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

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Abstract. Accurate prediction of thermal regime (i.e., the variation of soil temperature, θ , and heat flux, ϕ) to investigate the migration of thermal energy in soil mass, poses challenge to the geoenvironmental engineers while dealing with various thermo-active structures. In this context, several numerical approaches have been attempted to solve the heat transfer equation (HTE) for conduction to predict the 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 been made in the present study to develop a simplified, but numerically efficient, approach based on the finite difference method (FDM) to analyse one dimensional heat transfer in dry sands when the end boundary is not defined. Furthermore, a time dependent initial boundary condition has been applied to this model to simulate similar experimental condition and results have been compared vis-à-vis those obtained from the experiment and COMSOL Multiphysics[®] to validate the proposed approach.

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

1. Introduction

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 launching pads, buried conduits and electrical cables, air conditioning ducts (Kadali *et al.* 2013), 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 tanks (Mandal *et al.* 2013; Padmakumar 2013; Usmani *et al.* 2015), oil carrying pipelines (Brandon and Mitchell 1989; Abuel-Naga *et al.* 2008; Lee *et al.* 2010; Manthena and Singh 2001), solar ponds (Velmurugan and Srithar 2008), energy geostructures (Knellwolf *et al.* 2011; Loveridge and Powrie 2013; Salciarini *et al.* 2013; Yavari *et al.* 2014; Di Donna *et al.* 2016; Faizal *et al.* 2016; McCartney *et al.* 2016), which result in conveyance of thermal energy through the soil mass. Moreover, activities like dissociation of gas hydrates by heating (Feng *et al.* 2015; Song *et al.* 2015, 2016) and exploitation of oil sand by steam assisted gravity drainage (SAGD) (Elsayed *et al.* 2015; Lazzaroni *et al.* 2016) and also soil-atmosphere interaction (Heusinkveld *et al.* 2004; Ochsner *et al.* 2007; Cui *et al.* 2013) involve heat migration through soil mass. These applications necessitate studies to understand how heat migrates in the soil mass by means of predicting the 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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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 *et al.* 1992; Han and Huang 2002; Wu and Sun 2004; Wang *et al.* 2011), Force Restore Method (FRM) (Liebethal and Foken 2007; Gao *et al.* 2008). Moreover, different analytical methods like Harmonic Method, Laplace Transform Method, and Fourier Transform Method, have been considered by several researchers (Heusinkveld *et al.* 2004; Gao *et al.* 2007; Evett *et al.* 2012; 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 involve complicated mathematics which is not convenient to the practising engineers. Moreover, 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 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. 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®, 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.

2. Statement of the Problem

This section deals with the details of the problem investigated in the present study, which essentially has been derived from the experiments conducted by Mondal *et al.* (2016). A 20 cm 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 top surface of this column, as depicted in Fig1a. Furthermore, as depicted in Fig1b, the flux sensors, and thermocouples were embedded at 5 cm and 9 cm depths, respectively, in the sample (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 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 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, the steady-state condition could be achieved in it. Hence, the novelty of the present study is that it’s an attempt to establish a simple numerical approach, based on finite difference method (FDM), to identify the correct end boundary conditions, which would facilitate determination of thermal regime for one-dimensional heat conduction in dry sands.

Table 1. Thermal Properties of Sand used in this study

Sand	Dry density (γ_d) (g/cm ³)	Thermal Conductivity (k) (W/°C/m)	Specific Heat (C_p) (J/kg /°C)
SI	1.556	0.315	171

3. The Proposed Methodology

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

$$96 \quad \frac{\partial \theta}{\partial t} = \alpha \frac{\partial^2 \theta}{\partial z^2} \quad (1)$$

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

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

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

105

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:

$$109 \quad \theta_{i+1}^n = \frac{\alpha \Delta t}{(\Delta z)^2} (\theta_i^{n+1} - 2\theta_i^n + \theta_i^{n-1}) + \theta_i^n \quad (3)$$

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.

113

114 3.2 Determination of the End boundary

115 The purpose of this simple numerical method is to analyse the experimental data where the
116 end boundary condition is not defined. As described by Mondal *et al.* (2016) neither the
117 temperature nor the thermal flux was measured at the end boundary while performing the
118 experiment. Hence, it became mandatory to devise a methodology that could be utilized to define
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, ΔL , 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
124 is considered as the end point of the additional depth. As a result, at this end boundary the
125 prevailing temperature could be considered as ambient when numerical simulation is being
126 conducted. The obtained result, for different values of ΔL were compared with the analytical
127 solution of HTE (refer Eq. 4) for establishing the most suitable depth of end boundary.

$$128 \quad \theta(z, t) = (\theta_j - \theta_0) \operatorname{erf}\left(\frac{z}{2\sqrt{\alpha t}}\right) + \theta_0 \quad (4)$$

129 where θ_j and θ_0 are initial and applied temperature respectively.

130

131 3.3 Time dependent boundary condition

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

137 the true experimental conditions, a step thermal loading of $0.4 \text{ }^\circ\text{C/min}$ has been imposed at the
138 second time step of the FDM, until the first node achieves the maximum applied temperature.

139

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
143 depicted in Fig 3. It can be observed from Figs. 3 (a) and (b) that the results obtained from the
144 FDM, for an additional depth (ΔL) of 20 cm, exhibit the best agreement with the results obtained
145 from analytical solution. Based on this finding, the end boundary condition for the FDM was
146 considered as an optimum additional depth of 20 cm when there is no significant improvement for
147 further increment of ΔL . Moreover, the experimental data has been compared vis-à-vis the results
148 obtained from the FDM and COMSOL Multiphysics[®]. It is worth mentioning here that the lateral
149 boundaries of the COMSOL model have been assumed to be ‘adiabatic’ and the bottom boundary
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[®] 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[®] 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[®] simulation and the experiments.
159

160 5. Concluding Remarks

161 Prediction of realistic thermal regime in soil mass by means of mathematical approach enforces
162 challenges to geoenvironmental practitioners. In this context, a simple FDM has been developed
163 to solve one-dimensional HTE equation in order to establish thermal regime in sandy soil mass. A
164 simple mathematical approach has been proposed to define end boundary for the FDM, as in case
165 of the experiment the temperature at the end boundary could not be monitored. It is worth
166 mentioning that the proposed numerical approach can be used for any dry sandy soil to define the
167 end boundary and to determine the thermal regime. Moreover, experimentally obtained thermal
168 regime has been compared vis-à-vis that obtained from the FDM and COMSOL Multiphysics[®]
169 and it has been demonstrated that the FDM results match satisfactorily with experimental results
170 as compared to the COMSOL Multiphysics[®]. Hence, it is believed that the proposed FDM would
171 be an efficient tool to estimate thermal regime in sandy soils. However, the applicability of the
172 proposed model should be checked in clays to enhance its versatility.
173

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180 Electrical Engineering, IIT Bombay.
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182 References

- 183 Abuel-Naga, H. M., Bergado, D. T., and Bouazza, A. (2008). “Thermal conductivity evolution of
184 saturated clay under consolidation process.” *International Journal of Geomechanics*, American
185 Society of Civil Engineers, **8**(2), 114–122.
186 [https://doi.org/10.1061/\(ASCE\)1532-3641\(2008\)8:2\(114\)](https://doi.org/10.1061/(ASCE)1532-3641(2008)8:2(114)).
- 187 Bittelli, M., Ventura, F., Campbell, G. S., Snyder, R. L., Gallegati, F., and Pisa, P. R. (2008).
188 “Coupling of heat, water vapor, and liquid water fluxes to compute evaporation in bare soils.”
189 *Journal of Hydrology*, **362**(3–4), 191–205.
190 <https://doi.org/10.1016/j.jhydrol.2008.08.014>.

191 Brandon, T. L., and Mitchell, J. K. (1989). "Factors Influencing Thermal Resistivity of Sands."
192 *Journal of Geotechnical Engineering*, American Society of Civil Engineers, **115**(12), 1683–
193 1698.
194 [https://doi.org/10.1061/\(ASCE\)0733-9410\(1989\)115:12\(1683\)](https://doi.org/10.1061/(ASCE)0733-9410(1989)115:12(1683)).

195 Cui, Y. J., Ta, A. N., Hemmati, S., Tang, A. M., and Gatmiri, B. (2013). "Experimental and numerical
196 investigation of soil-atmosphere interaction." *Engineering Geology*, **165**, 20–28.
197 <https://doi.org/10.1016/j.enggeo.2012.03.018>.

198 Dao, L. Q., Cui, Y. J., Tang, A. M., Pereira, J. M., Li, X. L., and Sillen, X. (2015). "Impact of
199 excavation damage on the thermo-hydro-mechanical properties of natural Boom Clay."
200 *Engineering Geology*, **195**, 196–205.
201 <https://doi.org/10.1016/j.enggeo.2015.06.011>.

202 Delage, P., Cui, Y. J., and Tang, A. M. (2010). "Clays in radioactive waste disposal." *Journal of Rock
203 Mechanics and Geotechnical Engineering*, **2**(2), 111–123.
204 <https://doi.org/10.3724/SP.J.1235.2010.00111>.

205 Di Donna, A., Ferrari, A., and Laloui, L. (2016). "Experimental investigations of the soil–concrete
206 interface: physical mechanisms, cyclic mobilization, and behaviour at different temperatures."
207 *Canadian Geotechnical Journal*, NRC Research Press, **53**(4), 659–672.
208 <https://doi.org/10.1139/cgj-2015-0294>.

209 Elsayed, N. A., Barrufet, M. A., and El-Halwagi, M. M. (2015). "An integrated approach for
210 incorporating thermal membrane distillation in treating water in heavy oil recovery using
211 SAGD." *Journal of Unconventional Oil and Gas Resources*, **12**, 6–14.
212 <https://doi.org/10.1016/j.juogr.2015.07.002>.

213 Evett, S. R., Agam, N., Kustas, W. P., Colaizzi, P. D., and Schwartz, R. C. (2012). "Soil profile
214 method for soil thermal diffusivity, conductivity and heat flux: Comparison to soil heat flux
215 plates." *Advances in Water Resources*, **50**, 41–54.
216 <https://doi.org/10.1016/j.advwatres.2012.04.012>.

217 Faizal, M., Bouazza, A., and Singh, R. M. (2016). "Heat transfer enhancement of geothermal energy
218 piles." *Renewable and Sustainable Energy Reviews*, **57**, 16–33.
219 <https://doi.org/10.1016/j.rser.2015.12.065>

220 Feng, J.-C., Wang, Y., Li, X.-S., Li, G., and Chen, Z.-Y. (2015). "Production behaviors and heat
221 transfer characteristics of methane hydrate dissociation by depressurization in conjunction with
222 warm water stimulation with dual horizontal wells." *Energy*, **79**, 315–324.
223 <https://doi.org/10.1016/j.energy.2014.11.018>.

224 Gao, Z., Bian, L., Hu, Y., Wang, L., and Fan, J. (2007). "Determination of soil temperature in an arid
225 region." *Journal of Arid Environments*, **71**(2), 157–168.
226 <https://doi.org/10.1016/j.jaridenv.2007.03.012>

227 Gao, Z., Horton, R., Wang, L., Liu, H., and Wen, J. (2008). "An improved force-restore method for
228 soil temperature prediction." *European Journal of Soil Science*, **59**(5), 972–981.
229 <https://doi.org/10.1111/j.1365-2389.2008.01060.x>.

230 Han, H., & Huang, Z. (2002). A class of artificial boundary conditions for heat equation in unbounded
231 domains. *Computers & Mathematics with applications*, **43**(6-7), 889-900.
232 [https://doi.org/10.1016/S0898-1221\(01\)00329-7](https://doi.org/10.1016/S0898-1221(01)00329-7)

233 Heusinkveld, B. ., Jacobs, A. F. ., Holtslag, A. A. ., and Berkowicz, S. . (2004). "Surface energy
234 balance closure in an arid region: role of soil heat flux." *Agricultural and Forest Meteorology*,
235 **122**(1), 21–37.
236 <https://doi.org/10.1016/j.agrformet.2003.09.005>.

237 Kadali, S., Lakeshmi, S. S., Sharma, S., and Singh, D. N. (2013). "Investigations to establish the
238 influence of the thermal energy field on soil properties." *ACTA Geotechnica Solvenica*, **10**(2),
239 59–76.
240 http://fgserver6.fg.um.si/journal-ags/pdfs/AGS_2013-2_article_5.pdf

241 Knellwolf, C., Peron, H., and Laloui, L. (2011). "Geotechnical Analysis of Heat Exchanger Piles."
242 *Journal of Geotechnical and Geoenvironmental Engineering*, American Society of Civil
243 Engineers, **137**(10), 890–902.
244 [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000513](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000513).

245 Krishnaiah, S., and Singh, D. N. (2004). "Centrifuge modelling of heat migration in soils."

246 *International Journal of Physical Modelling in Geotechnics*, **4**(3), 39–47.
247 <https://doi.org/10.1680/ijpmg.2004.040303>.

248 Lazzaroni, E. F., Elsholkami, M., Arbiy, I., Martelli, E., Elkamel, A., and Fowler, M. (2016). “Energy
249 infrastructure modeling for the oil sands industry: Current situation.” *Applied Energy*, **181**, 435–
250 445.
251 <https://doi.org/10.1016/j.apenergy.2016.08.072>

252 Lee, J., Kim, J.-T., Chung, I.-M., and Kim, N. W. (2010). “Analytical solution for heat and moisture
253 diffusion in layered materials.” *Canadian Geotechnical Journal*, **47**(6), 595–608.
254 <https://doi.org/10.1139/T09-125>

255 LeVeque, R. J. (2002). *Finite volume methods for hyperbolic problems*. Cambridge University Press,
256 Cambridge, United Kingdom

257 Liebethal, C., and Foken, T. (2007). “Evaluation of six parameterization approaches for the ground
258 heat flux.” *Theoretical and Applied Climatology*, Springer-Verlag, **88**(1–2), 43–56.
259 <https://doi.org/10.1007/s00704-005-0234-0>

260 Loveridge, F., and Powrie, W. (2013). “Temperature response functions (G-functions) for single pile
261 heat exchangers.” *Energy*, **57**, 554–564.
262 <https://doi.org/10.1016/j.energy.2013.04.060>

263 Mandal, A., Chakravarthy, C. P., Nanda, A., Rath, R., and Usmani, A. (2013). “Analysis and design
264 approach for large storage caverns.” *International Journal of Geomechanics*, American Society
265 of Civil Engineers, **13**(1), 69–75.
266 [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0000180](https://doi.org/10.1061/(ASCE)GM.1943-5622.0000180)

267 Manthana, K., and Singh, D. (2001). “Measuring soil thermal resistivity in a geotechnical centrifuge.”
268 *International Journal of Physical Modelling in Geotechnics*, **1**(4), 29–34.
269 <https://doi.org/10.1680/ijpmg.2001.010403>

270 McCartney, J. S., Sánchez, M., and Tomac, I. (2016). “Energy geotechnics: Advances in subsurface
271 energy recovery, storage, exchange, and waste management.” *Computers and Geotechnics*, **75**,
272 244–256.
273 <https://doi.org/10.1016/j.compgeo.2016.01.002>

274 Mondal, S., Padmakumar, G. P., Sharma, V., Singh, D. N., and Baghini, M. S. (2016). “A
275 methodology to determine thermal conductivity of soils from flux measurement.” *Geomechanics
276 and Geoengineering*, **11**(1), 73–85.
277 <https://doi.org/10.1080/17486025.2015.1020346>

278 Mondal, S., Sharma, V., Singh, D. N., and Baghini, M. S. (2017). “Determination of Thermal Regime
279 in Sandy Soils: Mathematical Framework ATHERES.” *International Journal of Geomechanics*,
280 **17**(9), 4017045.
281 [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0000918](https://doi.org/10.1061/(ASCE)GM.1943-5622.0000918)

282 Mondal, S., Singh, D. N., & Baghini, M. S. (2018). Detection of thermal response of geomaterials: a
283 critical appraisal. *Emerging Materials Research*, **7**(3), 178-191.
284 <https://doi.org/10.1680/jemmr.16.00156>

285 Ochsner, T. E., Sauer, T. J., and Horton, R. (2007). “Soil heat storage measurements in energy
286 balance studies.” *Agronomy Journal*, American Society of Agronomy, **99**(1), 311–319.
287 <https://doi.org/10.2134/agronj2005.0103S>

288 Padmakumar, G. P. (2013). “Laboratory investigations on heat migration through soil mass.” Indian
289 Institute of Technology Bombay, India.

290 Rao, M. V. B. B. G., and Singh, D. N. (1999). “A generalized relationship to estimate thermal
291 resistivity of soils.” *Canadian Geotechnical Journal*, NRC Research Press Ottawa, Canada,
292 **36**(4), 767–773.
293 <https://doi.org/10.1139/t99-037>

294 Salciarini, D., Ronchi, F., Cattoni, E., and Tamagnini, C. (2013). “Thermomechanical effects induced
295 by energy piles operation in a small piled raft.” *International Journal of Geomechanics*,
296 American Society of Civil Engineers, **15**(2), 4014042.
297 [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0000375](https://doi.org/10.1061/(ASCE)GM.1943-5622.0000375)

298 Sharratt, B. S., Campbell, G. S., and Glenn, D. M. (1992). “Soil heat flux estimation based on the
299 finite-difference form of the transient heat flow equation.” *Agricultural and Forest Meteorology*,
300 Elsevier, **61**(1), 95–111.

301 [https://doi.org/10.1016/0168-1923\(92\)90027-2](https://doi.org/10.1016/0168-1923(92)90027-2)
302 Song, Y., Cheng, C., Zhao, J., Zhu, Z., Liu, W., Yang, M., and Xue, K. (2015). "Evaluation of gas
303 production from methane hydrates using depressurization, thermal stimulation and combined
304 methods." *Applied Energy*, **145**, 265–277.
305 <https://doi.org/10.1016/j.apenergy.2015.02.040>
306 Song, Y., Wang, J., Liu, Y., and Zhao, J. (2016). "Analysis of heat transfer influences on gas
307 production from methane hydrates using a combined method." *International Journal of Heat
308 and Mass Transfer*, **92**, 766–773.
309 <https://doi.org/10.1016/j.ijheatmasstransfer.2015.08.102>
310 Timlin, D. J., Pachevsky, Y., Acock, B. A., Šimunek, J., Flerchinger, G., and Whisler, F. (2002).
311 "Error analysis of soil temperature simulations using measured and estimated hourly weather
312 data with 2DSOIL." *Agricultural Systems*, **72**(3), 215–239.
313 [https://doi.org/10.1016/S0308-521X\(01\)00075-0](https://doi.org/10.1016/S0308-521X(01)00075-0)
314 Usmani, A., Kannan, G., Nanda, A., and Jain, S. K. (2015). "Seepage behavior and grouting effects
315 for large rock caverns." *International Journal of Geomechanics*, American Society of Civil
316 Engineers, **15**(3), 6014023.
317 [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0000449](https://doi.org/10.1061/(ASCE)GM.1943-5622.0000449)
318 Velmurugan, V., and Srithar, K. (2008). "Prospects and scopes of solar pond: A detailed review." *Renewable and Sustainable Energy Reviews*, **12**(8), 2253–2263.
319 <https://doi.org/10.1016/j.rser.2007.03.011>
320 Wang, L., Gao, Z., Horton, R., Lenschow, D. H., Meng, K., and Jaynes, D. B. (2012). "An analytical
321 solution to the one-dimensional heat conduction–convection equation in soil." *Soil Science
322 Society of America Journal*, The Soil Science Society of America, Inc., **76**(6), 1978–1986.
323 <https://doi.org/10.2136/sssaj2012.0023N>
324 Wang, Z.-H., Bou-Zeid, E., and Smith, J. A. (2011). "A Spatially-Analytical Scheme for Surface
325 Temperatures and Conductive Heat Fluxes in Urban Canopy Models." *Boundary-Layer
326 Meteorology*, Springer Netherlands, **138**(2), 171–193.
327 <https://doi.org/10.1007%2Fs10546-010-9552-6>
328 Wu, X., & Sun, Z. Z. (2004). Convergence of difference scheme for heat equation in unbounded
329 domains using artificial boundary conditions. *Applied Numerical Mathematics*, **50**(2), 261–277.
330 <https://doi.org/10.1016/j.apnum.2004.01.001>
331 Yavari, N., Tang, A. M., Pereira, J.-M., and Hassen, G. (2014). "A simple method for numerical
332 modelling of mechanical behaviour of an energy pile." *Géotechnique Letters*, **4**(2), 119–124.
333 <https://doi.org/10.1680/geolett.13.00053>
334

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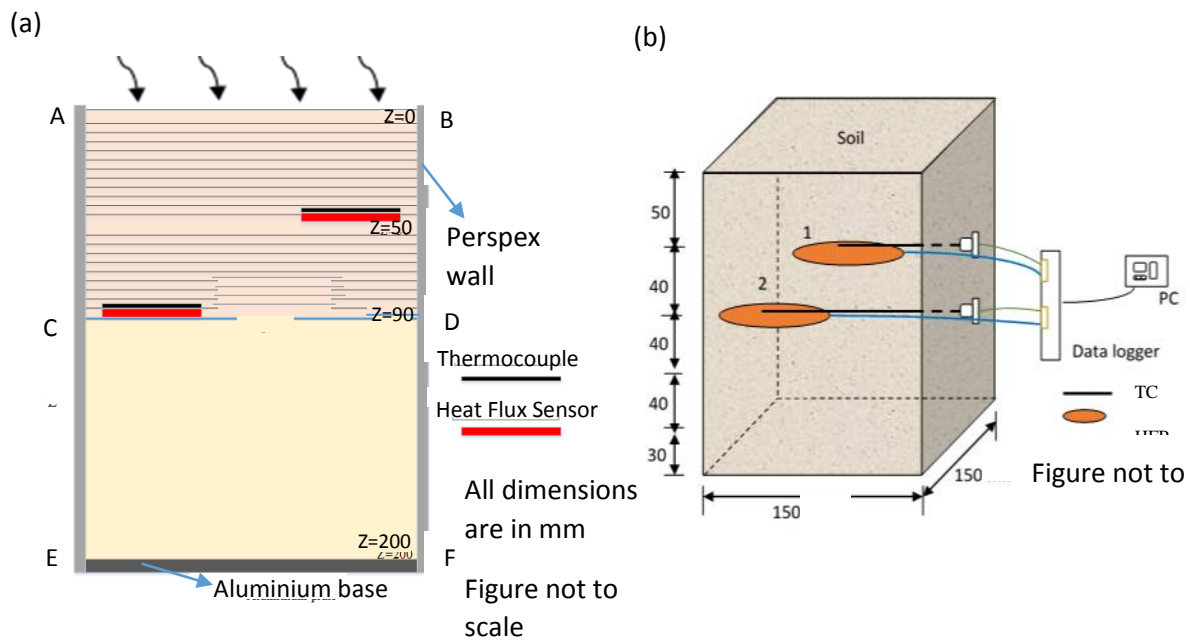
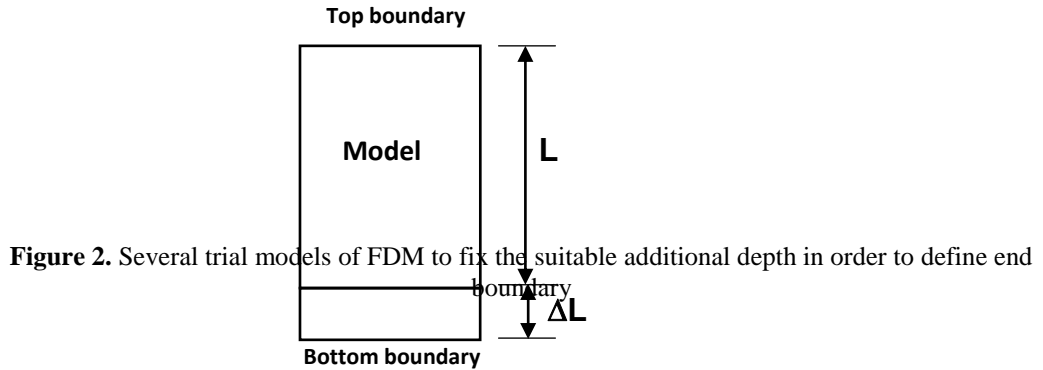


Figure 1. (a) The schematic diagram of experiment setup (b) The arrangement of heat thermocouples



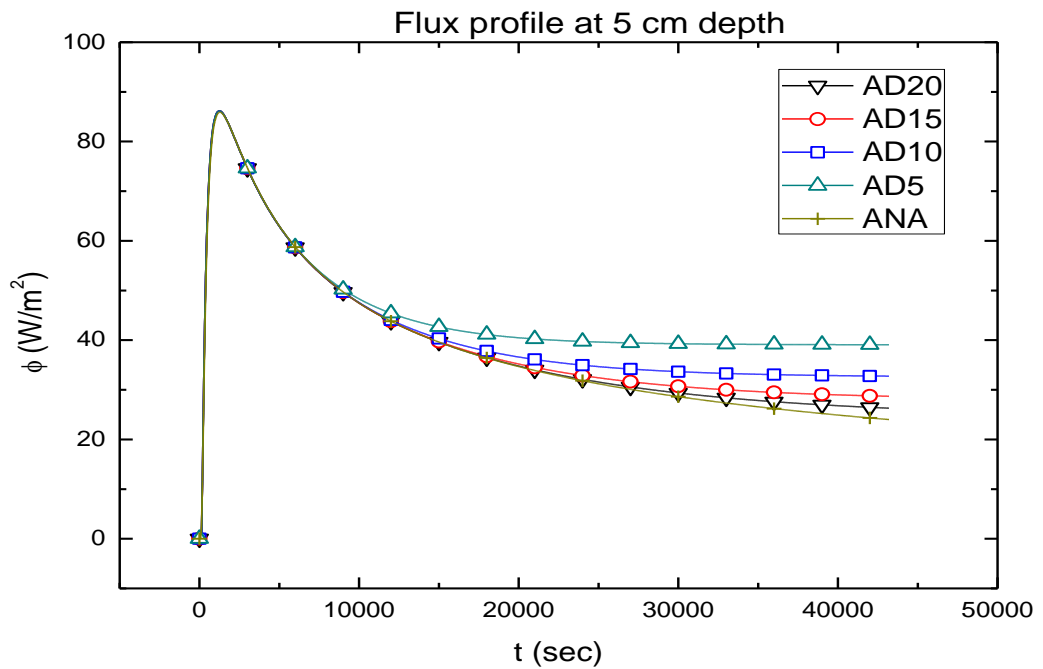
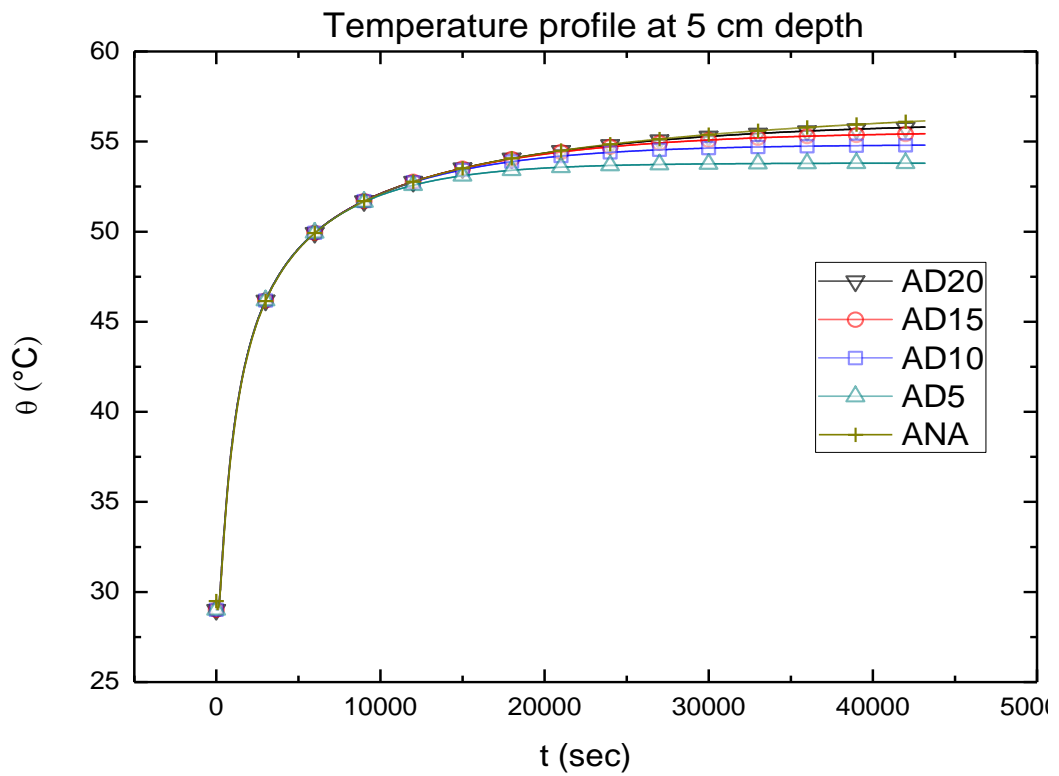


Figure 3(a). Thermal regime obtained at 5 cm depth for different additional depths in FDM and analytical model, for applied temp 60°C, soil SI

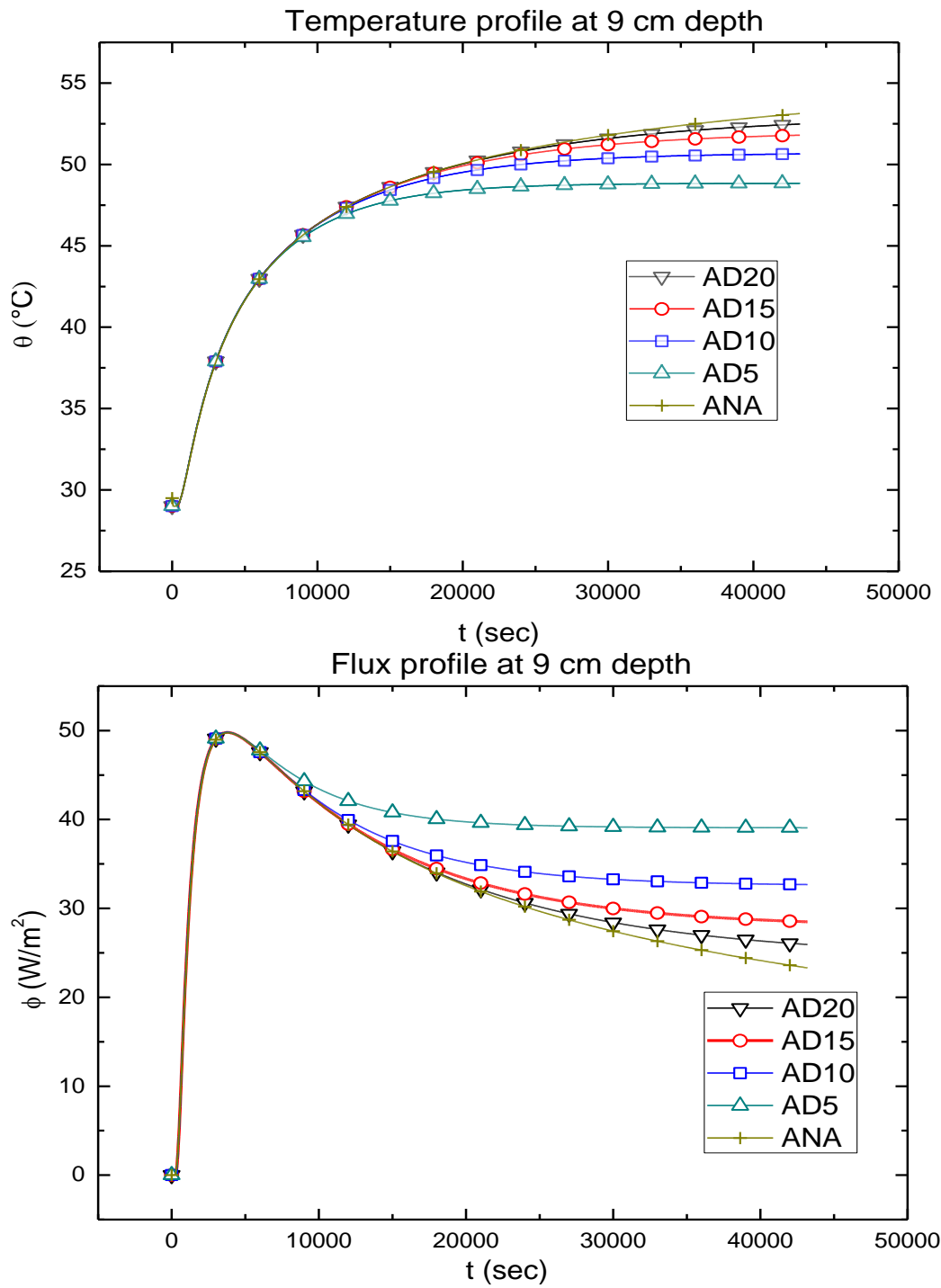


Figure 3(b). Thermal regime obtained at 9 cm depth for different additional depths in FDM and analytical model, for applied temp 60°C, soil SI

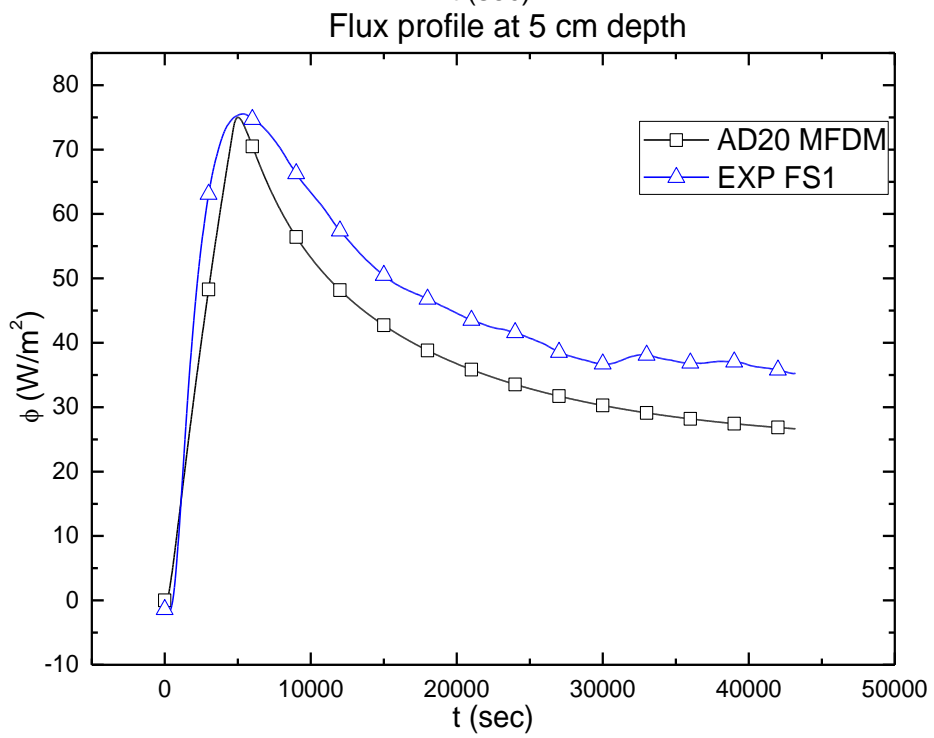
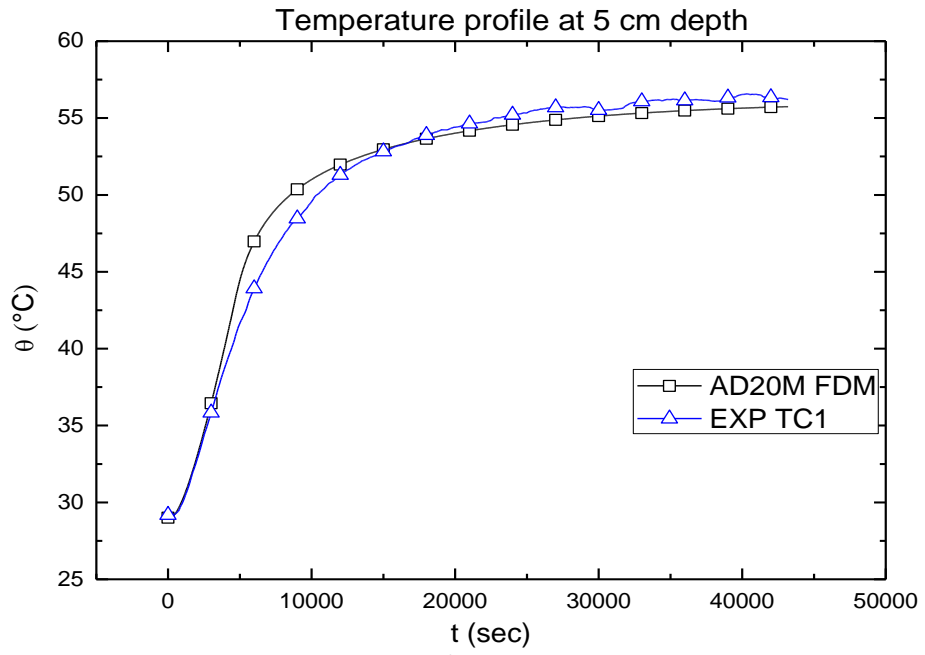


Figure 4(a). Thermal regime obtained at 5 cm depth in FDM and experiment, for an applied temp 60°C in step, soil SI

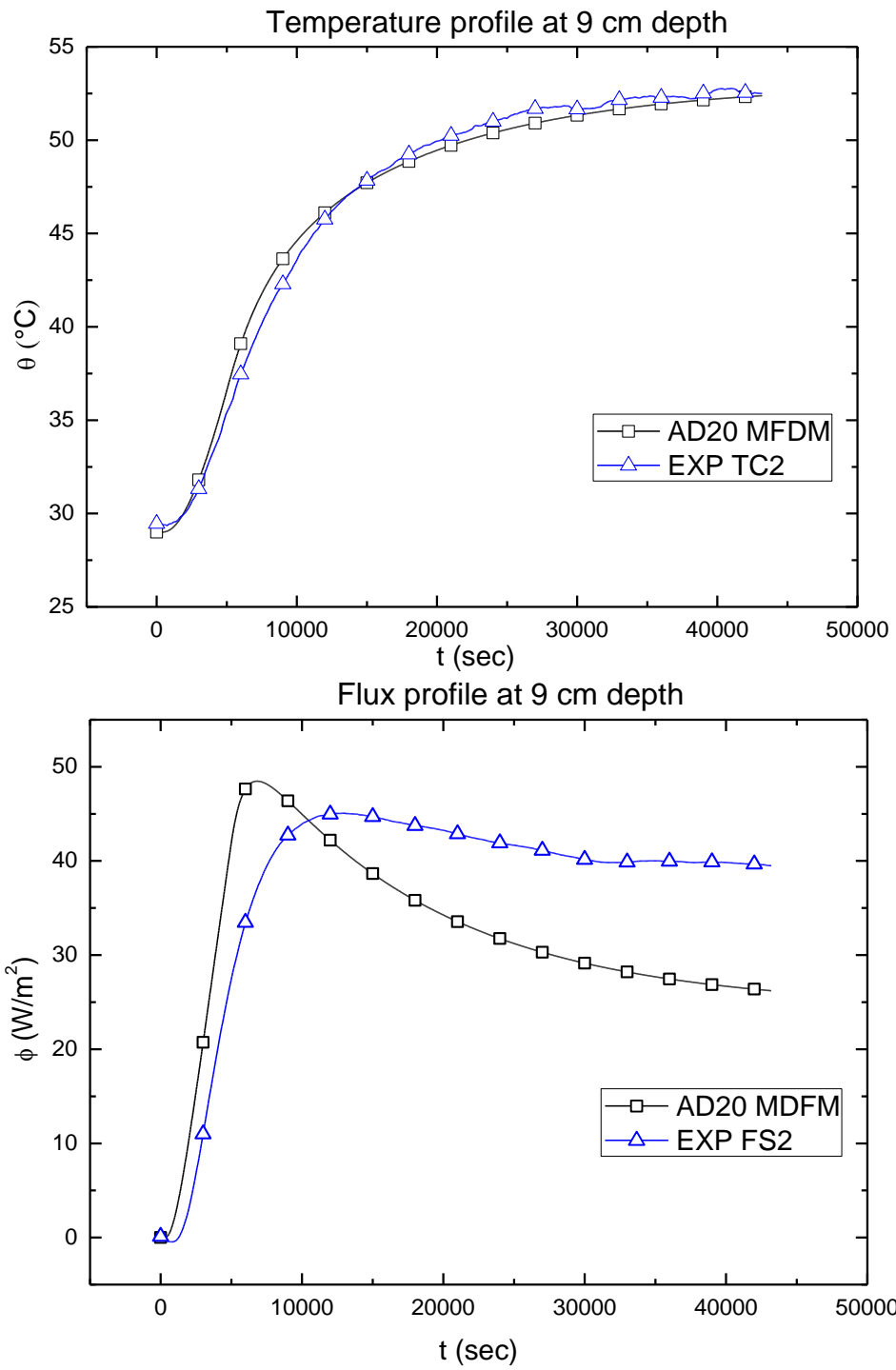


Figure 4(b). Thermal regime obtained at 9 cm depth in FDM and experiment, for an applied temp 60°C in step, soil SI

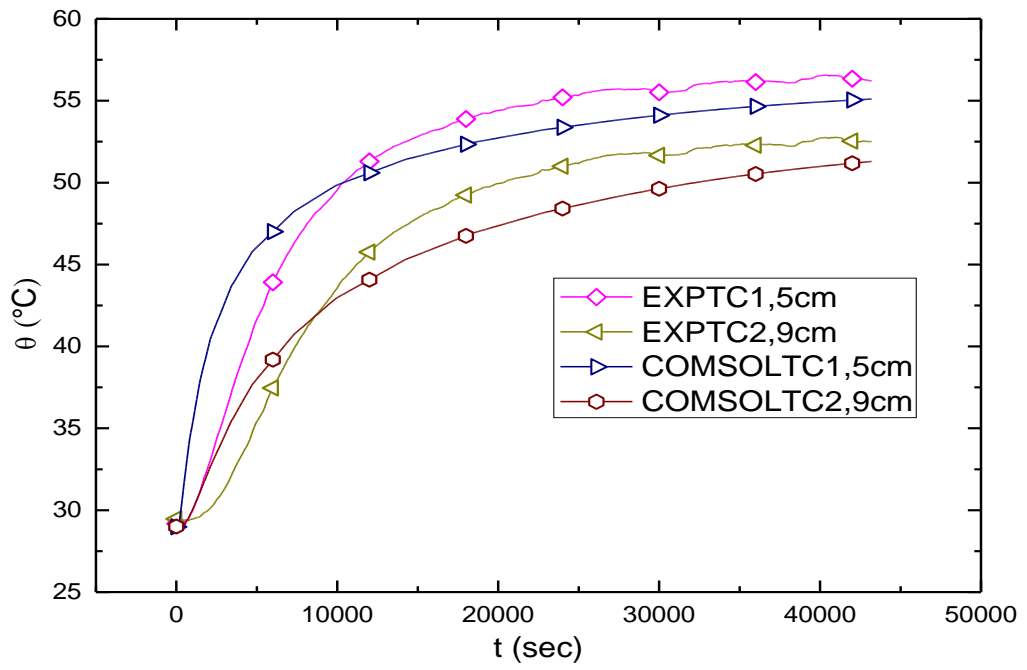


Figure 5. Temperature profile obtained at 5 and 9 cm depth from experiment and COMSOL Multiphysics®, for an applied temp 60°C in step, soil SI

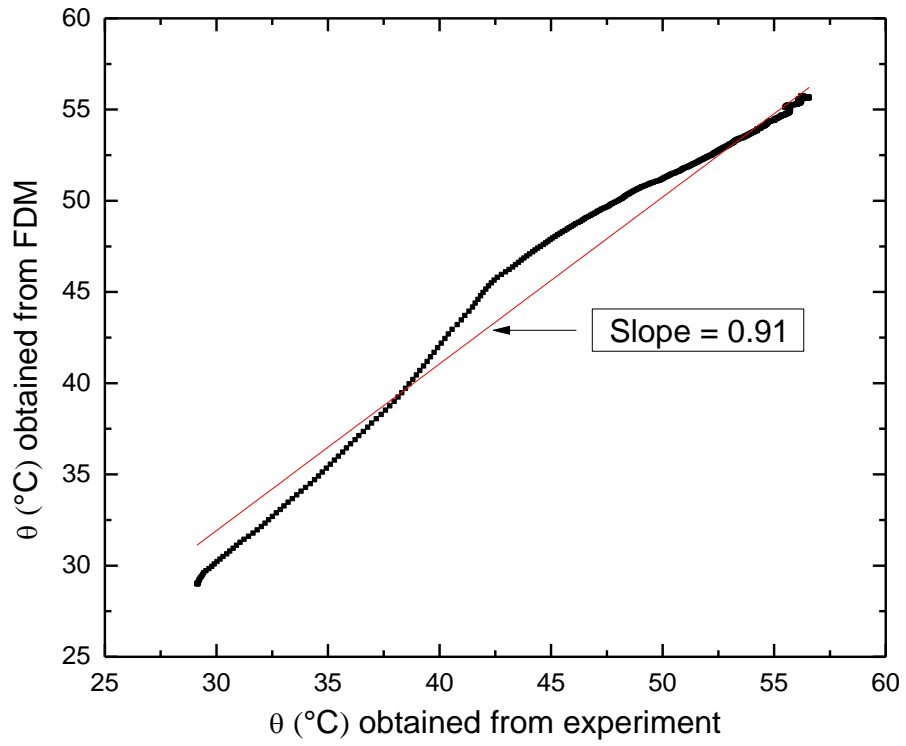


Figure 6. Comparison of the temperature values at 5 cm depth obtained from the FDM and experiment

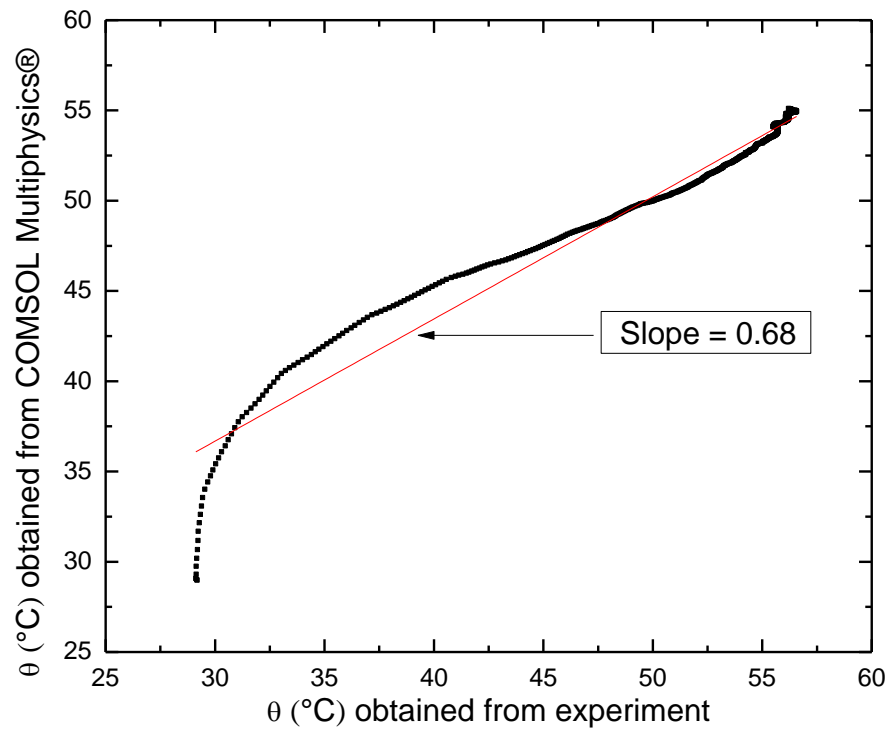


Figure 7. Comparison of the temperature values obtained at 5 cm depth from the COMSOL Multiphysics® and experiment