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# ► To cite this version:

Somenath Mondal, Devendra N Singh, Anh Minh A.M. Tang, Jean-Michel Pereira. A finite difference model for undefined end boundary to analyse the heat transfer in dry sands. International Journal of Geotechnical Engineering, 2022, 16 (2), pp.256-262. 10.1080/19386362.2020.1854972. hal-03053673

# HAL Id: hal-03053673 https://enpc.hal.science/hal-03053673

Submitted on 11 Dec 2020  $\,$ 

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# A Finite Difference Model for Undefined End Boundary to Analyze the Heat Transfer in Dry Sands

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16 **Abstract.** Accurate prediction of thermal regime (i.e., the variation of soil temperature,  $\theta$ , and heat flux, 17  $\phi$ ) to investigate the migration of thermal energy in soil mass, poses challenge to the geoenvironmental 18 engineers while dealing with various thermo-active structures. In this context, several numerical 19 approaches have been attempted to solve the heat transfer equation (HTE) for conduction to predict the 20 thermal regime. However, most of them need accurate boundary condition defined and involve complicated numerical approach which is inconvenient for the practising engineers. Hence, an attempt has 21 22 been made in the present study to develop a simplified, but numerically efficient, approach based on the 23 finite difference method (FDM) to analyse one dimensional heat transfer in dry sands when the end 24 boundary is not defined. Furthermore, a time dependent initial boundary condition has been applied to this 25 model to simulate similar experimental condition and results have been compared vis-à-vis those obtained from the experiment and COMSOL Multiphysics<sup>®</sup> to validate the proposed approach. 26

27 **Keywords:** sands; thermal regime; heat transfer equation; numerical analysis; finite difference model;

#### 28 **1. Introduction**

29 Contemporary geoenvironmental engineering and practices deal with design and construction of several thermo-active structures such as furnaces, boiler units, forging units, brick kilns and rocket 30 31 launching pads, buried conduits and electrical cables, air conditioning ducts (Kadali et al. 2013), 32 disposal facilities of waste from the nuclear and thermal power plants (Rao and Singh 1999; Krishnaiah and Singh 2004; Delage et al. 2010; Dao et al. 2015), underground crude oil storage 33 tanks (Mandal et al. 2013; Padmakumar 2013; Usmani et al. 2015), oil carrying pipelines ( 34 35 Brandon and Mitchell 1989; Abuel-Naga et al. 2008; Lee et al. 2010; Manthena and Singh 2001), 36 solar ponds (Velmurugan and Srithar 2008), energy geostructures (Knellwolf et al. 2011; 37 Loveridge and Powrie 2013; Salciarini et al. 2013; Yavari et al. 2014; Di Donna et al. 2016; Faizal 38 et al. 2016; McCartney et al. 2016), which result in conveyance of thermal energy through the soil 39 mass. Moreover, activities like dissociation of gas hydrates by heating (Feng et al. 2015; Song et 40 al. 2015, 2016) and exploitation of oil sand by steam assisted gravity drainage (SAGD) (Elsayed et 41 al. 2015; Lazzaroni et al. 2016) and also soil-atmosphere interaction (Heusinkveld et al. 2004; 42 Ochsner et al. 2007; Cui et al. 2013) involve heat migration through soil mass. These applications 43 necessitate studies to understand how heat migrates in the soil mass by means of predicting the 44 thermal regime (i.e., time dependent temperature and thermal flux) in it.

In this context, several studies have been carried out to predict thermal regime of soil mass by
 solving HTE (Heat Transfer Equation) either numerically or analytically. Some of the broadly used

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47 approaches are Finite Element Method (FEM) (Timlin et al. 2002; Han and Huang 2002; Bittelli et al. 2008,), Finite Volume Method (LeVeque 2002), Finite Difference Method (FDM) (Sharratt 48 et al. 1992; Han and Huang 2002; Wu and Sun 2004; Wang et al. 2011), Force Restore Method 49 (FRM) (Liebethal and Foken 2007; Gao et al. 2008). Moreover, different analytical methods like 50 Harmonic Method, Laplace Transform Method, and Fourier Transform Method, have been 51 considered by several researchers (Heusinkveld et al. 2004; Gao et al. 2007; Evett et al. 2012; 52 53 Wang et al. 2012) to solve HTE in order to predict the thermal regime in soil mass (Mondal et al. 2017). Nonetheless, the major hindrance of some of the abovementioned methods is that they 54 55 involve complicated mathematics which is not convenient to the practising engineers. Moreover, 56 for any numerical approach, proper boundary conditions are necessary to be defined. On the contrary, many a times while performing experimental investigations, proper boundary conditions 57 58 are not monitored. This results in a real challenge to adopt a numerical study in order to conduct comparative analysis between experimental and numerical outcomes of any particular problem. 59

Keeping this in view, an effort has been made to develop a computationally efficient and
simplified numerical model based on FDM to predict (i) the end boundary and to estimate (ii) the
realistic thermal regime in sandy soils, which would be very convenient for the practising
geotechnical engineers. Furthermore, the results obtained from FDM and COMSOL
Multiphysics<sup>®</sup>, a commercially available FEM based analysis tool, have been compared vis-à-vis
with experimental results, details of which are presented in this paper.

The distinctiveness of this model lies in the fact that it is simpler than the complicated analytical solutions yet numerically efficient. This would make the model widely accepted among practicing engineers who are working in the projects of construction of thermo-active structures. Moreover, this FDM can be employed to define the appropriate boundary conditions (in case of comparative analysis between experimental investigations with undefined boundary) to obtain an accurate numerical solution.

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## 2. Statement of the Problem

74 This section deals with the details of the problem investigated in the present study, which 75 essentially has been derived from the experiments conducted by Mondal et al. (2016). A 20 cm 76 long (L) column of the Indian standard sands, designated as SI (refer Table 1 for the thermal properties of the sands) was used in the experiments. A temperature of 60 ° C was applied at the 77 top surface of this column, as depicted in Fig1a. Furthermore, as depicted in Fig1b, the flux 78 79 sensors, and thermocouples were embedded at 5 cm and 9 cm depths, respectively, in the sample 80 (Mondal et al. 2017). The heat gun was kept at a height of 400mm which ensured uniform heat application at the top surface of the column. Since the lateral boundary is maintained adiabatic as 81 82 explained in Mondal et al. (2016) and the base of the column is made up of aluminium, which has very high thermal conductivity as compared to that of sand, the bottom boundary of this column 83 84 can be considered as the 'open end boundary' through which thermal flux could exit. As such, the heat transfer through this column can be assumed to be one-dimensional, and after a specific time, 85 86 the steady-state condition could be achieved in it. Hence, the novelty of the present study is that 87 it's an attempt to establish a simple numerical approach, based on finite difference method (FDM), 88 to identify the correct end boundary conditions, which would facilitate determination of thermal 89 regime for one-dimensional heat conduction in dry sands.

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Table 1. Thermal Properties of Sand used in this study

Sand	Dry density $(\gamma_d)$	Thermal Conductivity	Specific Heat ( <i>C<sub>p</sub></i> )
	$(g/cm^3)$	(k) (W/ $^{\circ}C/m$ )	(J/kg /°C)
SI	1.556	0.315	171

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## 94 **3. The Proposed Methodology**

95 The one-dimensional heat conduction equation can be written as:

$$\frac{\partial \theta}{\partial t} = \alpha \frac{\partial^2 \theta}{\partial x^2} \tag{1}$$

97 where  $\theta(z,t)$  is the temperature in the soil mass, at the depth of z and corresponding to time, t, and 98  $\alpha$  is the thermal diffusivity of the soil mass which can be determined if  $\kappa$ , thermal conductivity 99 and *C*, Specific heat for a particular bulk density,  $\rho$ , of the soil mass is known (refer Eq. 2).

100 
$$\alpha = \frac{\kappa}{\rho C}$$
(2)

101 It should be noted that the conduction is the predominant mechanism of heat transfer through 102 solids (Jackson and Taylor 1986; Mondal *et al.* 2018) and hence, equation of heat conduction is 103 considered.

104 3.1 The model based on the FDM

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106 The one-dimensional HTE, Eq. 1, is discretised in time and space using simple difference 107 equations and ignoring the truncation error, which is negligibly small. Subsequently, the explicit 108 solution has been obtained as:

$$\theta_{i+1}^n = \frac{\alpha \Delta t}{(\Delta z)^2} \left( \theta_i^{n+1} - 2\theta_i^n + \theta_i^{n-1} \right) + \theta_i^n \tag{3}$$

110 It is worth mentioning that the condition of stability for this explicit solution is  $\frac{\alpha \Delta t}{(\Delta z)^2} \leq \frac{1}{2}$ . As 111 such, in order to maintain the stability, a time step of 30 seconds which corresponds to 112 characteristic length of 1 cm, has been chosen.

#### 114 3.2 Determination of the End boundary

115 The purpose of this simple numerical method is to analyse the experimental data where the end boundary condition is not defined. As described by Mondal et al. (2016) neither the 116 117 temperature nor the thermal flux was measured at the end boundary while performing the experiment. Hence, it became mandatory to device a methodology that could be utilized to define 118 119 the end boundary. With this in view, beyond the considered depth of the model, L (=20 cm), an 120 additional depth of the soil mass of length,  $\Delta L$ , has been chosen (refer Fig. 2). This additional 121 depth of the soil mass is beyond the zone of influence of the temperature applied at the top 122 boundary, for a particular time, and is constrained by the bottom boundary. Hence, changes in the 123 applied temperature at the top surface of the model would not be felt by the end boundary which is considered as the end point of the additional depth. As a result, at this end boundary the 124 prevailing temperature could be considered as ambient when numerical simulation is being 125 conducted. The obtained result, for different values of  $\Delta L$  were compared with the analytical 126 solution of HTE (refer Eq. 4) for establishing the most suitable depth of end boundary. 127

$$\theta(z,t) = \left(\theta_{j} - \theta_{0}\right) \operatorname{erf}\left(\frac{z}{2\sqrt{\alpha t}}\right) + \theta_{0}$$

$$\tag{4}$$

129 where  $\theta_i$  and  $\theta_0$  are initial and applied temperature respectively.

#### 131 3.3 Time dependent boundary condition

As described by Mondal *et al.* (2016), the top surface of the sand column takes some time to achieve the applied temperature (i.e., the temperature at which the heat gun is set). While, in case of the FDM, corresponding to the second time step, the first node is considered to have achieved the maximum applied temperature, which results in higher rate of heat transfer. Hence, to simulate

- 137 the true experimental conditions, a step thermal loading of  $0.4^{0}$  C/min has been imposed at the 138 second time step of the FDM, until the first node achieves the maximum applied temperature.
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#### 140 **4. Results**

141 To define the bottom end boundary for the FDM, a methodology has been adopted as described 142 in Section 3.2 and the results are compared vis-a-vis the analytical solution (refer Eq. 4), as depicted in Fig 3. It can be observed from Figs. 3 (a) and (b) that the results obtained from the 143 FDM, for an additional depth ( $\Delta L$ ) of 20 cm, exhibit the best agreement with the results obtained 144 from analytical solution. Based on this finding, the end boundary condition for the FDM was 145 considered as an optimum additional depth of 20 cm when there is no significant improvement for 146 further increment of  $\Delta L$ . Moreover, the experimental data has been compared vis-à-vis the results 147 obtained from the FDM and COMSOL Multiphysics<sup>®</sup>. It is worth mentioning here that the lateral 148 boundaries of the COMSOL model have been assumed to be 'adiabatic' and the bottom boundary 149 150 has been assigned the ambient temperature like the FDM. Subsequently, a comparison between 151 the results obtained from the experiments, and FDM and COMSOL Multiphysics<sup>®</sup> has been 152 depicted in Fig 4 and Fig 5, respectively.

153 It can be noticed from Fig 4 that there is a good match between the experimental and FDM 154 results. However, it can be noticed from Fig 5 that the COMSOL Multiphysics<sup>®</sup> predicts lower 155 temperatures as compared to experimentally obtained results. Furthermore, it can be observed 156 from Fig 6 that the temperature profile obtained from the FDM matches very well with the 157 experimentally obtained temperature profile. However, Fig 7 exhibits not so good match between 158 the temperature profiles obtained from COMSOL Multiphysics<sup>®</sup> simulation and the experiments.

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#### 160 **5. Concluding Remarks**

Prediction of realistic thermal regime in soil mass by means of mathematical approach enforces 161 challenges to geoenvironmental practitioners. In this context, a simple FDM has been developed 162 163 to solve one-dimensional HTE equation in order to establish thermal regime in sandy soil mass. A simple mathematical approach has been proposed to define end boundary for the FDM, as in case 164 of the experiment the temperature at the end boundary could not be monitored. It is worth 165 166 mentioning that the proposed numerical approach can be used for any dry sandy soil to define the end boundary and to determine the thermal regime. Moreover, experimentally obtained thermal 167 regime has been compared vis-à-vis that obtained from the FDM and COMSOL Multiphysics<sup>®</sup> 168 and it has been demonstrated that the FDM results match satisfactorily with experimental results 169 as compared to the COMSOL Multiphysics<sup>®</sup>. Hence, it is believed that the proposed FDM would 170 171 be an efficient tool to estimate thermal regime in sandy soils. However, the applicability of the proposed model should be checked in clays to enhance its versatility. 172

## 174 Acknowledgements

The authors wish to acknowledge the support of the European Commission via the Marie Curie
IRSES project GREAT 'Geotechnical and geological Responses to climate change: Exchanging
Approaches and Technologies on a world-wide scale' (FP7-PEOPLE-2013-IRSES-612665) and
the funding received from the Department of Electronics and Information Technology (DeitY),
MCIT, Government of India, through the Center of Excellence in Nanoelectronics, Department of
Electrical Engineering, IIT Bombay.

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- Figure 7. Comparison of the temperature values at 5 cm depth obtained from the COMSOL Multiphysics<sup>®</sup>, and experiment



Figure 1. (a) The schematic diagram of experiment setup (b) The arrangement of heat thermocouples





**Figure 3(a).** Thermal regime obtained at 5 cm depth for different additional depths in FDM and analytical model, for applied temp 60°C, soil SI



**Figure 3(b).** Thermal regime obtained at 9 cm depth for different additional depths in FDM and analytical model, for applied temp 60°C, soil SI



Figure 4(a). Thermal regime obtained at 5 cm depth in FDM and experiment, for an applied temp 60°C in step, soil SI



Figure 4(b). Thermal regime obtained at 9 cm depth in FDM and experiment, for an applied temp 60°C in step, soil SI



Figure 5. Temperature profile obtained at 5 and 9 cm depth from experiment and COMSOL Multiphysics®, for an applied temp 60°C in step, soil SI



Figure 6. Comparison of the temperature values at 5 cm depth obtained from the FDM and experiment



Figure 7. Comparison of the temperature values obtained at 5 cm depth from the COMSOL Multiphysics® and experiment