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COMPUTATIONAL AND THEORETICAL ESTIMATION OF NEAR-SURFACE GROUND TEMPERATURE PROFILE AT VARIOUS SOIL DIFFUSIVITIES FOR MANAGEMENT OF HYDROTHERMAL SYSTEMS

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Abstract

Validated data of near-surface soil temperature profiles are crucial for effectively managing thermal systems. The problem is that the available analytical models exhibit discrepancies in ground temperature estimates compared to site measurements, due to their sensitivity to soil thermal diffusivity. The objective of the current investigation is to estimate, analyse, and compare the near-surface temperature profile at various soil thermal diffusivities. The near-surface soil temperature estimation methods are computational, using ALTAIR software and three well-established analytical models. The near-surface domain is a cylindrical configuration with a depth of 3.5 m and a diameter of 2.0 m. The research variables considered in the analysis are soil properties, four different thermal diffusivities of 0.04, 0.06, 0.08, and 0.10 m2/day, mean daily ambient temperature, and solar irradiation. The ground temperatures have been predicted at 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 m depths. The computational results of the thermal profile are in good agreement with the analytical results. However, the empirical and simulation results have shown a reduced influence of the thermal diffusivity as going deeper into the ground. The results generated provide useful data to researchers and engineers in underground installations such as gas pipes, water piping networks, underground cabling, and in-ground energy storage.

Keywords: Ground thermal profile, Near-surface soil, Soil temperature, Soil diffusivity, Thermal management.

1. Introduction

The near-surface soil temperature profile is crucial for many engineering applications. Precise thermal profiling of the near-surface soil is important for the proper design, operation, and sizing of Ground Heat Exchangers (GHEs) to ensure efficient heat exchange. Water-Earth heat exchangers are widely used to manage the thermal status of solar photovoltaic modules [1-3]. Earth-to-Air Heat Exchangers (EAHEs) have wide applications across construction and industry. They could be used to support building cooling in tropical areas, reducing energy consumption. Moreover, they could be utilized for pre-heating and pre-cooling of air for industrial processes. Koshlak [4] performed a comprehensive review, from fundamental principles to the application of energy systems. They concluded that EAHEs rely on soil temperature profiles for effective heat transfer. A recent overview of EAHEs and the main parameters affecting their performance, cost, and environmental impact is summarized in the chapter of [5]. They concluded that the most used passive EAHEs comprise solar chimneys or wind towers, allowing the natural circulation of air. Additionally, the capital cost of the EAHE systems can be reduced by integration into the building foundation. Compared with traditional air-conditioning systems, EAHEs have shown significant ecological benefits during operation, while their negative impacts are mostly associated with the manufacturing and recycling processes.

By taking advantage of the relatively constant subsurface temperature, EAHEs offer an efficient and sustainable method for heating and cooling buildings. In the building sector, EAHEs have wide applications in residential and commercial buildings. From single-family homes to large-scale commercial complexes, EAHEs contribute to improved thermal comfort and reduced energy consumption. Their applications are diverse and include ventilation [6-8], space heating and cooling [9-11], process cooling [12], and agricultural greenhouses environmental control [13].

Moreover, good prediction of soil temperature distribution is essential for designing and optimizing ground energy storage facilities. There is a new R&D trend in hydrogen ground storage, where the soil temperature plays a big role in the design and safety of storage systems [14]. Bradshaw [14], an Edinburgh-based company, revealed its plan to construct 3 energies in 1 ground shaft, where the surrounding temperature of the soil plays a considerable role in managing the storage of electric energy, thermal energy, and hydrogen. Near-surface ground temperature is referred to as shallow ground thermal profiling in some publications. The estimation of the near-surface ground temperature could be achieved by experimental measurements, numerical simulations, and theoretical methods.

Experimental measurements are used and reported by many researchers. Al-Hinti et al. [15] developed, through experimental measurements, a daily, seasonal, and annual ground temperature distribution profile for Zarqa city, Jordan. The ground temperature profiles are presented for various depths. Another experimental measurement has been reported by Abdel-Ghany et al. [16], performed for the agriculture engineering department, King Saud University. The selected location of the measurements is in Riyadh, Saudi Arabia. They measured the annual temperature profile of the ground up to 3.5 m depth. They recommended an analytical equation to be adopted to simulate the ground temperature for a depth of more than 3.0 m. The reason is the difficulty of digging deeper into the ground. Eight thermocouples have been fixed in a PVC pipe wall at levels of 0.1, 0.5, 0.9, 1.3, 1.7, 2.1, 2.5, and 3.0 m below the ground surface. Serageldin et al. [17] have experimentally produced the ground temperature profile with depth, in a site located at the Egypt Japan University of Science and Technology, Alexandria, Egypt. The experimental measurements were performed during March 2015. They also suggested an analytical model to estimate the ground temperature profile. Greene et al. [18] reported the experimental measurement results in the Irish maritime climate in 2007 during the cold winter and spring seasons. The experiment investigated a ground source heat pump to utilize ground heat using a horizontal air heat exchanger buried at 1.0 m depth. A temperature profile was developed to a depth of 1.8 m by measuring the soil temperature at seven different vertical points in the ground.

Numerical simulation and analysis are used in the prediction of the soil temperature in a wide range of research related to embedded GHEs, heat exchange with air or water, and energy storage. [1, 3] estimated the near-surface temperature profiling, up to 1.5 m depth, utilizing ANSYS to investigate embedded GHE integrated with PV/T systems under Malaysian weather conditions. Wahhab and Jassim [2] performed shallow ground thermal analysis by ANSYS software to support the adoption of PV/T in southern Iraq, up to 1.5 m depth. Naranjo-Mendoza et al. [19] performed analytical and numerical predictions of shallow soil temperature profiles and compared the results with experimental measurements in Leicester, UK, up to 2.75 m depth. They concluded that it is useless to predict the long-term variation at depths greater than 1 meter, as high uncertainty exists. Also, they advised using the near-surface air temperature as the boundary condition for the numerical simulation.

Theoretical methods have been used to estimate the near-surface ground temperature. Three well-proven models are widely used in the estimation of ground temperature projects and research [1-3, 16, 20]. The first and early model was proposed by Kusuda and Achenbach [21], which was used and explained further by Khalajzadeh et al. [22] in 2011. The second was proposed by Badache et al. [23] in 2015, and the newest model was proposed by Larwa [24] in 2018. All three models estimate the produced thermal profile of the ground, in terms of temperature versus depth, at various times of the day, month, and year, depending on the data input of the solar irradiation, surface temperature, and ambient temperature. However, in almost every related work on ground temperature profiling, the theoretical results are not adopted far away from further estimation methods, experimental, and/or numerical. The reason is the sensitivity of the models to the soil properties and the discrepancy between their temperature predictions.

Literature confirms that the adoption of one estimation method of near-surface soil temperature is not appropriate. Almost all the literature demonstrates that more than one estimation method should be used for the proper thermal design of applications related to underground heat exchange. The existing theoretical models have different sensitivities to the thermal diffusivity of the soil, which differs from one location to another. The objective of the current work is to investigate the influence of the soil thermal diffusivity on the near-surface thermal profiling by three theoretical models and a developed numerical model. Four different soil diffusivities have been considered in both numerical and theoretical methods.

The novelty and significance of the work are that attempts to solve and compare the performance of the existing model are made for the first time. The previous reviews have compared the models, but not by solving them using the same input data. The previous comparisons are based on different applications of the models. In this work, we used lab-measured soil properties and real weather data in Malaysia. Hence, the comparison is very accurate, and the determination of the models' performances is more logic. Furthermore, this work represents the first time a CFD simulation of the ground thermal profiling has been conducted using ALTAIR simulation software.

2. Methodology

The methods used to investigate near-surface soil temperature include mathematical and numerical approaches. The mathematical estimation of the near-surface soil temperature is achieved by coding the three available and widely used methods in earlier research. The development of computational simulation achieves numerical estimation. The input data and variables are mainly based on weather data of Ipoh city in Malaysia. However, in alignment with the research objective, the focus is on the thermal diffusivity influence on the thermal profiling.

2.1. Research variables and materials properties

The thermal profile was predicted using the same soil properties and weather conditions, whether by analytical models or computational simulation. In the current investigations, Ipoh meteorological data of the year 2021 have been used to predict the temperature distribution in the Malaysian ground. Weathers Park tools located at Sultan Azlan Shah Airport, Ipoh, Malaysia, were used to provide statistical analysis of ambient temperature. The daily ambient average temperature over the year is shown in Fig. 1. The annual mean daily temperature is 27 °C. The mean minimum and mean maximum of hourly readings are 26 °C and 33 °C, respectively.

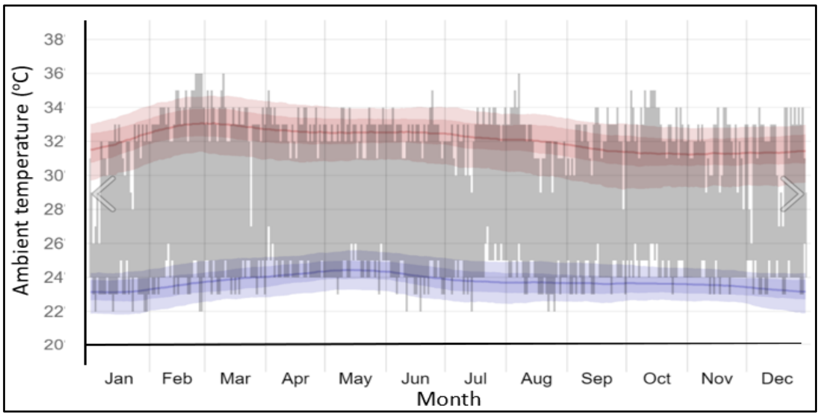

Fig. 1. Ambient temperature recorded by Weathers Park weather tools located at Sultan Azlan Shah Airport, Ipoh city in Malaysia, for the year 2021.

The input soil properties to solve the models and to perform the simulation are adopted from laboratory measurements of five samples of dry soil in the solar research site in UTP, Malaysia. The soil samples were collected from different depths up to 1.0 m below the surface. The thermophysical properties are the mean measurement results of the five samples of soil. The thermal conductivity is 1.0 W/m·K; the specific heat capacity is 800 J/kg·K, and the density is 1,500 kg/m^3. The other correlation variables needed to solve the models are listed in Table 1.

Table 1. The required variables and parameters for the analytical models' solutions.

Month	Monthly Average Ambient temperature (°C)	Amplitude of surface temperature variation (°C)	Time elapsed from the beginning of the calendar year (day)	Phase constant since the beginning of the year, of the lowest average ground surface temperature (day)
Jan	27	4.5	15	15
Feb	27	4.5	45	15
Mac	27	4.5	75	15
Apr	27	4.5	105	15
May	28	4.5	135	15
Jun	28	4.5	165	15
July	27	4.5	195	15
Aug	27	4.5	225	15
Sep	27	4.5	255	15
Oct	27	4.5	285	15
Nov	26	4.5	315	15
Dec	26	4.5	345	15

2.2. Analytical approach

Three models have been utilized to solve the temperature distribution as a function of depth and time. To establish a good understanding of the three models, it is important to describe the thermal balance within the ground and upper surface thermal zone. Figure 2 shows the criteria for heat transfer and thermal energy balance.

Heat conduction is the primary mode of heat transport in the Earth, which is unsteady, one-dimensional, in the z-direction. The governing equation of heat conduction is the simple 1D, unsteady conduction heat transfer, Eq. (1).

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

where: T_g = ground temperature in Kelvin; α = soil thermal diffusivity in m^2/s, m^2/day, and m^2/month, for instantaneous, daily, and monthly, respectively, for prediction of T_g; z = depth of ground below the surface (m); and t = time (s).

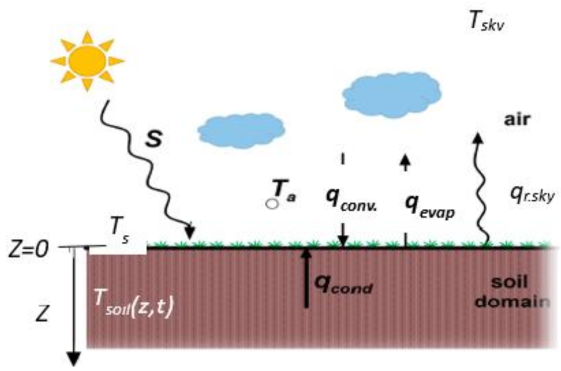

Fig. 2. Thermal balance of a near-surface ground domain.

The solution of the equation requires appropriate boundary conditions that could be derived from the heat balance shown in Fig. 2. Variable heat fluxes occur on the upper surface of the ground on a regular basis. The annual and daily cycles of these flows are equally varied. Based on the assumed surface boundary conditions, three models have been developed as follows.

Model-I is introduced by Kusuda and Achenbach 1965 [21]. The ground is assumed to be a semi-infinite medium with constant physical properties. The variation of the surface temperature over time is annual sinusoidal, Eq. (2). The term $T_{g\infty}$ is the deep ground temperature, which is defined from measurements or previous geological tests. Model-I is also named the sinusoidal, where $A_{g.s}$ is the annual amplitude of the surface temperature. Model I has been generated by solving Eq. (1) under the following boundary and initial conditions. $T(\infty,t) = T_{g.\infty}$ = constant obtained from geological tests

$$T(0,t) = \bar{T}_{g\infty} + A_{g.s} \times \cos\left(\frac{2\pi}{365}(t - t_o)\right) \quad (2)$$

$$T(z,0) = To \quad (3)$$

The solution of Eq. (1) led to Model-1, as shown in Eq. (4)

$$T_g(z,t) = \bar{T}_{g\infty} + A_{g.s} \times \exp\left(-z\sqrt{\frac{\pi}{365\alpha}}\right) \times \cos\left(\frac{2\pi}{365}\left(t - t_o - \frac{z}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right) \quad (4)$$

where: t is the Julian day number in the year (1, 2, 3, … 365), A_s is the amplitude of soil surface temperature [(max-min)/2] in ºC, t_o is the Julian day with the lowest surface temperature in the year,

The model is successful in predicting the near-surface thermal profile daily. Model-II was developed by Badache et al. [23] in 2016. The inputs of parameters are based on the meteorological data. This model is less affected by the inaccuracy of input factor estimation. The energy balance equation is used as a boundary condition at the ground surface to determine the amplitude and the phase angle of the temperature at this location, while the annual average ground surface temperature is calculated using an empirical correlation. Unlike previous energy balance models, which assume periodic variations in solar radiation and ambient air temperature, this model assumes periodic variations in sky temperature.

$$T(z,0) = \bar{T}_s \quad (5)$$

$$T(0,t) = \bar{T}_s - A_s.\cos(\omega t - \emptyset_s) \quad (6)$$

$$T(\infty,t) = \bar{T}_s \quad (7)$$

where Φ_s is the phase angle in radians and corresponds to the time of the year in which the surface soil temperature is minimal.

Solution of Eq. (2) using the above boundary and initial conditions leads to Model-II, Eq. (8)

$$T(z,t) = \bar{T}_s - A_s \times exp^{\frac{-z}{\delta}} \times \cos(\omega t - \emptyset_s - \frac{z}{\delta}) \quad (8)$$

where $\boldsymbol{\delta} = \sqrt{\frac{2a}{\omega}}$ (m), $\boldsymbol{\omega} = \frac{2\pi}{t}$ (time^{-1}), and Φ_s = phase angle (rad) corresponds to the time of the year in which the surface soil temperature is minimal.

Model-III was developed by Larwa [24] in 2019. The ground is treated as a plate with a finite thickness. Variable heat fluxes occur on the surface of the ground, both in the annual and daily cycles. He hypothesized that the daily cyclic change of the ground temperature is limited to 1.0 m depth, and almost stabilizes in soil depth lower than 1.0 m. The boundary condition on the surface of the ground is given by:

$$BC1 \ldots\ldots at\ z = 0, t: \ q_{cond} = S + q_{conv} - (q_{r.sky} + q_{evap}) \quad (9)$$

where: q_{cond} = flow of conductible heat (W/m^2), q_{conv} = flow of convective heat (W/m^2) from air to ground, S = solar flux heat radiation (W/m^2), $q_{r.sky}$ = heat flow from long-wave radiation (W/m^2); q_{evap} = flow of evaporative heat from the surface to ambient (W/m^2).

Larwa [24] assumed that the deep geothermal flux is stable and has a negligible impact on the near-surface temperature profile and is not considered in this model development. Therefore, the second boundary condition is as follows:

$$BC2: at\ z = z(\infty,t),\ {\partial T_g}/{\partial z} = 0 \quad (10)$$

Larwa [24] assumed that the undisturbed ground temperature is the same as the average surface temperature. Hence, BC3: $T(z,0) = T_{s.m}$

The daily average temperature of the near-surface soil temperature is

$$T(z,t) = T_{s.m} - A_s \times \exp(-\frac{z}{L}) \times \cos(\omega t - P_s - \frac{z}{L}) \quad (11)$$

The variables in the correlations mentioned above are: $T_{s.m}$ = annual mean ground surface temperature (°C), A_s = amplitude of the ground surface's daily average temperature (K), P_s = solar phase angle (rad), L = damping depth (m) defined as:

$$L = \sqrt{\frac{2a}{\omega}} \quad (12)$$

where ω is the regularity of temperature swings. The frequency for occurrences that take place on an annual cycle is 2π/365 (days^{-1}).

2.3. Numerical approach

CFD is a powerful tool for thermal analysis. It has been adopted in current investigations, and the ground thermal profile is predicted using the ALTAIR commercial computer simulation tool.

2.3.1. Computational model and boundary conditions

The computational model was developed using CAD tools. The developed model in CAD, shown in Fig. 3, is a cylinder with a 2.0 m diameter and 3.5 m depth.

This model was then exported to ALTAIR software. In ALTAIR software, only half of the cylinder is considered as the computational domain, utilizing the asymmetrical feature to reduce the computational time and size. The 3D model is exported to ALTAIRE and meshed. The material is set as soil with the parameters of thermal conductivity, heat transfer coefficient, density, and specific heat capacity of the soil, specifically in Malaysia, as displayed in section 2.1. It is implemented by applying the annual mean daily temperature of 27 °C, obtained from the analysis of Weathers Park at Sultan Azlan Shah Airport, Ipoh city, Malaysia, shown in Fig. 1, for the year 2021. Symmetry was utilized to reduce the computational size and time, as only half of the cylinder was considered. The airport utilizes several meteorological instruments to provide real-time data. Anemometers, used to measure wind speed and direction, are located at 210 and 270 m. Barometers: A measure of atmospheric pressure was achieved using Barometers (QNH), while hygrometers and thermometers are used for humidity and ambient air temperature measurements.

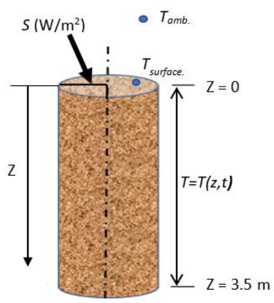

Fig. 3. Computational model.

The simulation has been performed using January data, where the annual mean daily ambient temperature is 27 ºC. The thermophysical properties are those obtained from the laboratory measurement, as discussed in the next section, including the thermal conductivity, specific heat capacity, and density of 1.0 W/m·K, 800 J/kg·K, and 1,500 kg/m^3, respectively.

2.3.2. Mesh generation and independence check.

The computational model shown in Fig. 3 is meshed, as shown in Fig. 4, using finite element discretization. The computational domain has been meshed by subdividing the domain into layers in the depth, *z* direction, as shown in Figs. 4(a) and 4(b). Each layer is meshed to unstructured elements, as shown in Fig. 4c. The feature of Hex Meshing provides an adequate 3D model description of the solid domain in ALTAIR. It creates and edits meshes composed of hexahedral (cube-like or brick-shaped) elements, which are known for providing high accuracy.

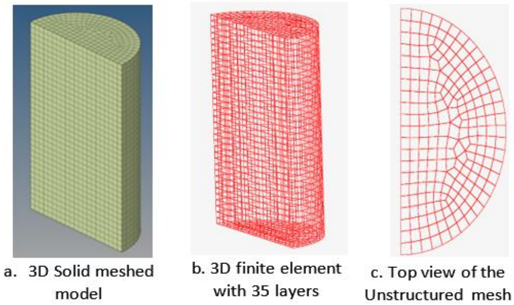

Fig. 4. The grid generation of the computational model.

The number of layers in the depth direction has been varied to check the dependency of the simulation results on the mesh size. Three simulations have been run with three different mesh sizes: 35, 50, and 75 layers, corresponding to 413,445, 895,750, and 25,68,450, respectively. The predicted temperatures by the three mesh sizes simulations are presented in Fig. 5.

At the maximum depth of 3.5 m, the predicted temperatures are 22.2, 22.2, and 22.2 ºC for meshes with layers of 35, 50 and 75, respectively. The mean absolute percentage of temperature differences are 2.84%, 2.9%, and 2.9% for the cases for 35, 50 and 75 layers, respectively. The lowest error in the case of 35 layers, with 413,445 elements, is sufficient to perform the other simulations and produce results for various soil thermal diffusivities. However, Table 2 summarizes the mesh independency check.

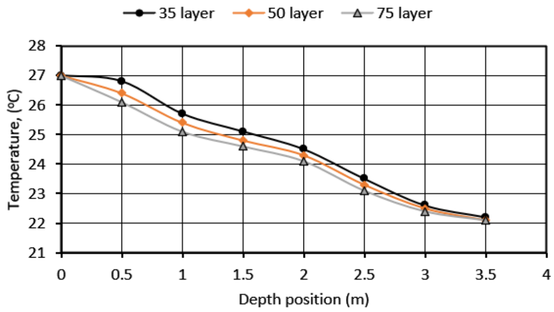

Fig. 5. Results of mesh size simulations for independency checking.

Table 2. The mesh independency checking conditions and results.

Number of layers	No. of elements	No. of nodes	Soil temp. at 3.5 m depth	Mean % of error
35	413,445	978456	22.2	2.84
50	895,750	1789453	22.1	2.90
75	2,568,450	2988754	22.1	2.90

3. Results and Discussion

3.1. Analytical results and analysis

The three models have been solved, and the produced results for soil sensitivities of 0.04, 0.06, 0.08, and 0.1 m^2/day are presented in Figs. 6(a) to 6(d), respectively.

The result from Model-II, developed by Badache et al. [23], is the most subtle compared to the other two correlations' results, but it continues to justify comparisons. Comparing Malaysia's situation with the other two, they are quite similar. Model-I by Kusuda and Acheubach [21] and Model-II by Larwa [24] show similar, closer results for each depth. The temperature difference between Model-I and Model-II at the ground surface for January, with thermal diffusivities of 0.04 m^2/day, is only 0.147 °C. However, the temperature disparities decreased as depth increased to 3.5 m. The temperature variation for these two relationships appears to be the most dependable and constant among the data. Thus, the underground thermal stability with a mean temperature less than the ambient temperature is required to implement GHE for cooling purposes. Additionally, the study's pattern of temperature change can deliver a sufficient, consistent cooling capacity.

The problem in Model-I is that the model could accurately estimate the ground temperature profile up to 2.0 m depth. Also, it is quite good to establish the daily and annual shallow ground temperature, but not able to estimate the sub-daily temperature profile.

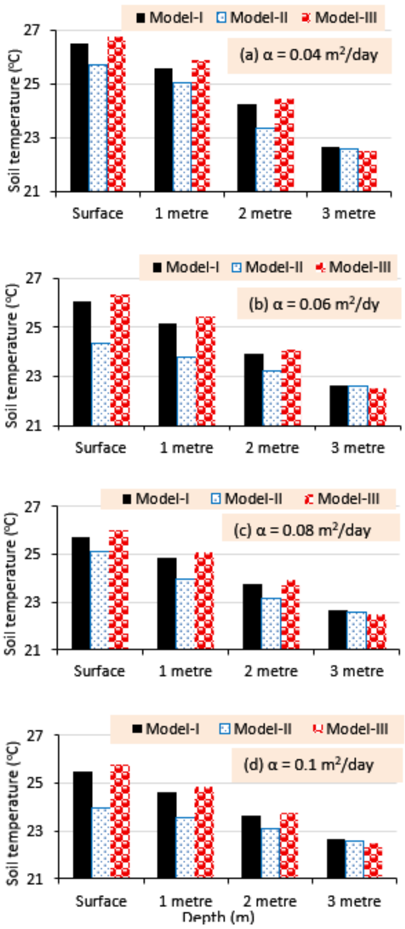

Fig. 6. Comparison of three correlations at various thermal diffusivities with weather data in June 2021. (a) 0.04 m^2/day, (b) 0.06 m^2/day, (c) 0.08 m^2/day, and (d) 0.10 m^2/day.

3.2. Computational simulation results

3.2.1. Validation of the computational procedure

The computational procedure results have been subjected to a sensitivity test before presenting and discussing the computational thermal profiling results. Four cases have been selected for validation of the computational procedure, with parameter values shown in Table 2. Then, the achieved results have been compared to the analytical results gained by Model-I. The variables and correlation constants are for January.

The validation has been achieved by comparing the predicted ground temperatures at 1.0 and 3.0 m depth by simulation and by mode-1. The selected parameter to produce the validation is given in Table 3.

Table 3. The prediction and simulation values of the validation parameters.

Validation case	Soil thermophysical properties				Ground depth (m)
	Density (kg/m^3)	Thermal conductivity (W/m·K)	Specific heat capacity (J/kg·K)	Diffusivity (m^2/day)	
Case 1	1500	1.0	800	0.04	1.0
Case 2				0.04	3.0
Case 3				0.1	1.0
Case 4				0.1	3.0

First, the comparison was performed with 0.04 m^2/day soil diffusivity, and second, the comparison with 0.1 m^2/day soil diffusivity, as shown in Figs. 7(a) and 6(b), respectively. The discrepancy between the analytical, Model-I, and the simulation-predicted temperatures with low thermal diffusivity, of 0.04 m^2/day, is close, with a mean relative percentage of error of 1.5%. By prediction with 0.1 m^2/day thermal diffusivity, the mean relative percentage of error increases to 4.65%. This indicates that the value of the soil thermal diffusivity is an effective factor in the precise prediction of the near-surface soil thermal profile. However, in terms of validation, the mean relative percentage of error has not exceeded 5%, indicating proper numerical procedure and validated results of the near-surface thermal profile simulation.

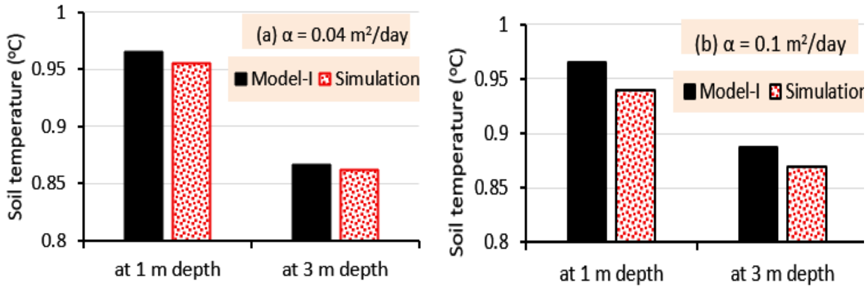

Fig. 7. Comparison between the prediction and simulation results of near-surface temperature.

3.2.2. Simulation analysis with various thermal diffusivities

The simulation results are presented as contours of the temperature gradient in Fig. 8. Four simulation cases are shown in Figs. 8(a) to 8(d). The simulation was repeated to investigate the ground temperature profile for different soil thermal diffusivities of 0.04, 0.06, 0.08, and 0.10 m^2/day. The trend is similar across all cases of diffusivity: soil temperature decreases with depth. The surface predicted temperatures are 26.8, 26.4, 26.1, and 25.8 °C for soil diffusivities of 0.04, 0.06, 0.08, and 0.10 m^2/day, respectively. At a depth of 3.0 m, the simulation predicted soil temperatures of 23.34, 23.28, 23.23, and 23.18 °C for soil diffusivities of 0.04, 0.06, 0.08, and 0.10 m2/day, respectively.

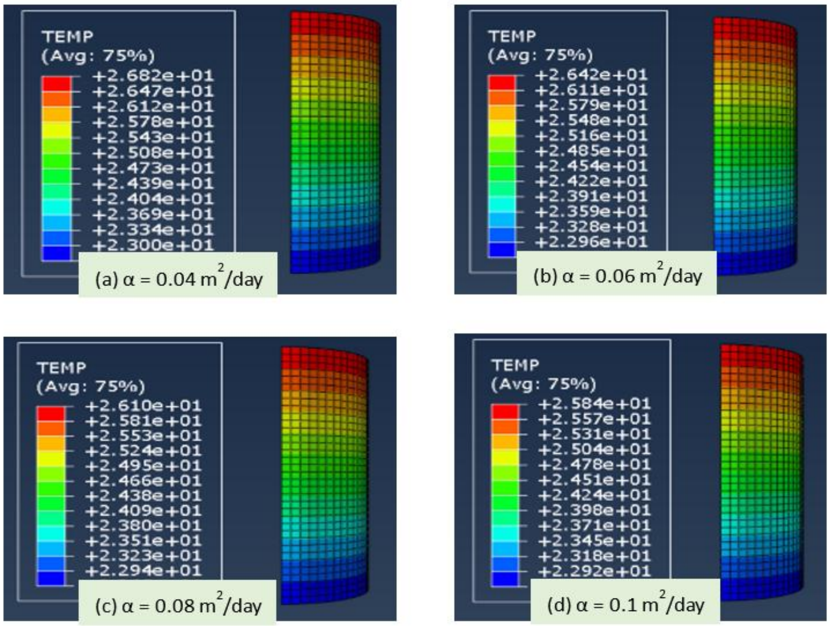

Fig. 8. The simulation results of the temperature variation along the 3.5 m ground depth for thermal diffusivities (a) 0.04 m^2/day, (b) 0.06 m^2/day, (c) 0.08 m^2/day, and (d) 0.10 m^2/day.

The difference between the predicted surface and 3.0 m depth temperatures for the four diffusivities indicates that the simulation accounts for soil properties. The higher soil diffusivity resulted in slightly higher surface and soil temperatures at various depths. The simulation results are comparable to the model's temperature predictions.

Since the simulation results in Fig. 8 are qualitative, a quantitative presentation is essential to analyse the effect of soil thermal diffusivity. All the qualitative numerical results have been compiled and presented in Fig. 9. The results show that, for higher thermal diffusivity, the ground temperatures at all depths are lower than the surface and near the surface. Another observation is that the thermal diffusivity effect is reduced with depth, and the soil temperature becomes the same for all diffusivity values at a depth of 3.3 m. At the surface, the simulated soil temperatures indicate a stronger influence of the soil sensitivity. Furthermore, this influence decreases with depth.

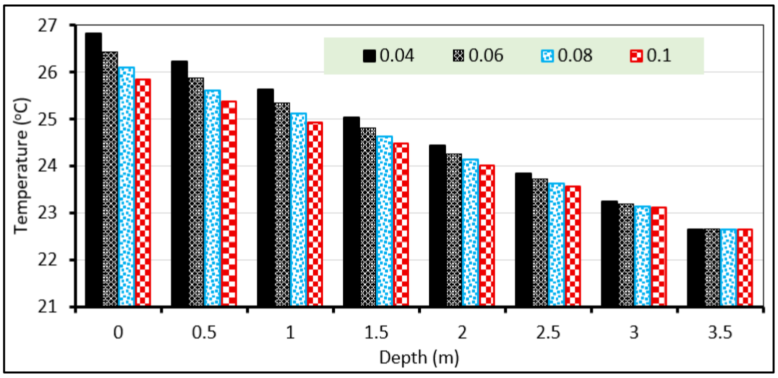

Fig. 9. Simulation results of the ground temperature profile at various soil thermal diffusivities of 0.04, 0.06, 0.08, and 0.1 m^2/day.

4. Conclusions

Analytical predictions, using three different models from the literature, and numerical predictions, using a developed computational procedure in ALTAIR software, generated near-surface thermal profiles for various soil thermal sensitivities. The numerical procedure has been validated with a maximum mean percentage of error of less than 5%. The novelty of the work lies in the solution and comparison of results using the same soil and weather data, and in its first-time ground thermal profiling using ALTAIR software. The significant finding is that soil thermal diffusivity is a sensitive predictor of near-surface thermal profiles. However, numerical and analytical results demonstrate that the influence of thermal sensitivity decreases with depth but remains effective on surface and near-surface temperatures. The results generated from the prediction and computational simulation provide useful data to researchers and engineers in underground installations such as gas pipes, water piping networks, underground cabling, and in-ground energy storage. It is recommended to perform a near-ground thermal profiling under wet and dry soil conditions.

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Nomenclature

C_p	Specific heat, (J/kg·K)
G	Solar irradiation, (W/m^2)
h	Convective heat transfer coefficient, (W/m^2·K)
k	Thermal conductivity, (W/m·K)
Symbol	Definition
T	Temperature, ºC, K
t	Time, s, Day
V	Velocity, m/s

z	Depth in the ground, m
Greek letters	
α	Thermal diffusivity, m^2/s, m^2/day
σ	Stefan-Boltzmann constant, $W/m^2 \cdot K^4$
δ	Annual dumping depth, m
ω	Angular frequency, rad/day
Φ	Phase angle, radian
Abbreviations	
EAHEs	Earth-to-Air Heat Exchangers
GHE	Ground Heat Exchanger
RH	Relative humidity of the air

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