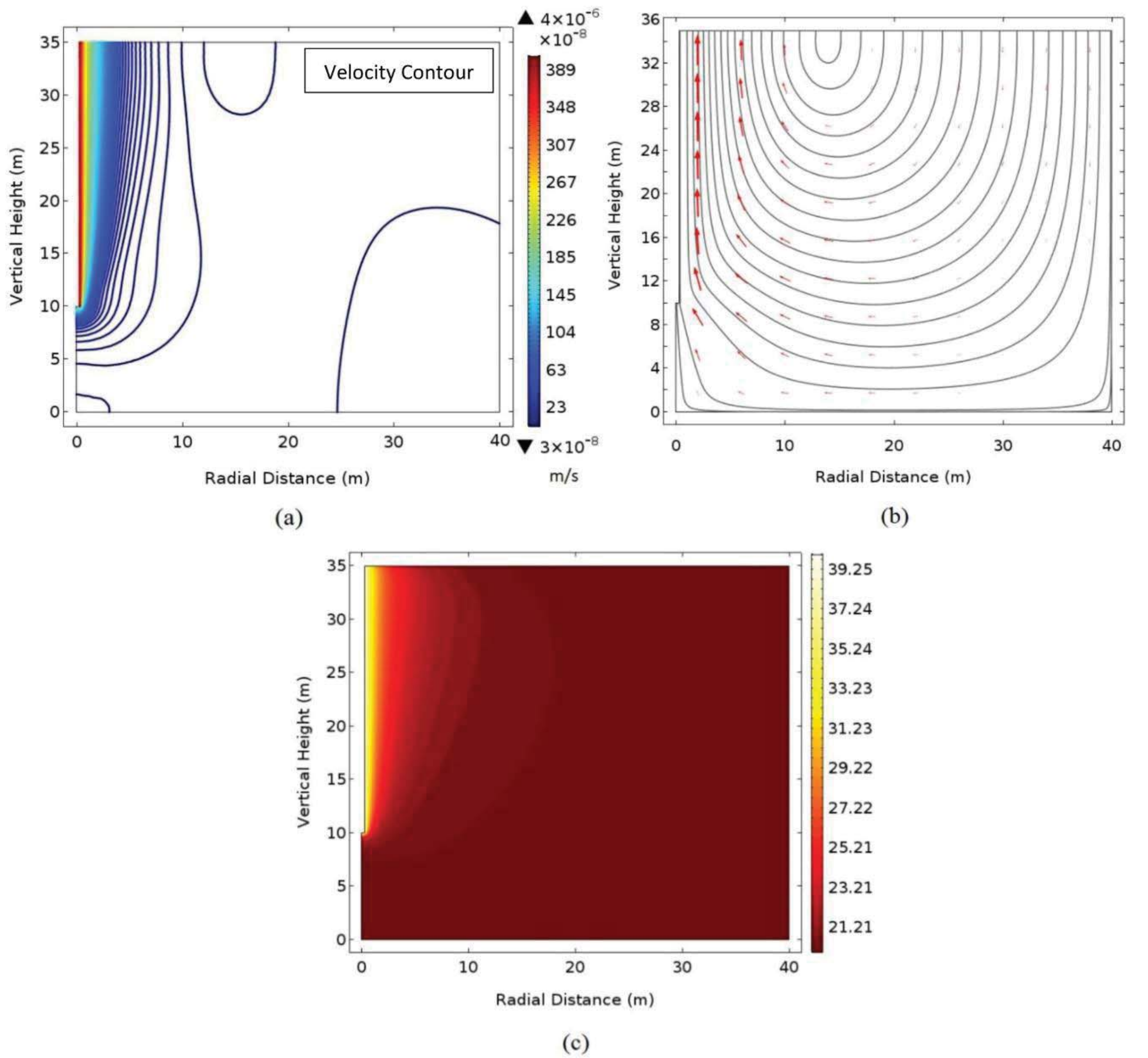

FIG. 3. (a) Velocity magnitude contour, (b) streamlines, (c) Isotherms for $\mathbf{Da} = 0.00005$, $\mathbf{Ra} = 687$, $\mathbf{Pe} = 1.2$ where $\mathbf{Pr} = 7$

Considering the scale of the problem, $\mathrm{Pe} > 1$ shows the strong heat convection in comparison to heat conduction (van der Kamp and Bachu, 1989). On the contrary, $\mathrm{Da} = 0.000005$ with $\mathrm{Pe} < 1$ is not showing any significant convection due to the relatively lower pore fluid flow. Comparison of the temperature distribution of soil considering no heat convection and Figure 4 (c) with low permeability (Da= 0.000005), confirm that the thermally induced pore fluid flow is insignificant in this condition.

Figures 5 compares the temperature distribution differences along the heat source and its variation with radial distance from the heat source for the cases of $\mathrm{Da}=0.0005$, 0.00005, 0.000005, and no convection where only conduction is considered (only Equation 2 is solved). It is shown that in $\mathrm{Da}=0.000005$ case the soil temperature is almost identical to the case where only heat conduction is solved. However, for $\mathrm{Da}=0.00005$ ($\kappa=5\times10^{-11}\,\mathrm{m}^2$), where strong heat convection is evident, the average temperature difference with the model in which only heat conduction is considered is as high as 50 %.

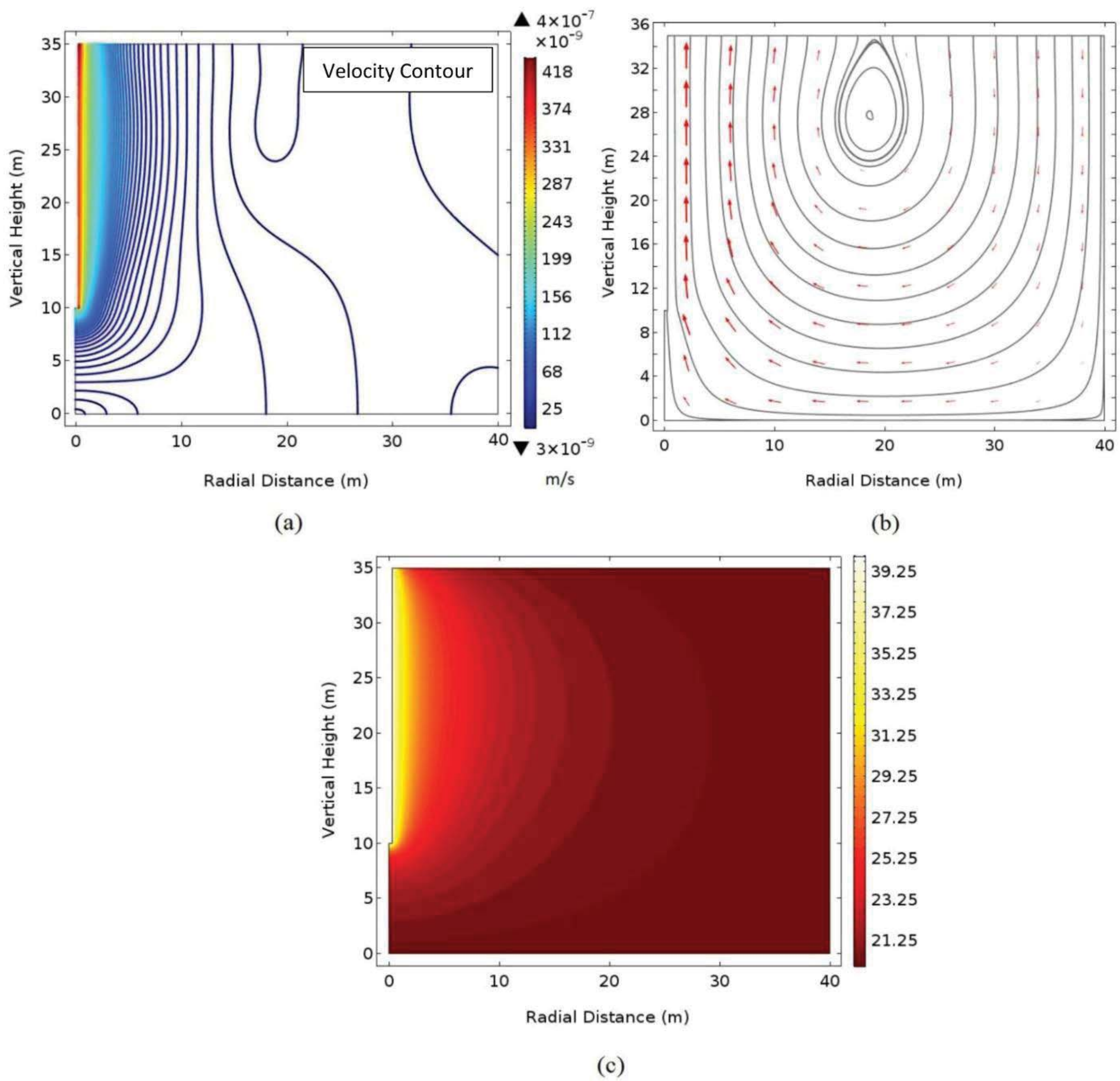

FIG. 4. (a) Velocity magnitude contour, (b) streamlines, (c) for $\mathrm{Da}=0.000005$, $\mathrm{Ra}=69$, $\mathrm{Pe}=0.3$ where $\mathrm{Pr}=7$

CONCLUSIONS

A numerical study was conducted on heat transfer problem in a 2D axisymmetric domain of water-saturated soil with vertical isothermal heat source. The soil thermal response and heat transfer mechanism for different soil types were compared through analyzing dimensionless numbers. It was observed that natural convection can be a dominant heat transfer mechanism for high permeability soil (e.g., Gravel and sand) and can play a role in soil temperature response even for low permeability sand. Furthermore, thermally-induced pore fluid flow happened to be feasible by solving Darcy's momentum equation coupled with energy equation. It was found that thermally-induced pore fluid flow changes the temperature distribution patterns for high permeability soil (e.g. sand) in the ground at the hydrostatic condition even for longer distances from the heat source.

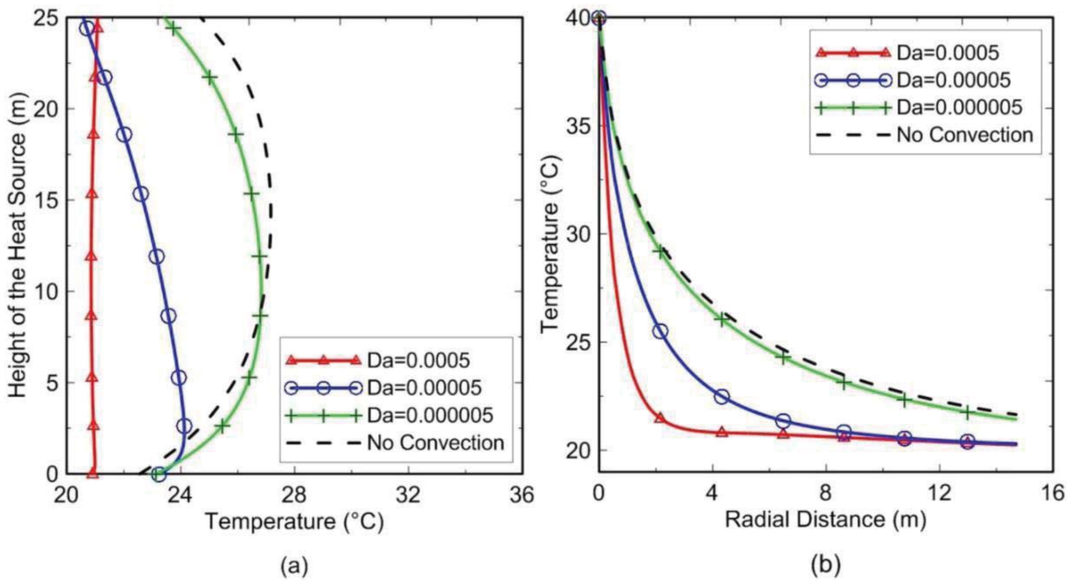

FIG. 5. (a) Temperature distribution along the heat source at 4 m radius, (b) temperature distribution at the middle the heat source in radial distance for Da $= 0.0005$**,** 0.00005**,** 0.000005 **, and with no convection**

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REFERENCES

Ahmadipur, A., and Basu, P. (2016). Temperature-Induced Alterations of the Shaft and Base Resistances of a Model Geothermal Pile in Dry Sand Geo-Chicago 2016 (pp. 155-165).

Anderson, M. P. (2005). "Heat as a Ground Water Tracer." Ground Water, 43(6), 951–968.

Aydin, O. and Yang, W. J. (2000). "Natural convection in enclosures with localized heating from below and symmetrical cooling from sides." International Journal of Numerical Methods for Heat & Fluid Flow, 10(5), 518-529.

Boushehri, R., Estahbanati, S. H., Ghasemi-Fare, O. "Controlling Frost Heaving in Ballast Railway Tracks Using Low Enthalpy Geothermal Energy." 2019.

Côté, J., Fillion, M. H. and Konrad, J. M. (2011). "Intrinsic permeability of materials ranging from sand to rock-fill using natural air convection tests." Canadian Geotechnical Journal, 48, 679–690.

COMSOL, (2013). COMSOL MultiphysicsTM v4.3b: User's guide and reference manual.

COMSOL, Burlington MA
Eskilson, P. (1987). “Thermal analysis of heat extraction boreholes.” Ph.D. Thesis, University of Lund, Department of mathematical Physics, Lund, Sweden.
Ghasemi-Fare, O. and Basu, P. (2013). “A practical heat transfer model for geothermal piles.” Energy and Buildings, 66, 470-479.
Ghasemi-Fare, O and Basu, P. (2015a). “Numerical Modeling of Thermally Induced Pore Water Flow in Saturated Soil Surrounding Geothermal Piles.” IFCEE (ASCE).
Ghasemi-Fare, O., Basu, P., (2015b). “Thermal operation of geothermal piles installed in sand - a comparative assessment using numerical and physical models”, IFCEE, ASCE, 1721-1730. doi: 10.1061/9780784479087.156
Ghasemi-Fare, O. and Basu, P. (2016a). “Predictive assessment of heat exchange performance of geothermal energy piles”, Renewable Energy, 86, 1178-1196.
Ghasemi-Fare, O., Basu, P., (2016b). “Thermally-induced pore pressure fluctuations around a geothermal pile in sand”, Geo-Chicago, GSP 270, ASCE, August 14-18, 176-184. DOI:10.1061/9780784480137.018
Ghasemi-Fare, O., Basu, P., (2017). “Role of thermally induced buoyant flow in altering energy harvesting through geothermal piles”, Geotechnical Frontiers 2017, GSP 280, ASCE, 113-123, March 12-15, Orlando, Florida.
Hossain, M. A. and Wilson, M. (2002). “Natural convection flow in a fluid saturated porous medium enclosed by non-isothermal walls with heat generation.” International Journal of Thermal Science, 41, 447–454.
Hughes, T. J., Henstock, T. J., Pilgrim, J. A., Dix, J. K., Gernon, T. M. and Thompson, C. E. L. (2015). “Effect of Sediment Properties on the Thermal Performance of Submarine HV Cables.” IEEE Transaction in Power Delivery, 30(6).
Jalaluddin, E., Miyara, A., Tsubaki, K., Inoue, S., Yoshida, K. (2011). “Experimental study of several types of ground heat exchanger using a steel pile foundation.” Renewable Energy, 36, 764–771.
Joshaghani, M., Ghasemi-Fare, O., Ghavami, M. (2018). “Experimental Investigation on the effects of temperature on physical properties of sandy soils”, IFCEE, ASCE, Orlando, FL March 5-10.
Kramer. C.A., Ghasemi-Fare, O. and Basu, P (2015). “Laboratory thermal performance tests on a model heat exchanger pile in sand”, Geotechnical and Geological Engineering, 33, 253-271.
Krishnaiah, S. and Singh, D. N. (2004). “Centrifuge modeling of heat migration in soils.” International Journal of Physical Modeling in Geotechnics, 3, 39-47.
Moradi, A., Smits, K. M., Lu, N. and McCartney, J. S. (2016). “Heat Transfer in Unsaturated Soil with Application to Borehole Thermal Energy Storage.” Vadose Zone Journal, 15(10).
Nield, D. and Bejan, A. (2013). “Convection in porous media”. 4th edition, Springer, New York.
Ranganathan, P., Farajzadeh, R., Bruining, H and. Zitha, P. L. J. (2012). “Numerical Simulation of Natural Convection in Heterogeneous Porous media for CO_2 Geological Storage.” Transport in Porous Media, 95, 25–54.
Romero, L. A. (1994). “Low or High Peclet Number Flow Past a Sphere in a Saturated Porous Medium.” SIAM Journal on Applied Mathematics, 54(1), 42-71.
Schubert, G. and Straus, J. M. (1979). “Three-dimensional and multicellular steady and unsteady convection in fluid-saturated porous media at high Rayleigh numbers.” Journal of Fluid Mechanics, 94(1), 25-38.
Stewart, M. A. and McCartney, J. S. (2013). “Centrifuge Modeling of Soil-Structure Interaction

in Energy Foundations.” ASCE Journal of Geotechnical and Geoenvironmental Engineering. 140(4), 04013044-1-11.

van der Kamp, G. and Bachu, S. (1989). “Use of dimensional analysis in the study of thermal effects of various hydrogeological regimes.” Conference: Hydrogeologial Regimes and their Subsurface Thermal Effects, Vancouver, BC, Canada.

Zhao, C., Hobbs, B. E., Baxter, K., Mühlhaus, H. B. and Ord, A. (1999). "A numerical study of pore-fluid, thermal and mass flow in fluid-saturated porous rock basins", Engineering Computations, 16(2), 202-214.